Towards an improved flyway monitoring:

A heuristic framework to integrate count and tracking data

Written by Mohamed Henriques

With thoughts and inputs from:
Theunis Piersma, Allert Bijleveld, Wouter Vansteelant, José A. Alves & Jeroen Reneerkens

Photo: Roeland Bom

Image:

BIRDEYES
rijksuniversiteit groningen
campus fryslân faculty of science and engineering
NIOZ
50 jaar Sovon

Towards an improved flyway monitoring:
A heuristic framework to integrate count and tracking data

Written by Mohamed Henriques[1, 2]

With thoughts and inputs from:
Theunis Piersma[1, 2, 3], Allert Bijleveld[2], Wouter Vansteelant[1, 4], José A. Alves[5, 6] and Jeroen Reneerkens[7].

[1] BirdEyes, Centre for Global Ecological Change at the Faculties of Science and Engineering and Campus Fryslân, University of Groningen, Leeuwarden, The Netherlands.
[2] Department of Coastal Systems, NIOZ Royal Netherlands Institute for Sea Research, Texel, The Netherlands.
[3] GELIFES Groningen Institute for Evolutionary Life Sciences, University of Groningen, Groningen, The Netherlands.
[4] Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, The Netherlands.
[5] CESAM—Centre for Environmental and Marine Studies, University of Aveiro, Aveiro, Portugal.
[6] South Iceland Research Centre, University of Iceland, Laugarvatn, Iceland.
[7] SOVON Dutch Centre For Field Ornithology, Nijmegen, The Netherlands.

This report was produced upon request of Sovon, Dutch Centre for Field Ornithology, to BirdEyes, Centre for Global Ecological Change, University of Groningen, as part of the project 'Innovations for Migratory Bird Monitoring Along the East Atlantic Flyway'. This project is coordinated by the Coastal & Marine Union (EUCC) and financed by the Technical Support Instrument (TSI) as operated by the European Commision's Directorate General for Structural Reform Support (DG REFORM). The project is requested by the Dutch Ministry of Agriculture, Nature and Food Quality also on behalf of its counterparts in Germany and Denmark.

Summary

Migratory waterbirds connect distant regions through seasonal movements, forming migratory pathways or flyways, essential ecological units for conservation. However, human activities and climate change threaten these flyways, underscoring the need for effective monitoring. Current count-based monitoring schemes, while valuable, have limitations in coverage, resolution, and focus on patterns rather than population processes. Electronic tracking devices collect and record position data of individual birds, providing detailed information on spatial-temporal patterns of their movements. Therefore, an integration of tracking technologies into monitoring efforts would offer ways to enhance flyway monitoring, and with due governmental force, flyway conservation. This paper introduces such an integrated monitoring framework. We first outline the knowledge foundations and data types necessary for promoting an effective flyway conservation. Then, with these in mind, and focusing on the potential added value of tracking data, we identify the most outstanding limitations of count-based monitoring and introduce tracking technology as a method to tackle these limitations, using examples of tracking studies in the literature as evidence. We introduce a holistic framework for integrating tracking data into count-based monitoring at flyway scales, in an eight-step roadmap: (1) Defining key stakeholder roles; (2) Selecting target species; (3) Choosing appropriate tracking technology; (4) Designing sampling strategies; (5) Determining tracking effort and duration; (6) Establishing governance structures; (7) Integrating tracking and count data; and (8) Translating results into management and conservation actions. While focusing on coastal waterbirds in the East Atlantic Flyway, the concepts and framework are applicable to any migratory bird group and flyway. As a model for the implementation of such a framework, we work out an integrated waterbird monitoring proposal for the East Atlantic Flyway, providing an exercise of selection of 11 priority species, and offering a flexible budgeting example for 3 representative species. Finally, ethical considerations are discussed, including the need for long-term commitments to financial and institutional investments, carefully consideration of target species to track and catching sites to avoid disturbance and negative impacts of tracking devices, and awareness of the existing regional inequity, investing on long-term capacity building and promotion of fair access to tracking technology and skills.

Table of Contents

List of Tables

1. Introduction

Migratory waterbirds of all kinds connect far away regions of the globe by their seasonal movements between breeding and non-breeding ranges (van de Kam *et al.* 2004). By defining the overall boundaries of corridors used by different species and populations, the concept of flyway was born as “ecological units” within which conservation, monitoring, and research endeavours have been organized (Boere *et al.* 2006, UNEP/CMS Secretariat 2009, Amano *et al.* 2010, van Roomen *et al.* 2013a, 2022, Chan *et al.* 2019b, Li *et al.* 2019, Eren *et al.* 2024). In this way, bird movements not only link different regions of the world, but also the people therein, connecting different cultures, languages, and societal realities.

The waterbirds of a flyway depend on networks of sites with different functions like breeding, foraging, moulting, fattening, emergency stop sites, social gathering, among others (van de Kam *et al.* 2004, Newton 2007, Piersma 2007, Navedo & Piersma 2023). Therefore, the quality and conservation status of these sites will have a strong impact on the life cycle of these birds, directly affecting movement patterns, health, and affecting the vital statistics (survival and breeding success) (Piersma 2012, Piersma *et al.* 2016). The observed increase in human pressure on coastal resources (Halpern *et al.* 2019), and the different forms of anthropogenic occupation and resulting degradation of natural habitats in these sites (Newton *et al.* 2020, Williams *et al.* 2022), have been among the main threats to waterbird populations, directly causing local population declines (Sutherland *et al.* 2012, Martín *et al.* 2015, Chen *et al.* 2022, Martay *et al.* 2023). These pressures reduce or may even eliminate the potential resilience of bird populations, and the ecosystems they depend on, to climate change (Bernhardt & Leslie 2013). It is why, for many decades now, researchers and managers have been working towards assuring the protection of the network of sites migratory waterbirds depend on, with international initiatives like the AEWA (Agreement on the Conservation of African-Eurasian Migratory Waterbirds; https://www.unep-aewa.org/), the CMS (Convention on Migratory Species; https://www.cms.int/), and the WSFI (Wadden Sea Flyway Initiative; https://flyway.waddensea-worldheritage.org/), shaping this necessity into intergovernmental political frameworks, based on the concept of flyways, and defined by the movement ecology of shorebirds.

Under all these agreements there is a strong purpose of pulling efforts to engage in flyway level conservation, which goal could be summarized as ***preserving migratory waterbird populations and the habitats they depend on throughout the network of sites that constitute their flyway*** (Lewis 2016). To achieve this purpose, it is evidently necessary to keep track of the changes in waterbird populations in the flyway to alert responsible agencies when conservation interventions fall short. Amongst the various possible ways to track waterbird populations, the count-based monitoring schemes of non-breeding population levels were chosen and set up at, organized by country, at many sites along the flyway. Nevertheless, because resources are limited, only a fraction of all the sites used globally by waterbirds can be monitored, and as a general strategy, counts are focused on the sites holding a larger number of birds at a given time of the year(Schmeller *et al.* 2012a, van Roomen *et al.* 2013a). Moreover, typically the monitoring of site use is most complete in countries where more financial and human resources are available; take, as an example, northwest Europe or the Atlantic North America (Schmeller *et al.* 2012b, a, Ziolkowski *et al.* 2022, Smith *et al.* 2023).

Once the flyway concept was accepted (Eren *et al.* 2024) it became necessary to integrate knowledge at the flyway scale. Thus, under the formerly called International Waterfowl and Wetlands Research Bureau, now Wetlands International, the International Waterbird Census was started in 1967 and currently includes 143 countries around the globe, representing the major flyways of the world (Wetlands International 2023). Within this program, regular waterbird counts are conducted in a coordinated way (i.e. counts are performed during the non-breeding season of the birds, in January, at all sites), and then numbers are translated into population size assessments and analysed to depict annual trends for each species, at site and at flyway levels (e.g. Hansen et al. 2016, van Roomen et al. 2022).

With so many species and habitats being lost at unprecedented rates (Sala & Knowlton 2006, Cardinale *et al.* 2012, Barton *et al.* 2023), most of which can be attributed to human activities including climate change (Harley *et al.* 2006, Maclean *et al.* 2008, Eriksson *et al.* 2010, Godet *et al.* 2011, Doney *et al.* 2012, Chen *et al.* 2016, Donohue *et al.* 2017, Wauchope *et al.* 2017, Jackson *et al.* 2021), many waterbird populations are also facing declines in most flyways (Boere *et al.* 2006, Piersma *et al.* 2016, van Roomen *et al.* 2022). Thus, there is an urgent need to redouble flyway conservation efforts to protect waterbirds from going ecologically or fully extinct by preventing the loss of key sites along the flyway. Nevertheless, the current monitoring schemes, mostly based on static counts in a selection of sites along the flyway, are far from a perfect all-round method to collect the information needed to achieve the purpose of flyway conservation(Thomas 1996, Finger *et al.* 2016, Schummer *et al.* 2018, Johnson *et al.* 2020, Piironen *et al.* 2023, VonBank *et al.* 2023). This is subject of discussion of this review. We aim to explore ways to improve the current monitoring schemes, inspired by the wave of technological and technical advancements currently made (Pimm *et al.* 2015, Berger-Tal & Lahoz-Monfort 2018, Lahoz-Monfort & Magrath 2021).

The concept of flyway was first used in the Americas between the 1920s and the 1930s, by ornithologists working for the American Museums of Natural History collecting banded dead specimens to investigate migration routes and the distribution of bird species (Eren *et al.* 2024). Only in 1980 it was recycled by ecology researchers as a better term to describe the “biogeographic regions” on which they were counting waterbirds along the East Atlantic Flyway (Altenburg *et al.*

1982). From there on, flyway ecology research for conservation purposes became eminent, particularly in the context of bird mark-resighting (dying with paint first ca. mid 1980s, and then colour-ringing later, from 1990 onwards) to study survival, and migratory patterns and connections along the flyway (Dick *et al.* 1987, Piersma & Jukema 1990, Piersma & Davidson 1992, Piersma *et al.* 1992, Boyd & Piersma 2001, Brochard *et al.* 2002). Movement ecology entered in an already buzzing flyway research and conservation scene, and the science of studying bird movement patterns at different scales fitted like a glove (Eren *et al.* 2024). In quickly became one of the first and obvious fields of knowledge we can turn to, looking for ways to improve monitoring schemes. In fact, the application of movement ecology to address conservation issues has been growing since 2009 (Eren *et al.* 2024), with an increasing number of articles being published between then and 2019 (Katzner & Arlettaz 2020). Despite this, still too few studies exist, with a total of only 16 articles in 2019 (Katzner & Arlettaz 2020).

Indeed, studying the movement of birds is not easy. Traditional methods to track waterbirds, which generated the knowledge that helped to roughly define the boundaries of flyways, involved individual marking (colour dying, rings, and later colour ring schemes (Davidson *et al.* 1999). This is now among the most popular methods allowing to mark high numbers of birds with rings that can be read from the range of a telescope, which steadily developed from ca. 1990 (Piersma & Jukema 1990, Piersma & Davidson 1992, Piersma *et al.* 1992, Davidson *et al.* 1999, Gill *et al.* 2005). Undeniably, ring reading has yielded crucial knowledge on migratory pathways, informed about the links between sites in the flyway, and produced data on the timing of migration, among other important information (Rogers *et al.* 2010, Verkuil *et al.* 2012, Lok *et al.* 2015, Lislevand *et al.* 2017, Reneerkens *et al.* 2020, Bom *et al.* 2022). Nevertheless, this method requires a lot of effort and time investment; learning about individual bird movements involves either recapturing the bird at another moment and in another place, or, more efficient, reading their unique (colour) ring codes.

Tracking devices have been introduced in flyway ecology studies for a few years now, allowing to overcome the shortcomings of individual marking with rings (Davidson *et al.* 1999, Hebblewhite & Haydon 2010, Lei *et al.* 2019, Lahoz-Monfort & Magrath 2021). These devices collect and record the position data of each tagged individual using different types of localization technology and allow us to follow the movements of individuals with very little or no effort after deploying the device (Lahoz-Monfort & Magrath 2021). With the technological advancements, more and more advanced tracking devices are being created, with smaller footprints and higher capabilities in terms of the quality, quantity, and variety of data they can collect. This has led to an increase in the number of tracking studies in recent years (Katzner & Arlettaz 2020, Joo *et al.* 2022).

In this paper we aim to discuss a framework under which the current wave of availability of tracking data and technological advancements in biologging sensors can be used to improve the existing monitoring schemes which are fully reliant on counts, aiming at increasing the knowledge required for an effective flyway conservation. In this review we will first introduce the knowledge foundations required to achieve an effective flyway conservation, and frame what types of data are needed to build such knowledge. Under this conceptual framework, we will list and analyse the current limitations and gaps of count-based monitoring schemes that are hampering the construction of the required knowledge base. Then, we will introduce the current tracking methods used to study migratory waterbird movement ecology, review the available technology, device configurations, and the typology of data that they collect, and highlight the groups of species that are more and less studied. Building on all this, we will then discuss, based on literature and case studies, how each of the limitations and gaps of count-based monitoring can be overcome with tracking technologies and the integration of movement data. Finally, we will lay out a general framework with a roadmap for an improved monitoring at flyway scales by introducing a set of guidelines to combine count-based efforts with tracking data. While doing this, we will also discuss some ethical and fundamental considerations that need to be taken into account when planning the implementation of such framework.

2. What needs to be known for an effective flyway conservation?

Flyway conservation can only be achieved if management interventions are evidence-based. Effective conservation actions need to be built on scientifically sound knowledge foundations about the issues underlining population trends, and on tested solutions. For this, we need to first understand what the questions are that need to be asked. A good ecological question is the first step towards achieving well-thought and well-planned management interventions. Thus, for the purpose of flyway conservation, we need to first determine the knowledge required. In our view, there are seven fundamental questions that need to be answered: (1) What is the spatial-temporal distribution of different species and populations of waterbirds? (2) What is the structure of the populations of each species? (3) How are sites along the flyway connected to each other? (4) What is the population size of different species and sub-species? (5) What are the trends of (sub)populations and (sub)species at the site and at the flyway level? (6) How can changes in population size be understood in terms of the vital rates (recruitment and survival) of each (sub)species, and how do these rates vary in space and time? (7) Do conditions and events at one site affect the options of the birds later on and at subsequent sites and during subsequent seasons (domino and various carry-over effects)? We will further illuminate and expand on each of these questions in the rest of this section.

Spatial-temporal distributions: It concerns mostly the movement patterns of (sub)populations of waterbird species in space and time. As individuals move along their annual cycle through different sites of the flyway, they use specific areas at specific times according to the function of the sites (e.g., (Dodd & Colwell 1996, Reese & Skagen 2017, Chan *et al.* 2019b, Kölzsch *et al.* 2019, Lei *et al.* 2019). This means that building knowledge on spatial-temporal movement patterns will allow to better understand at which periods each site is used, and therefore, when they need to be more protected (Henriques *et al.* 2024). Likewise, by looking at site fidelity, and depending on degrees of environmental variability, we can gain insights on how flexible birds can be in changing their spatial-temporal patterns in face of changes in the availability and quality of sites (Zhang *et al.* 2018, Chan *et al.* 2023). Not less important is the knowledge that studying spatial-temporal distributions can offer regarding the turnover rates of the sites. Turnover rates relate to the number of different individuals using a certain site at a longer timeframe. For example, some sites might be used by few birds at any given moment, but at longer timeframes by a much higher number of individuals, which typically spend little time there, and at different days (e.g., (Frederiksen *et al.* 2001, Lehnen & Krementz 2005, Loonstra *et al.* 2016, Lok *et al.* 2019). Another example is the function the sites serve for birds, which can be inferred by studying how and when they use them in their annual cycle (e.g. (Kölzsch *et al.* 2019, Navedo & Piersma 2023, de Boer *et al.* 2024). Knowledge on these different spatial-temporal patterns of distribution can help us redefine the meaning of importance of a site for waterbird (sub)populations (e.g., (Chan *et al.* 2019b, Lei *et al.* 2019), transcending the traditional, but narrowed, view of the importance of sites only regarding their size or the number of birds of different species using it at a given time (BirdLife International 2016).

Population structure: The occurrence of individuals from different subpopulations or different sub-species in the same site, and at the same time, is relevant when interpreting population trends (Bom *et al.* 2022). This is because different populations and sub-species cannot be interpreted as one unit, as it might significantly influence our perceptions on the trends and population sizes. For example, the importance of a site, and therefore its priority for monitoring and conservation, would be different if we knew that there were more sub-populations of a certain species depending on the area, or if there were sub-species or sub-populations with a higher conservation priority (i.e. higher level in the IUCN Red List of threatened species, or experiencing declines; (Murray *et al.* 2018)). Another example would be if at a certain site co-occurred two different sub-populations that would subsequently migrate to different regions (for example, to different breeding areas or different non-breeding residencies; e.g., (Piersma *et al.* 1994, Kuang *et al.* 2020, Bom *et al.* 2022)); it could be that one of these sub-populations or sub-species would be using areas of higher conservation concern (Lok *et al.* 2011, Studds *et al.* 2017, Kuang *et al.* 2020), and therefore be of higher conservation priority. Knowledge on the structure of populations of waterbird species will help to build a much better perception of the importance of the sites, and help building much sharper management plans that take into account the different needs of different subpopulations or sub-species.

Connectivity: While moving, different migratory waterbird species link different sites throughout the flyway (van de Kam *et al.* 2004). By building knowledge on this connectivity at flyway scales, but also at the scale of countries or regions, we enable the assessment of conservation needs and management actions at the appropriate scale, by integrating the range of sites that are part of each population's life cycle (Boere *et al.* 2006, UNEP/CMS Secretariat 2009). In this way, inter-governmental agreements can be formed, and resources can be pulled to protect species that are not restricted to the borders of just one country. Likewise, knowledge on the connectivity among sites can inform us about the full range of threats and pressures that might be affecting those populations (Iwamura *et al.* 2013, Studds *et al.* 2017, Morrick *et al.* 2022). The intensity of links among sites is also informative, as it indicates what are the sites that are more interconnected by the birds, and therefore need reinforced conservation measures (Iwamura *et al.* 2013, Madsen *et al.* 2014).

Population sizes: The size of a population is among the most used knowledge types for flyway conservation. It is usually based on data that are collected in count-based monitoring schemes (Nagy & Langendoen 2020, Wetlands International 2021, van Roomen *et al.* 2022). The estimation of bird population sizes is very challenging, but nevertheless essential to understand the relative importance of different sites along the flyway for specific waterbird species populations, and to enable trend analysis (Amano *et al.* 2010, van Roomen *et al.* 2022). Some international conventions and classifications of site importance use the relative population size as the main criteria to classify sites under specific labels. The Ramsar Convention and the label of Important Bird Area are examples of this, with very concrete implications for conservation and management of classified sites (Ramsar Convention 2014, BirdLife International 2018).

Population trends: Appropriate and informative assessments of population trends depend on high quality population size estimates (Hansen *et al.* 2016) and on a strong knowledge of the population structure. Within these conditions, population trends are the backbone of much of the conservation actions and prioritization of sites and waterbird species to protect (Boere *et al.* 2006). Building knowledge on population trends will enable the detection of problems at key sites or at flyway scales through the monitoring of waterbird species and populations (e.g. (Amano *et al.* 2010). Important conservation tools like the IUCN Redlist for threatened species depend on trend assessments to determine the conservation priority of populations and species, and their threat status.

Vital rates: Understanding vital rates, i.e. recruitment and mortality, is essential to inform what types of measures are needed to protect populations in decline (Baker *et al.* 2004, Rogers & Piersma 2005, Weiser *et al.* 2020). Although boiling down to the two basic elements of recruitment (for an increase in population size) and mortality (or its complement, survival; for the degree of decrease), the estimation of vital rates comprise several layers of complexity related to individual, sex, age, migration and breeding phenology, etc., entangled with issues of observation and estimation (Sandercock 2006, Weiser *et al.* 2020). Vital rates put the data on population trends into context by asking the questions: are populations changing due to survival (Weiser *et al.* 2020), reproductive output, or a combination of both (Rogers & Piersma 2005, Roodbergen *et al.* 2008, Weiser *et al.* 2018)? By knowing the answer to these questions, we can then start investigating the causes for lower survival or low recruitment (e.g.(Rogers & Piersma 2005, Weiser *et al.* 2018, 2020, Allen *et al.* 2022), and inform what types of management measures are needed (Reneerkens 2022). Survival and recruitment are two important measures at population level, but the former relies on measures at individual level. Individual-level differences in phenotype can be born at different life-history stages, influenced by different types of individual differences, which can be integrated in the individual phenotype, generate a potential carry-over effect, affect its fitness and, therefore, survival (Senner *et al.* 2015). Due to this individual variation within populations, monitoring vital rates require sampling sufficient individuals and during a long period to enable assessments at population level. Thus, it requires long-term data collection and high investment, but with worthwhile returns, as it is among the most valuable data to inform management actions (e.g. (Baker *et al.* 2004, Roodbergen *et al.* 2008, Gibson *et al.* 2018, Allen *et al.* 2022).

Functional linkages between sites: carry-over effects. T Carry-over effects as envisioned by O'Connor et al. (2014) as *'any situation in which an individual's previous history and experience explains their current performance'* were shown to be a mixed bag of inherited and developed phenomena by Senner et al. (2015). They argued that for the purposes of assessments of the role of quality differences of sites along the flyway the category of "reversible state effects", *i.e.*, the downstream consequences of issues at one site and time that can potentially be mitigated at subsequent sites and times is the relevant one. Within a flyway context, this can be interpreted as the effects of changes or pressures over bird individuals that occur in one site of the flyway, but that are manifested and responded to at other sites, periods, or life-history stages. A clear example provided by Rakhimberdiev et al. (2018) is of Bar-tailed godwits reducing their fuelling time on staging areas in the Wadden Sea, The Netherlands, during the northward migration to catch up with earlier snow melt on their breeding grounds, in Siberia. This came with a cost for their survival probability in the first year after reducing fuelling time and departing with lower than warranted fuel stores. Indeed, in years where food abundance in the Wadden Sea was higher, survival probability was no longer penalized in the declining counts at a single nonbreeding site within the Banc d'Arguin, Mauritania (Oudman *et al.* 2020), tallied precisely with the prediction based on conditions further north (Rakhimberdiev *et al.* 2018). Knowledge on such functional linkages show how issues at one site and season affect options at subsequent sites and seasons, with obvious flyway scale implications.

3. How can the required knowledge be built?

With the aim of answering the seven fundamental questions presented on the previous section, and in order to build the knowledge that is required for effective flyway conservation, data are needed. But what types of data? Limitations in resource access and the need to focus efforts advise to sharply define which data needs to be collected to support solid analysis that can answer our questions.

One of the most common data types are **count data**. These refer either to full counts of birds using each site at a given moment, or to partial counts that can then be used to estimate full population sizes using extrapolation methods (Hansen *et al.* 2016, van Roomen *et al.* 2022). Counting is the most traditional data collection method to monitor waterbird populations at local (e.g. (Agblonon *et al.* 2017) and flyway scales (e.g. (Amano *et al.* 2010, van Roomen *et al.* 2013a, 2022, Hansen *et al.* 2016), and have been used mostly with the purpose of monitoring changes in the ecological health of ecosystems, habitats, sites, or of species of conservation concern (Rosa *et al.* 2003, Amano *et al.* 2010, Catry *et al.* 2011, Oudman *et al.* 2020, Henriques *et al.* 2022). This data type contributes towards estimating population sizes, assess population trends, and gain insights into vital rates (in combination with other data types – see below). In this capacity, count data has been the main investment in terms of data collection to inform management and conservation efforts, as the trends in bird numbers is regarded as an indicator of changes or impacts on ecosystems and habitats (Mathot *et al.* 2018).

Genetic assignments are another type of data that contributes towards better defining what the population structure is at each site. By sampling several individuals of waterbird species using a given site and collecting DNA samples, it is possible to gain insights on the occurrence of different subpopulations or sub-species, provided that there is detectable genetic differentiation (e.g. (Rogers *et al.* 2010, Conklin *et al.* 2016, 2022, Zhu *et al.* 2021b, Bom *et al.* 2022) . This information can then be used in combination with other data types like counts and tracking data to answer key questions related to population trends and connectivity (Rönkä *et al.* 2021, Zhu *et al.* 2021b, Bom *et al.* 2022), where the population structure is well defined and then counts are scaled to reflect numbers of different sub-populations or sub-species. This structuring is essential to inform proper trend analysis and guide management and conservation focus (Bom *et al.* 2024).

Another data type that contributes towards building knowledge for flyway conservation is **individual marking and resighting**. By trapping birds, marking a significant portion of individuals from different (sub)populations (for waterbirds typically with metal and colour rings), and resighting them throughout their life cycle, we can estimate population sizes (Gunnarsson *et al.* 2005, Spaans *et al.* 2011), learn about their spatial-temporal distributions (both at population and at individual levels; e.g., (Piersma & Davidson 1992, Gill *et al.* 2005, Verkuil *et al.* 2012, Chan *et al.* 2023), study the connectivity within and between sites in the flyway (Piersma & Jukema 1990, Piersma *et al.* 1992, Davidson *et al.* 1999, Gill *et al.* 2005, Baillie *et al.* 2009, Verkuil *et al.* 2010), estimate vital rates (Boyd & Piersma 2001, Brochard *et al.* 2002, Rogers & Piersma 2005, Lok *et al.* 2017, Reneerkens *et al.* 2020), and even assess potential carry over effects (Weithman *et al.* 2017). Mark-recapture is among the most important data types that helped set the initial boundaries of the flyways, along with sequential and coordinated counts (Dick *et al.* 1987, Piersma & Davidson 1992, Piersma *et al.* 1992). Nonetheless, it requires a lot of effort, both in time and in personnel resources, to enable the collection of data at wide enough spatial and temporal scales.

Finally, **tracking data,** obtained from bio-logging devices that can be fitted onto waterbirds, allows us to monitor bird movements at unprecedented spatial and temporal scales (Hebblewhite & Haydon 2010, Williams *et al.* 2020, Joo *et al.* 2022). This data type is the most technologically dependent, as it relies on devices that collect or provide spatial position information with time stamps. In addition to this, tracking devices can be associated with other types of sensors that simultaneously collect data on environmental (temperature, pressure, salinity, etc), acceleration in 3 dimensions (movement sensors or accelerometers; (Bouten *et al.* 2013), and other types of parameters, which significantly increases our capacity to study birds' behaviours, movement patterns, and responses to anthropic and environmental stressors. Several types of tracking devices are currently available on the market, varying in the way they collect position data (e.g. GPS, satellite, VHF triangulation, etc.), and in the way they transfer the information to the end-user (e.g. radio base-stations, satellite, GSM networks; (Bridge *et al.* 2011). The major limitation in applying this technology to study waterbird movement ecology is the size and weight of the tags, which is known to impact the behaviour and survival of the birds if it exceeds a certain percentage of the weight of the individual, or if it significantly changes its flight aerodynamics, agility, and detectability (Lameris *et al.* 2018, Geen *et al.* 2019, Pakanen *et al.* 2020). Nevertheless, tracing devices typically need memory capacity to store location information, and some kind of energy source to allow location acquisition and information transfer. Because of this, they need to be at the same time large enough to carry the required energy sources (batteries and/or solar panels) and store the data (and potentially transmit it remotely), and small enough to be able to be fitted onto the birds without jeopardizing their safety, health, and capacity to perform their normal activities(Bridge *et al.* 2011, Geen *et al.* 2019, Pakanen *et al.* 2020). The current wave of miniaturization of technology allows for varied combinations of device longevity, spatial precision, spatial and temporal resolution of position data, data transmission, in devices of unprecedent small sizes and weight (Bridge *et al.* 2011, Bouten *et al.* 2013, Bijleveld *et al.* 2022). In this way, tracking data has the potential to contribute towards answering the same questions as individual marking and resighting, but requiring much less time and personnel costs, while typically yielding much higher quality data. In addition, it can also inform about the population structure by potentially showing the existence of different sub-populations or sub-species using a given site, through distinct space uses and spatial-temporal migratory patterns (e.g. (Zhu *et al.* 2021b, Bom *et al.* 2022).

4. Monitoring through counts

Monitoring birds through direct counts has been one of the cornerstones of bird conservation and research for more than a century (Moussy *et al.* 2022), providing a wealth of knowledge on population sizes and trends, and also some information on distributions and phenology (Bart 2005, Schmeller *et al.* 2012b, Simmons *et al.* 2015, Fei *et al.* 2017, Brlík *et al.* 2021, Ziolkowski *et al.* 2022, Belo *et al.* 2023). Count data has been the basis to inform migratory waterbird conservation efforts at multiple scales (local and flyway). For instance, long-term count data has been instrumental in highlighting the alarming declines of migratory shorebird populations worldwide (Martín *et al.* 2015, Simmons *et al.* 2015, Clemens *et al.* 2016, Murray *et al.* 2018, Oudman *et al.* 2020, van Roomen *et al.* 2022, Belo *et al.* 2023, Smith *et al.* 2023), prompting international conservation initiatives (Amano *et al.* 2010, Schmeller *et al.* 2012b, van Roomen *et al.* 2013a, Moussy *et al.* 2022). Beyond abundance metrics and distribution, counts can reveal valuable insights into habitat preferences (Yu & Swennen 2004, Granadeiro *et al.* 2006, 2007, Martins *et al.* 2016), migration patterns (Piersma & Jukema 1990, Piersma & Davidson 1992), and breeding success (Oudman *et al.* 2017), and has supported the identification of important areas for breeding, staging, and non-breeding residency (Albanese & Davis 2015, Chan *et al.* 2019a, Robinson *et al.* 2020). Additionally, data on age and sex ratios obtained during counts can inform population dynamics models (Weiser *et al.* 2018, Johnson *et al.* 2020). Age ratios, for example, can be used to estimate recruitment rates, a key parameter in understanding population growth and decline (Rogers & Piersma 2005, Méndez *et al.* 2018).

Standardized count data collected across flyways (e.g. (Amano *et al.* 2010, International 2012, van Roomen *et al.* 2013a, Wetlands International 2021, Ziolkowski *et al.* 2022) allows for the assessment of the overall health of waterbird populations. By combining data from various countries, researchers can identify populations undergoing decline even if trends are not apparent within individual countries (Amano *et al.* 2010, van Roomen *et al.* 2013b). International monitoring programs like the International Waterbird Census (IWC, (Wetlands International 2023) facilitate data sharing and collaboration between countries. This collaborative approach enables the development of coordinated conservation strategies across entire flyways (Boere *et al.* 2006, Iwamura *et al.* 2014).

While seemingly straightforward, bird count surveys involve a varied set of data collection procedures to ensure robust and comparable results (Rappoldt *et al.* 1985). Typically, trained observers visually identify and count birds within a defined area or along a transect. Standardized protocols, including survey timing, duration, and observer methodology, are essential to ensure data comparability across space and time (Fuller & Langslow 1984, Rappoldt *et al.* 1985, Gregory *et al.* 2004). Statistical analysis of count data allows for the calculation of population estimates. Commonly used methods include distance sampling, which accounts for the detection probability of birds at varying distances from the observer, and occupancy modelling, which estimates the probability of a species occurring within a specific area (Fuller & Mosher. 1987, Nichols *et al.* 2000, Thompson 2002, Burton *et al.* 2004, Gregory *et al.* 2004, Carrascal *et al.* 2008, Murn & Holloway 2016). Once population estimates are obtained from count data, simple statistical trend detection methods like linear regressions can be employed to identify population changes over time (Zeileis *et al.* 2008), making it more accessible to non-specialized professionals. Additionally, by incorporating data on environmental variables alongside count data, researchers can explore the factors influencing population dynamics, such as habitat availability, climate change, or food resource abundance (Catry *et al.* 2011, Summers *et al.* 2012, Simmons *et al.* 2015, Murray *et al.* 2018). Lastly, because of the relatively simple methodological procedures of count monitoring, there are ample possibilities of including citizen science and engaging the general public in monitoring programs (Hofmeyr *et al.* 2014, Robinson *et al.* 2020)

Despite their significant contributions, count-based monitoring programs have methodological limitations that need to be acknowledged. A key challenge is the variation in detection probability depending on several factors, like morphological or behavioural conspicuousness of individuals of the species, differences in habitat cover and visibility, observer experience, weather conditions, among others (Nichols *et al.* 2000, Murn & Holloway 2016). Another limitation of count programs is their potential to miss certain segments of the population. For instance, standard counts may not capture information on breeding success, as nesting birds are often secretive and difficult to detect. Additionally, non-breeding segments of the population, such as moulting birds in secluded areas, may also be underrepresented in count data. Finally, logistical challenges and resource limitations can restrict the frequency and comprehensiveness of surveys. Counting birds over large areas requires significant time and manpower, and budgetary constraints can limit the number of sites surveyed and the frequency of surveys.

5. Gaps and limitations of count-based monitoring

Despite the intrinsic and evident value of count data, and beyond the methodological limitations mentioned in the previous section, count data are also limited in several other ways, namely concerning how they support flyway conservation efforts. We argue that count-based monitoring has limitations that can be structured in three wide groups: (1) limitations related to sites, (2) related to species and (sub)populations, and (3) related to functional analysis and interpretation. In this section we will dissect each of these limitation groups and specify in which way they constitute gaps that significantly affect flyway conservation effectiveness.

<u>Limitations related to sites:</u>

I. **Missing important sites:** Often, count-based monitoring is based on previous knowledge on the location of areas of high congregation of birds at the same time. This knowledge is usually derived from local observations in the field. However, this naturally creates a strong bias towards areas that are more studied, more accessible, have more local resources, and a longer history of bird-related activities, like birdwatching and conservation. Such bias will naturally translate into missing important sites that should be included in the monitoring, but are not because they are not known, rather than because they are not used by a large number of birds. Another limitation is the way the importance of sites is considered. The concept of importance is traditionally linked to the number of birds that are using a given site at the same time (and with the current count regime, mostly in winter; see (Zwarts 1988, Zwarts & Piersma 1990, Amano *et al.* 2010, van Roomen *et al.* 2022, Navedo & Piersma 2023), and also the diversity of the bird community depending on that site, in accordance with international standards of labels like IBA (BirdLife International 2016). However, this is a limited concept of importance, as it does not consider the spatial-temporal aspects like turnover rates, connectivity, or seasonality (discussed below), nor does it take the function that the site may serve within the birds' life cycle into account.

II. **Function of sites:** The function that each site serves for the birds is a key aspect to understand its importance at local and flyway scales (Navedo & Piersma 2023). Nevertheless, count data is often unable to take this into account when defining the importance of sites, and when choosing priority sites to focus monitoring efforts on. Count data alone cannot capture the information on the function of the site, and traditionally, only field observations have been providing hints on this. Nevertheless, because the timeframe on which field observations is collected is typically limited, and because there is only so much information that can be collected through field observations alone, there is usually very little knowledge on the true function of particular sites for the local and the flyway populations of bird species. While functions like moult, foraging, or resting areas might still be possible to identify while counting birds, other functions might be much less obvious. For example, there are sites that might serve as emergency stopover areas during the migrations when there are bad conditions (Shamoun-Baranes *et al.* 2010, Overdijk & Navedo 2012), while other sites might not host many birds every year but may become crucial for entire bird populations when conditions in important sites are worse.

III. **Connectivity:** Through their movements, birds connect different sites during their annual cycle, both at local (Lamb *et al.* 2024) and flyway scales (Schmaltz *et al.* 2018, Lisovski *et al.* 2021, Verhoeven *et al.* 2021, Bom *et al.* 2024). However, these links are very difficult to capture and quantify only using count data. This is because with count data of waterbirds we are unable to track individual movements between different sites along the flyway, and although it is possible to get vague ideas on large scale movements along known sites in a flyway network (e.g. (Piersma & Davidson 1992), this knowledge is incomplete, biased to known sites, and prone to erroneous interpretations when different sub-populations are mixed in some of the sites of the network (Zhu *et al.* 2021b, Bom *et al.* 2022). In this way, count data is limited in how it can provide a good representation of the connectivity among sites, and of the varying levels of dependency of the birds to different sites along their annual cycle. Proper knowledge on the connectivity and movement patterns across different sites of migratory shorebirds has been proven to have a direct relevant impact in crucial managing decisions regarding infrastructure development within and around protected areas (e.g. (Nightingale *et al.* 2023).

IV. **Turnover at sites:** Counts represent a still picture in time of the numbers of birds at a certain location. This means that if the turnover rate at this site is high (i.e., the individuals are spending little time in the site and then moving on to another) and if in addition, there is a temporal mismatch between the individuals (i.e., individuals are not arriving and leaving the site at the same time), count data will provide a poor estimate of the real number of individuals using the site, and consequently underestimate its importance for the species' population.

V. **Seasonality:** The temporal patterns of birds' occurrence at sites is one of the major factors that need to be considered when planning count-based monitoring, particularly when dealing with partially or fully migratory bird populations. Depending on the objectives of the monitoring program, counts need to be conducted at a certain time of the year, allowing to sample the target populations either at the most stable period, or at the period with the highest count, depending on the goals. To understand the temporal patterns of occurrence at each site, highly frequent counts are required, especially in periods of more movement (e.g., migration, pre-breeding dispersal). Nevertheless, an effective count-based monitoring set-up and interpretation of the data depends on a solid knowledge on the seasonality of the bird populations using the target site, and count data is limited in the ways it can provide this information.

<u>Limitations related to species and populations:</u>

I. **Distributional range changes:** count-based monitoring is implemented through regular counts that aim to monitor changes in bird populations. When these counts are coordinated at flyway scales, the variation in the numbers of birds counted throughout time is analysed to depict trends in populations sizes. Nevertheless, birds might exhibit changes in their movement patterns in response to changes in their environment, which can amount to alterations in their normal distributional range at large scales. Alterations in distributional range can be due to range contraction (when the flyway-scale range is constricted to only some of the sites that were previously used) or to range shifts (when the normal range of the population changes, with the birds using alternative sites that were not used before while abandoning some of the sites previously used). When the distributional range of bird populations change, it becomes very difficult to disentangle the effects of potential population declines or increases from those caused by distributional range changes only using count data. Consequently, a reliable interpretation of trends from count data is hampered by this entanglement, as it becomes unclear whether trends at the monitored sites are expressing true population declines, or if these are just a manifestation of distributional range changes (e.g. (Rakhimberdiev *et al.* 2011, Verkuil *et al.* 2012). Distributional range changes can happen at both local and flyway scales.

II. **Mixed sub-populations or sub-species:** in sites where different sub-species or sub-populations of the same species occur, count data will very seldom be able to identify these differences and assess the numbers of each population unit separately. Nevertheless, as this knowledge is key (see section 2), any conservation assessments based solely on counts will potentially induce to major errors if sub-populations or sub-species are lumped together.

III. **Poorly covered species:** some migratory waterbird species are widely distributed across a large range, and do not occur in large numbers in a few important sites. A good example are sanderlings *Calidris alba*, which are typically challenging to cover with count-base monitoring schemes due to their low-density occurrence and are poorly monitored in most of their range only with count data(Burton & Blew 2008, Jeroen Reneerkens *et al.* 2009). This is because it is difficult to find and count the wide number of sites along which they are distributed. Other examples are species that are very difficult to detect for being too similar to other more numerous species, and that might therefore go unnoticed.

IV. **Demographic structure:** Demographic parameters like sex and age ratio have important implications in the productivity rates of bird populations, and these are typically poorly captured and represented in count data. Particularly in instances when male and female, or juvenile and adult individuals have different space use and migratory patterns, and when sexual and age-related dimorphism is not visually evident, count data will not be able to depict when there are sites mostly used by one of the sexes or age classes than others. This limitation leads to a poor knowledge on the implications of the loss of certain sites for population productivity and structure due to differential survival rates between ages and sexes. Additionally, when temporal changes on sex and age ratios occur, there will also be missed by count data.

Limitations related to data analysis and interpretation:

As a consequence of the limitations of count-based monitoring related to sites and related to species and populations, listed above, the analysis and interpretation of the resulting data can be heavily affected, compromising the quality of the knowledge we acquire from it. As a result, the way we interpret the count data we have will depend on additional knowledge that cannot be provided by count-based monitoring alone. More specifically, these limitations can be translated in the following:

I. Population estimate errors: count data is frequently used to perform estimates of the population size of bird species. Because it is often nearly impossible to count all birds using a given site, sampling and sub-sampling efforts are used in extrapolative models to devise the total number of individuals, both at local and flyway scales. Nevertheless, due to the limitations related to sites and related to species and populations, population size estimates might be prone to large errors. For example, poor knowledge on important sites to monitor, or about the sub-species or sub-population composition of monitored sites can significantly affect the population size estimates, affecting our perceptions of the trends and our capacity for effective conservation interventions.

II. **Sampling design:** often, count-based monitoring lacks sufficient knowledge on spatial-temporal patterns to set appropriate sampling designs, including the best sites, periods, and frequencies to conduct counts. This will lead to poor monitoring data and, consequently, poor knowledge on populations' sizes, conservation status, and trends. Similarly, changes in the distribution range throughout time can also make sampling designs inappropriate due to range shifts or range constrictions not be taken into account.

III. **Poor picture of real population trends**: frequently, the areas that are monitored with counts are chosen for the high number of birds they host. However, they often do not represent the fullness of the sites that are used by birds but are probably the areas of higher quality. In these cases, if the quality of the remaining sites decreases, with negative impacts on bird populations' survival, this will likely not be detected through count-data. This is because birds will tend to move to higher quality sites (e.g., (Gill *et al.* 2001, Ntiamoa-Baidu *et al.* 2014), giving an apparent perception of positive trends (or at least of non-decreasing trends) for the population, while in fact survival is decreasing and those populations are threatened.

6. The added value of tracking technology and data

Tracking technology plays a pivotal role in advancing our understanding of movement ecology in avian species. The utilization of tracking data offers unparalleled insights into the spatial and temporal dynamics of bird movements, surpassing traditional methodologies in accuracy and scope (Long & Nelson 2013). Unlike other methods like counts and mark-resighting, which are limited in spatial coverage and temporal resolution, tracking technology provides continuous, high-resolution data on individual bird movements (Bridge *et al.* 2011). This enables researchers to discern intricate patterns of behaviour, such as migratory routes, stopover sites, and habitat preferences, with unprecedented detail and accuracy (Robinson *et al.* 2010, Guilford *et al.* 2011, Joo *et al.* 2020).

Various tracking technologies have been developed to study bird movements comprehensively, each with distinct advantages and applications (Bernd-Ulrich Meyburg *et al.* 2011, Bridge *et al.* 2011, Guilford *et al.* 2011, Bouten *et al.* 2013, Bijleveld *et al.* 2022, Iverson *et al.* 2023, Gould *et al.* 2024). Broadly speaking, there are mainly three technical aspects to consider in the way tracking devices work, and that distinguishes the various options that are currently available: (1) how location acquisition is done, (2) the way data transmission occurs, and (3) how they are powered. These three aspects will be the main determinants of how small the devices can be, which spatial and temporal resolution they will deliver, and which ecological answers they can provide (Bridge *et al.* 2011, Williams *et al.* 2020). Regarding location acquisition, tracking technologies utilize diverse positioning methods, including GPS, radio frequency identification (RFID), and geolocation, each offering different spatial and temporal resolutions (Bridge *et al.* 2011, Gould *et al.* 2024). While GPS devices provide high-precision coordinates at frequent intervals, geolocators offer lower resolution but can be deployed on smaller bird species. For data transmission, some device constructs employ satellite communication or GSM/LTE connection protocols for real-time data transmission and tracking, while others store data onboard for later retrieval, which can be done with limited range remote connections (hand-held antennas or fixed towers) or directly from the device itself. Both the position acquisition and data transmission are energetically costly, with the most efficient and convenient methods being typically more energetically expensive. This is what will determine power source configurations, with on board lithium batteries being the current standard, frequently coupled with additional solar panels for longer-term data collection. Ultimately, the selection of tracking technology depends on the research objectives, target species, and logistical constraints, with each approach offering unique advantages for studying bird movements and informing conservation efforts (Hebblewhite & Haydon 2010, Bridge *et al.* 2011).

Satellite telemetry, for instance, enables long-distance tracking of birds across vast expanses, elucidating migratory flyways and habitat connectivity on a global scale (Gill *et al.* 2009, Chan *et al.* 2019b, 2023, Exo *et al.* 2019, Lei *et al.* 2019, Kuang *et al.* 2020, Bom *et al.* 2022, 2024). Furthermore, light-level geolocators provide valuable insights into migratory behaviour by recording changes in light intensity, thereby inferring latitude and longitude coordinates during bird migration (Niles *et al.* 2010, Fijn *et al.* 2013, Lisovski *et al.* 2016, 2021, Lislevand *et al.* 2017, Rakhimberdiev *et al.* 2017, Pakanen *et al.* 2018, Reneerkens *et al.* 2020). GPS tracking devices, on the other hand, offer fine-scale spatial resolution, facilitating detailed assessments of habitat use and movement patterns within specific areas (Bouten *et al.* 2013, Schwemmer *et al.* 2016, Bakker *et al.* 2021, Jourdan *et al.* 2021, Gauld *et al.* 2022, Rodrigues *et al.* 2023). An even finer level of spatial-temporal resolution can be achieved with some radar-based devices, which use very high frequency (VHF) signals emitted by the tags, that can be detected by receiver stations through triangulation (Iverson *et al.* 2023, Gould *et al.* 2024). To achieve a high resolution however, a high density of receivers is required at relatively small distances from the tags, which limits the spatial extent that can be effectively covered at high resolutions. The current state-of-art using VHF-emitting tags is represented by Time-of-Arrival systems like the Advanced Tracking and Localization of Animals in real-life Systems (ATLAS), which uses receiver towers to detect and determine the position of a tag by measuring the strength of the signal received and the time it takes to be detected (Bijleveld *et al.* 2022). For additional details on available tracking technologies and technical specifications of devices currently used to track birds of different sizes, see Annex 1 and tables within.

The bottom line is that tracking studies yield critical information needed to answer key biological and ecological questions (Hebblewhite & Haydon 2010), which should constitute the basis of conservation and ecological management strategies. By elucidating the spatiotemporal dynamics of bird movements, these studies inform habitat conservation efforts, delineate priority areas for protection, and identify potential threats along migratory routes (Katzner & Arlettaz 2020). As a vivid example, thanks to research powered by tracking data of the threatened Black-tailed Godwit *Limosa limosa*, the development of a new airport in the Tagus estuary (Portugal), next to one of the most important staging sites for this species' population along the East Atlantic Flyway, was stopped by environmental governmental agencies (Nightingale *et al.* 2023). In the same direction, recent research in the Wadden Sea islands has highlighted that a significant part of the habitat used by Eurasian Spoonbills *Platalea leucorodia* during post-breeding dispersion movements would be destroyed by current plans to build underground powerlines between the North Sea and the Dutch coast (Henriques *et al.* 2024).

7. Caveats of tracking technology

Notwithstanding their valuable contributions, the utilization of tracking devices for monitoring waterbird populations presents certain caveats that warrant careful consideration. Primarily, the attachment of tracking devices, especially on smaller bird species, may impose additional energetic demands and potentially alter their behavior or movement patterns due to the added weight or discomfort (Lameris & Kleyheeg 2017). For this reason, researchers are only able to track birds with sufficient resolution starting from a certain weight (see Guilford et al. 2011, Iverson et al. 2023, Gould et al. 2024, Michel et al. 2024). This limitation can have as a consequence a bias understanding (towards larger species and individuals) of flyway-scale movement patterns of waterbird populations as a whole. Additionally, the financial costs and other technological limitations associated with tracking technology (e.g., longevity of devices or of fitting materials, fitting methods, geographic varibility in network coverage to download data, etc.; (Scarpignato *et al.* 2023) can limit the sample size and duration of studies, potentially reinforcing biases (Michel *et al.* 2024) and hindering comprehensive assessments of population dynamics. This is because while tracking data provides valuable insights into individual movements, extrapolating these findings to the entire population requires caution, as individual variation and sampling biases may influence the representativeness of the data.

It is thus crucial to acknowledge that tracking data alone cannot provide a complete picture of waterbird populations. Integrating tracking information with complementary data sources, such as ground or aerial surveys, mark-recapture with colour-rings, and remote sensing, is essential for a holistic understanding of population trends, habitat utilization, and potential threats. By recognizing and addressing these caveats, researchers can maximize the benefits of tracking technology while ensuring the robust and comprehensive monitoring of waterbird populations. This can only truly be successful with committed support and investment (also finantial) of all flywyay conservation stakeholders.

Despite these caveats, specifically for the purpose of flyway conservation, tracking data contributes towards several of the required knowledges identified in section 2, which will be dissected in the next section. By contributing to our understanding of these ecological processes, tracking data can guide informed decision-making for flyway conservation and ecosystem management at local and global scales.

8. How can tracking contribute to improve count-based monitoring?

The limitations of count data in contributing towards the required knowledge for flyway conservation purposes were identified in section 5. The question now remaining is: how can tracking data help addressing these? In this section, we provide specific research examples from the literature that portrait results, methods or analysis that clearly supports in tackling each of the limitations of count-based monitoring. We primarily focus on showing examples that use tracking devices, but in the absence of these, we make use of research based on mark-resighting data to illustrate the potential of tracking studies.

Contributions to tackling limitations related to sites:

Focusing on identifying **missing important sites**, Chan et al. (2019) studied the movement of 32 Great Knots *Calidris tenuirostris* in the East Asian-Australasian Flyway with satellite transmitters (4.5 g solar PTTs from Microwave Telemetry). Within three years they found that 63% of all stopping sites used by these birds were not previously recognised as important sites for the species, while allowing at the same time to establish the **connectivity** among the different sites used by the species. Similarly, in the Americas Flyways, McDuffie et al. (2022) used 4.0g PinPoint GPS Argos-75 satellite tags (from Lotek Wireless) with high location precision, to study migration routes, connectivity and stop-over areas of Lesser Yellowlegs *Tringa flavipes*. The authors were able to identify several important stopping and non-breeding areas in Central and Southern America by following birds tracked in different breeding and staging areas in North America. They also showed how the different breeding populations were establishing the connectivity among the spatially segregated breeding areas, and the same stop-over and non-breeding sites they used further south. In the East Atlantic Flyway, eleven Grey Plovers *Pluvialis squatarola* were tracked from Lower Saxon Wadden Sea, in Germany, using solar powered 5 g ARGOS PTT satellite trackers (from Microwave Telemetry), which allowed to describe the connectivity of all sites used, and also unveil three entirely unknown staging sites between the Wadden Sea and the Arctic (Exo *et al.* 2019). Månsson et al. (2022) described the annual movements of 76 Greylag geese *Anser anser*, which were fitted with solar powered GPS tracking devices from Ornitela (OT-N35 and OT-N44) and Made-by-Theo (Theo Gerrits). Following these birds allowed us to learn of a new wintering area in Sweden, which was unknown for the species 30-40 years ago. Finally, satellite tracking of 21 birds from the newly described Black-tailed godwit subspecies *Limosa limosa bohai* (Zhu *et al.* 2021b), allowed to unveil their non-breeding residency in Thailand, and a previously uknown breeding area for the species in the Asian Arctic (Zhu *et al.* 2021a)

(Bom *et al.* 2022) studied the migration routes, breeding destinations and annual-cycle timing of 52 Bar-tailed Godwits *Limosa lapponica* using wintering areas in the Middle East (Oman) and West Africa (Mauritania and Guinea-Bissau). Using solar-powered 4.5-g Argos PTTs (from Microwave Telemetry), the authors established the **connectivity** between the used sites for the two populations of the species throughout all of the species annual cycle, and at flyway level, identifying important connections between breeding, staging, and non-breeding sites. At a more local level, (Nightingale *et al.* 2023) studied the connectivity among sites used by Black-tailed godwits *Limosa limosa* in the Tagus estuary, Portugal, aiming at assessing the impact of potential developments within and around that Especial Protection Area on these birds. While the authors used mark-resighting data for this analysis, the same kind of analysis could have been carried out using tracking data to determine the local scale connectivity among sites used by Black-tailed godwits, but with higher resolution, confidence, and robustness. Tracking data was used this way for the network analysis showing the connectivity among the sites used by Lesser Yellowlegs at the flyways scale in the Americas (McDuffie *et al.* 2022).

In the work of (Lok *et al.* 2023) and (Lok & Piersma n.d.), the authors classified several behaviours of Eurasian spoonbills *Platalea leucorodia* using UvA-BiTS GPS trackers equipped with tri-axial accelerometers and high-precision GPS receivers (ca. 1 m of error). Through these studies, Henriques et al. (2024) performed and assessment of the important sites used by these spoonbills in the Wadden Sea, and using the behavioural data obtained with the algorithms in (Lok *et al.* 2023), the authors determined the **function of these sites** (i.e. foraging areas or resting areas) for that breeding spoonbill population in the post-breeding dispersion period (Henriques *et al.* 2024). Kölzsch et al. (2019) used 91 high-resolution GPS tracks (collected by several solar powered device configurations, namely GSM/GPS, UHF/GPS, GPRS/GPS and Argos/GPS manufactured by E-obs GmbH, Univ. of Konstanz, Madebytheo and Microwave Telemetry, respectively) of Western Palearctic greater-fronted geese *Anser a. albifrons,* to identify sites with breeding and moulting functions for these populations by using different thresholds of time spent in the sites by tracked individuals.

Regarding the limitation of the **turnover at sites**, the work done by (Kempenaers & Valcu 2017), which aimed at studying male competition strategies in polygynous systems, showed that male individuals of Pectoral sandpipers *Calidris melanotos*, subsequently moved through a considerable part of the entire species breeding range sampling multiple potential breeding sites. By tracking the movements of these males using 5 g Solar Argos PTT-100 (Microwave Telemetry) satellite transmitter, the authors were able to describe this multiple site-sampling behaviour of 120 male Pectoral sandpipers. A by-product of this study, however, was that turnover rates at these sites could be calculated, which all had very high turnover rates of males as they move through them at different timings, and being these sites used by much more individuals than it would be assumed only using count data. Verkuil et al. (2010) also provided reliable estimates of **turnover rates** for Ruffs *Philomachus pugnax* staging in the Netherlands during the spring migration by estimating the total staging duration using radio-trackers on 95 birds. Nevertheless, in some contexts, colour-ringing might provide a more efficient method to calculate turnover at sites (e.g, Loonstra et al. 2016, Vervoort et al. 2022).

Bom et al. (2022) identified only a brief overlap at pre- and post-breeding Siberian staging areas between the occurrence of two distinct Bar-tailed godwit populations, one that breads in the Western Siberian plains and go to Middle East for the non-breeding residency period, and another that breeds in the Tamyr Peninsula and spends the non-breeding residency period in West Africa. If the sites where there is a brief overlap among the populations is to be monitored using counts, it would be crucial to know when this overlap occurs, so the timing of counts can be adjusted in such way that we always know from which population the birds that are being counted belong to. This qualifies as knowledge on the **seasonality** of bird populations and species, which tracking can contribute towards to tackle count data limitations in this aspect. In similar ways, studying the phenology of bird migrations (e.g. Carneiro et al. 2019, Chan et al. 2019b, Exo et al. 2019, Lisovski et al. 2021, McDuffie et al. 2022) will contribute towards the same goal, informing on the timings of the occurrence of birds in different sites and providing required framing for the interpretation of count data in these sites.

Contributions to tackling limitations related to species and populations:

Although **distributional range changes** have been detected also by analysing count data (like for e.g., with Graylags in the East Atlantic Flyway; Ramo et al. 2015), their detection is often late because it is dependent on being constantly on the lookout in field observations. With continuous tracking efforts to monitor bird populations, it is possible to detect range changes very early on (like the partial flyway-scale range change detected in Greylag geese in Sweden; Månsson et al. 2022), allowing for immediate adjustments on count areas and periods. Based on (qualitative and quantitative) count data, Rakhimberdiev et al. (2011) also reported a global redistribution towards the north of the Ruff population in the East Atlantic Flyway, due to a loss in habitat quality on staging sites in The Netherlands. The authors suggested that birds might have changed migration routes, avoiding The Netherlands and following a more eastern migration route, consequently ending up at more eastern breeding destinations. Nevertheless, due to the limitation of the count data used, strong assumptions had to be made to support the redistribution hypothesis and to explain the redistribution mechanisms, given other alternative explanations (Rakhimberdiev *et al.* 2011). The redistribution hypothesis and evidence for the mechanisms that caused it ended up being corroborated by ringing data from mark-resighting efforts, where it was shown a relationship between the redistribution of the population and decreased fuelling rates in The Netherlands due to farming practices (Verkuil *et al.* 2012). The potential use of tracking data for this analysis in place of mark-resighting of ringed birds would have provided the same evidence but with much higher detail, higher quality information, and less effort.

The clear delineation of populations along the entire annual cycle at flyway scales is crucial to allow the identification of **mixed sub-populations or sub-species** at monitored sites, which qualifies as one of the limitations of monitoring solely based on count data. Tracking studies can unequivocally tackle this gap by allowing to track the whereabouts of individuals from different populations and determine if there are any spatial-temporal overlaps during their annual cycle that can influence population estimates and trend assessment. (Kölzsch *et al.* 2019) provide an excellent example of this. By tracking 91 Western-Palearctic white-fronted geese from two different populations (North Sea and Pannonic), they were able to identify very strong spatial-temporal overlaps between the two populations during moult period in the Taimyr Peninsula, while very little to none during spring and autumn migrations, or elsewhere in their breeding and non-breeding ranges. On another hand, using satellite-tracking Bom et al. (2022) described the individual migrations of 52 Bar-tailed godwits of the *taymyrensis* taxon from two different non-breeding residencies (West Africa vs Middle East). The authors showed that birds from these two non-breeding ranges did not overlap in almost any part of their annual cycle, breeding in different regions of the Arctic, and only coinciding briefly and occasionally during pre- and post-breeding moments in Siberian staging areas. Nevertheless, despite the two populations units displaying virtually no overlap in their flyways, and differing significantly in body size and shape, no genetic differentiation was found, highlighting the crucial role of tracking data here to unveil the two population units and define potential (non)overlap sites (Bom *et al.* 2022). Finally, Zhu and others described a new sub-species of Black-tailed godwits (*L. l. bohai*) based on genetic assignments, morphological differences (Zhu *et al.* 2021b), and differential migratory annual patterns with satellite and GPS tracking of 21 birds (using PTT-100 5 g solar satellite transmitters from Microwave Technology, and HQPG2009P 9 g solar GPS/GSM trackers from Hunan Global Messenger; Zhu et al. 2021a).

Contributions to tackling limitations related to data analysis and interpretation:

Waterbird counts are used to produce population estimates, a crucial knowledge type to allow evaluating conservation status of population and inform management actions (e.g., (Stroud *et al.* 2004, Amano *et al.* 2010, van Roomen *et al.* 2022). Nevertheless, the accuracy of population estimates depends on a very well-timed monitoring set up and **correct sampling design**. Issues like the migratory connectivity and spatial dispersion of bird populations varying throughout the annual cycle will determine how much birds are clustered during the non-breeding season, severely influencing the areas that need to be monitored (Piironen *et al.* 2023). Likewise, annual variation or changes in environmental conditions that determine migratory phenology will also greatly affect the ideal timing to count different bird species to ensure good population estimates (Maclean *et al.* 2008, Finger *et al.* 2016, Piironen *et al.* 2023, Bom *et al.* 2024). Even the turnover of individual at sites that need to be monitored need to be taken into account, as the ideal scenario would be to monitor at the moment when turnover is lowest (Amano *et al.* 2010, Lok *et al.* 2019, Mu *et al.* 2022, Vervoort *et al.* 2022). Poor knowledge on these aspects will lead to **inadequate sampling designs**, which in turn can cause **population estimates errors** that might be too large to allow reliable trend assessments. For example, it was reported that count data of Pink-footed goose *Anser brachyrhynchus* in Svalbard was negatively biased at up to -20% compared to population estimates conducted using Integrated Population Models (Johnson *et al.* 2020).

The use of tracking data to mitigate population estimate errors from counts has been explored in recent studies. For example, using tracking data of 68 Taiga Bean geese *Anser fabalis fabalis* (tracked with 30 g “Ibis” solar GPS/GSM by Ecotone Telemetry, and with Ornitella’s UAB 45 g OrniTrack-44 and 38 g OrniTrack-38 GPS/GSM devices), (Piironen *et al.* 2023) studied which where the best areas and periods to count birds of this population during the non-breeding residency period. The authors did this by describing the migratory connectivity and the spatial-temporal changes in migratory and distribution patterns, and tested the performance of several years of census data in counting in the right time and places throughout the years. They found that because migratory connectivity between breeding and non-breeding areas was moderate to low, and because there was a substantial variation within the non-breeding season in the connectivity and spatial dispersion timing, current autumn and spring count schemes were underestimating the true population size. Similar examples of the application of tracking data to demonstrate that count data often underestimate true population size were reported by several authors on multiple waterbird species (e.g. (Finger *et al.* 2016, Schummer *et al.* 2018, Johnson *et al.* 2020, Chen *et al.* 2021).

9. A framework for an integrated flyway monitoring: perspectives on an implementation roadmap

In previous sections we made the point that there were many knowledge types that, combined, could provide the best possible insights to guide flyway conservation efforts. In that sense, we advocate for an integrated flyway monitoring for bird populations, where these different data types are incorporated within a structured multidisciplinary monitoring scheme. While it is our opinion that this data and knowledge integration needs to be done for all data types identified in section 3, in this section we focus on proposing a framework to guide a roadmap on how the integration of tracking and count data can be achieved, with the aim of improving current and new monitoring programs at flyway scales.

Within our proposed framework we advocate that when designing a roadmap for such integration, several steps need to be taken, which if prioritized will guide to a **successful, cost-efficient, ethical, and inclusive implementation.** **Successful** refers to a monitoring program that will provide the best possible knowledge to inform successful measures to tackle current declining trends in bird populations, and actually reverse them, improving the health and status of bird populations and of their habitats. **Cost-efficient** relates to a well-balanced setting in which investments in tracking devices and in field expeditions to deploy them will inform an efficient selection of key monitoring sites and of count methods, potentially lowering the cost-benefit ratio in the long-term, compared to traditional count-only settings. **Ethical** in ways that ensure the best practices during tagging and counting activities to minimize the disturbance and other negative impacts over bird communities, in the way the different roles of implementation actors and stakeholders are recognized and respected, and also by ensuring equitable data sharing policies. And **inclusive** refers to a monitoring scheme that places local institutions, researchers and indigenous communities at the heart of the implementation process, based on the sharing of knowledge between these actors and international partners, ensuring a truly inclusive fusion of local and global flyway approaches.

The framework for an implementation roadmap

Bellow we introduce the key steps that in our opinion need to be taken when designing a roadmap for an integrated flyway monitoring program.

Step 1: Defining the role and involvement of key stakeholders

Taking into account the needed expertise and multidisciplinary nature of an integrated monitoring program, the first step into building a roadmap is to consider which are the stakeholders that need to be involved from the initial design phase, and what their role will be. An open and inclusive approach at early stages will ensure that the monitoring program can be implemented with the participation of the right experts, national and international institutions, and of members of the local communities. Ensuring a collaboration among all these stakeholders is a must if we want to set-up a well-structured and sustainable monitoring program.

Connecting with **professionals with long-term experience in counting, tagging and tracking in the target sites and along the flyway** will be essential to ensure a successful and cost-effective monitoring program, building on previous experience and allowing to also standardize methods across the flyway. **Local and international researchers** are among the most important stakeholders to ensure long-term and well-designed tagging sampling at site and flyway scales. **International and national conservation and management institutions** accumulate extensive experience in setting and implementing monitoring programs and on conducting counts.

Designing the monitoring programs at local levels together with **local institutions and local communities** will ensure a healthy relationship with international partners and a local sense of ownership of the monitoring scheme, aspects that are crucial to guarantee a long-term successful and stable program. Promoting locally driven data collection and curation is also essential to empower local institutions and communities, which can be achieved by promoting their involvement, and where needed, by supporting strong and long-term capacity building. **Local NGOs and community associations** are the ideal partners to implement this. **Governmental parties** like ministers of environment, national park institutions, and others, are also essential partners that will provide legal permission of access, support the setting up of monitoring activities, and will often be involved in data collection, curation, and coordination.

Step 2: Selecting target species

Selecting the species on which efforts of combining tracking and counts should be made is before anything else a very flyway and site-specific exercise. Bird species that will be target of such monitoring effort should be typically seen **as sentinels of change in their environment**, and storytellers that would bring forth the message about how global changes (in climate and in human development and activity patterns) are affecting them, and their environment. In practice this means that species that are more sensitive to these changes or that respond to them in more "measurable" ways should be favoured.

In addition, depending on the main motivation for the monitoring program, the selected **species should be representing more than just themselves**; for example, they may represent the different habitats within the ecosystems composing the flyway, the different ecosystem functions of the bird species (e.g., benthivores, piscivores, filter-feeders, etc.), distinct foraging behaviours, migratory strategies (e.g., residents, partially migratory, or fully migratory), migration types (e.g., loop, leapfrog), or other ecological or conservation-related subjects.

Another important selection factor to take into account is the **conservation status of the species**, by ensuring the inclusion of species representing different extinction threat levels (based on global and/or national IUCN RedList of Threatened Species (IUCN 2023) or with different perceived or measured trends (e.g., (Koleček *et al.* n.d., Ramo *et al.* 2013, Nagy & Langendoen 2020, van Roomen *et al.* 2022, Smith *et al.* 2023). This will help us assess what is underlying the differences between species or populations that are doing well and those that are declining. The national and international i**mportance of species as cultural and conservation emblems** might be another factor to take into consideration, as selecting species with high profile will contribute towards winning the support of the society (both at local and flyway scales) and open funding prospects.

Not less important are more practical considerations about **how adequate are the species for fitting tracking devices**, in terms of their size, body structure, and behaviour in relation to the available technology (i.e., if they can be safely fitted with tracking devices without hindering their normal activity patterns or reducing their fitness and survival probabilities). Likewise, it is important to take into account **how possible is to set up a count scheme for the species**, with representative sampling, and easily standardizable. It is always advisable to select species for which **there is already experience in handling, trapping, and tracking**, as well as for which **there is already long-term data available**. This will ensure that the tagging efforts are already informed by previous experience, making it more efficient and less costly, while also adding to more long-term efforts already in place, with the evident benefits that come with building on ongoing knowledge and pulling resources. Additional details about ways to select priority species for tracking can be found in Annex 2. This includes a summary of a recent global review on shorebird tracking studies, with a list of priority shorebird species for tracing globally (Michel *et al.* 2024), and a proposal from the authors of the report for a list of 11 priority species to be considered for an integrated monitoring in the East Atlantic Flyway (Table S3 within Annex 2).

Step 3: Choosing the right type of tracking technology

After the target species selection, the adequate tracking setting needs to be chosen for each of them. But this might prove to be more difficult than expected, despite the diverse range of tracking technologies currently available and the constant advances in the miniaturization of devices (Williams *et al.* 2020). Several aspects come into play in this step. These should be considered while always keeping in mind the main purpose (integrated monitoring) and the questions that are being targeted with the tracking effort (sections 3 and 7; (Börger 2016, Katzner & Arlettaz 2020, Williams *et al.* 2020).

Firstly, depending on the species ecology and behaviour, the **minimum spatial and temporal resolutions** need to be chosen. These will determine how detailed is the tracking data (i.e., how the location is acquired) and how frequently will location data be acquired and stored. Naturally, the higher the resolution, the higher the quality of the data, but this comes at the cost of battery life, longevity, and weight of the device. Light-based (GLS) and satellite triangulation technologies provide low spatial resolution but lighter devices, while GPS enabled devices acquire much more accurate locations but are heavier and more prone to drain battery fast.

Also weighing in to this trade-off is **the data transmission method**, with more convenient technologies like satellite and/or GSM/GPRS transmission not requiring going to the field to retrieve the data, but costing more financially and in terms of battery consumption and wight of the device. Radio and Bluetooth technologies on the other hand, require going to the field with receiving antennas that need to be at a minimum distance of the tracking devices to connect to them and download the data, but allow the devices to be much smaller and to consume much less battery. For species that are easier to recapture, devices without data transmission (i.e., that need to be retrieved to collect the data) can also be considered, allowing to make them even lighter and more precise.

The behaviour of the species is key to understand which the ideal device is to track their movements; species that spend a lot of time in or under water (like diving ducks or seabirds) will require special casing around the devices to ensure water proofing. In the case of some seabird species, like puffins or guillemots, the time spend under water is so high while foraging that it might not make sense to fit a high frequency location acquisition device. There are also species that spend a lot of time, at certain stages of their annual cycle, in areas with very poor GPRS and 4G coverage, which might influence our choice in the data transmission method or strategy. For species that use areas that are difficult to approach to use antennas to download data, the data transmission method also needs to be carefully considered.

The **spatial scope of the tracking** is another key aspect that will help determine the ideal tracking device for a species. If the intent is to track the movement throughout its whole annual cycle, location acquisition and data transmission methods need to be selected in order to allow for that (e.g., using GPS-GSM or satellite tracker devices with solar panels). If the main interest, however, is focused at understanding the fine scale movement of birds at a specific site, systems like ATLAS might be more adequate, lowering costs and increasing the quality of data within a limited area.

Finally, and inarguably the most important factor is **the final weight of the tracker**, and which percentage of the total body weight of the animal it represents. The usual “rule-of-thumb” is that the device weight (including all casing and attachment accessories) should not surpass 3% of the total weight of the individual it is being fitted on, but this will largely depend on the device shape and size as well (Geen *et al.* 2019, Gould *et al.* 2024). Additional considerations regarding the minimum weight individuals can carry need to be made if tracking devices are intended to remain attached for at least one entire annual cycle; many bird species will have considerable weight fluctuations throughout different annual life stages (Pienkowski *et al.* 1979, Scott *et al.* 1994, Zwarts *et al.* 1996). Device weight is among the main limiting factors in fitting tracking devices onto smaller species. Bird species like sanderlings *Calidris alba*, curlew sandpipers *Calidris ferruginea*, and smaller, have been seldom tracked due to this limitation and GLS devices have been among the few that have wielded information on their movements (Weiser *et al.* 2015, Lisovski *et al.* 2016, 2021, Reneerkens *et al.* 2020). Very recent and ongoing studies are now finally using the latest available GPS devices that use Bluetooth and radio to transmit data (see Annex 1), and which will reveal new information on movement patterns for these small migratory waterbirds.

Step 4: Setting an adequate sampling design (sample size and representativity)

It is common knowledge that the selection of counting sites needs to be done in such a way that they are representative of the diversity of habitats and the spatial distribution of the populations being monitored. The same concerns regarding the **spatial representativity** should also apply to tracking birds. Depending on specificities related to the behaviour and movement patterns of the target species, trapping to fit tracking devices need to ideally aim at representing the highest diversity of sites used. There are two ways of trying to achieve this. One is by trying to use the local knowledge on the occurrence of the species to define several trapping sites distributed throughout the potential area of occurrence of the species. These need to match, as much as possible, the sites that will be counted. The other way, which can apply to migratory birds and that depends on previous knowledge on the connectivity between sites in the flyway (for example, through ringing data), is actually to identify one area in the flyway that all, or most, birds of that population visit, and tag them there. This will allow a random sampling of the birds of that population (assuming that there is no sex- or age-dependent timing of migration or use of the area), which will later migrate back to our sites of interest and distribute evenly throughout the areas that will be counted. This method is still rarely used intentionally due to administrative constraints related to where the funds can be spent and where the trackers should be fitted.

The **representativity of the age and sex structure in the population** is also another important sampling design consideration. Many coastal waterbird species show sex or age differences in timing of migration and/or habitat and site use during parts of their annual cycle, often due to sexual dimorphism, differences in personality, and experience (Mathot *et al.* 2007, Catry *et al.* 2012, Van Den Hout *et al.* 2017a). Some young birds might explore different foraging areas than adults (Van Den Hout *et al.* 2017b) or migrate differently (e.g., by going to different non-breeding areas (e.g., Snell et al. 2021), or by staying in non-breeding residency areas during the first summer; Martínez-Curci et al. 2020, Navedo & Ruiz 2020, Reneerkens et al. 2020), while some females might find more prey in some habitat layers than males (Duijns *et al.* 2014, Basso *et al.* 2024). These differences might warrant being captured by the sampling design when setting up a counting and tracking integrated monitoring program, by targeting to track birds of both sexes, and both adults and juveniles, and by attempting to also include sites to include both sexes and ages, and discern between these groups during counting, when possible and feasible.

Lastly, the **sample size** needs to be very carefully considered (i.e., the number of birds of each species and of each age and sex class). A weak investment in tracking can wield sample sizes that are too low to draw any conclusions or might even bias our perception and understanding of the movement patterns of the birds. But not every species needs an especial consideration of the sex or age structure (because they might all be doing the same, e.g., (Gherardi-Fuentes *et al.* 2020), and some populations are more variable in their space use patterns than others. Because we cannot know this beforehand, pilot studies are important to help determine the minimum sample sizes that are needed for each specific species. Very often these are already available in the literature, from previous or ongoing studies, which need to be carefully considered during planning of an integrated monitoring program. We advise to consider maintaining a sample size of at least 20-30 individuals per (sub)population in each year, for species with narrower distributions, and 50-60 individuals for species with wider distributions. For more details on sample sizes for example tracking efforts following this framework, see Table 1.

Step 5: Defining the minimum duration of the tracking effort

The inclusion of tracking into count-based monitoring efforts wield primarily two advantages: a short-term, where the knowledge on the space use, distribution, spatial temporal patterns, connectivity at local and flyway scales, and migratory patterns is established, and a longer-term advantage, where the potential temporal changes in these movement patterns can be picked up, and used to adjust counting sites, periods, frequencies, and methods. To benefit from the later advantage, tracking efforts need to be long-term, based on continuous efforts of trapping and tagging birds of the target species to maintain a relatively high number of tracked birds throughout several years. Defining the minimum duration of the tracking effort is as easy as defining the minimum duration of the counting data, in the sense that by definition tracking efforts should be kept for as long as the monitoring program is in place and for as long as monitoring itself is needed (which we would argue that it is always).

The frequency at which birds need to be captured and new tags need to be fitted will depend on the longevity of the tracking devices in use, on the type of tracking devices deployed, and on the survival rate of the birds of the population. Some tracking devices will remain for several years on the bird they were fitted on, while others will either fall/be removed from/by the bird, have a dead battery, or malfunction within a year. Sometimes the mortality rate of the birds during their annual cycle is so high that the probability of losing a tracked bird within a year is quite significant. These factors will determine with which frequency (if early, or if more sparse) new devices will need to be deployed to maintain a minimum number of birds tracked for that population.

Step 6: Designing the governance structure

An integrated monitoring program combining both local and flyway scales will invariably produce tracking and counting data with intricate institutional ownership characteristics. Data should be collected through an international effort but lead at national and regional levels. It thus requires an **international governance structure representing all the stakeholders** listed in Step 1 of this section at an institutional level. This body of institutions throughout the whole flyway should function as a **coordination unit for all the monitoring efforts** taking place at national levels, ensuring the standardization of the methods, and coordinating data integration, sharing, and the communication among stakeholders of different areas and regions. The suggested governance structure will thus be supported by interinstitutional agreements with clear and simplified administrative procedures, and would include **several technical coordinating units**, including one for tracking and movement data, one for counting set-ups, one for data integration, analysis and production of technical reports, one for capacity building and technical support to national partners, and one for communication between partners and towards the society.

Data curation will be an important role within the governance structure and given the complexity of integrating data bases with different origins, a **global data base** should be created, which will serve as a template for local data bases, ensuring maximum compatibility between the data sets. Good recent examples of this for shorebirds are the European Global Wader Tracking Data Project (https://www.globalwader.org) and the Shorebird Science and Conservation Collective (Harrison *et al.* n.d.), and for seabirds the longer-term well-established Seabird Tracking Database (https://www.seabirdtracking.org). **Norms of standardization and ethical guidance for tracking and count data** should be put together in manuals (based on relevant ongoing efforts and proposals in the literature at several of the flyways), which would be made available to all data collection partners. A close collaboration between scientific researchers, conservation managers, governmental agencies, local and international NGOs, and local communities will be key for the success of the governance structure of such an integrated monitoring scheme. Nevertheless, it is essential that the procedures of this body are made as simple and accessible as possible, based on ethical and collaborative guidelines, and to be absolutely transparent in its procedure and decision making to ensure it is trusted by all partners.

Step 7: Integrating tracking and count data

The integration of both data types should start before data collection, when the sampling designs and methods are being defined, when the tracking devices are being selected, and through the collaboration of researchers, conservation institutions and local communities. Following these stages, when synchronized tracking and counting data are finally available, the stakeholders more involved in the technical aspects of monitoring (like data analysis) would be responsible for the integration of the two data sets. Being the primarily objective to improve our knowledge on how bird populations are changing at local and flyway scales, the first steps would be to describe, for each year of tracking, what was the space use (e.g., home and core ranges), habitat use (e.g. relative time spent in different habitats, or habitat suitability models), behavioural patterns (e.g., by classifying behaviours with accelerometer data or using speed thresholds, and applying machine learning, State-Space, Dynamic Time Warping, or Hidden Markov models), migratory pathways (e.g., using migration corridor or directionality analysis, or models like Individual-Based and Dynamic Brownian Bridge Movement models), connectivity between sites (e.g., with network analysis), migration phenology, turning rates at sites, among others. Similarly, for count data, for each year the population size (either from total counts or from sampling and then using extrapolation models based on suitable habitat area) should be estimated.

With these descriptive steps concluded for the first year of data, a close inspection of both data sets will allow to determine (1) whether the sites that are highlighted as the most important with the tracking data (based on analysis of space and habitat use, behavioural patterns, turnover rates, and connectivity) coincide with the sites that were selected for the counts, both at local and flyway scale, and (2) if the periods when the counts are being made are when most of the tracked birds are already using the sites, based on the analysis of migratory phenology and turnover rates to determine seasonality and other temporal patterns in the movements of the birds.

As subsequent steps, the changes between years need to be assessed by analysing the variation in all descriptive variables measured with tracking data, both spatially and quantitatively, and for count data by means of trend analysis, where the changes in the estimated population sizes will be quantified. Combining these two data sets would then allow to (1) assess if the changes in the space and habitat use patterns along the years led to the emergence of new important areas, or the abandonment of other important areas in ways that warrant an update of the selection of count sites; (2) analyse the variation in the temporal patterns of occurrence caused by changes in migratory phenology, turnover rates, or in the seasonal movement patterns, and assess the need to update count periods and frequency; (3) reinterpret any trends depicted from count data by looking at possible large scale changes in the spatial-temporal dynamics of the bird populations that can bias count data (e.g., range distribution changes, persistent shift in migratory phenology, change in habitat use and preference).

Through a process such as the one described above, both data types can be integrated in complementary ways to improve monitoring at flyway scales. But in addition to that, the integration of both data sources will also improve how we interpret count data and potentiate more accurate measures of population sizes and trends. By using count data and a sufficiently large sample size of tracked birds, fair inferences can be made regarding the survival rates of the population (combining population trends and survival of tagged individuals) and the processes that might underline declining trends. Moreover, by informing about the areas where mortality might be more elevated, and where threats might be significantly affecting the species at population levels, population trends can be put into quite informing contexts. The contextualization layer that tracking adds to count data is among the most powerful outcomes of their integration.

Step 8: Translating integrated monitoring results into management and conservation

The final step within this framework for a roadmap is the same as the first step within management and conservation action plans (Schwartz *et al.* 2018). Management decisions towards the purpose of flyway conservation should be based on what we know rather than on what we think, i.e. scientific knowledge (Schwartz *et al.* 2018) including the properly analysed data coming from monitoring programs. Nevertheless, the knowledge transpiring from an integrated monitoring setting, published as stepping stones in the scientific literature, needs to be made available to be used to design and implement conservation action plans. This can be done (1) with targeted conservation and management reports, which reviews the research published in scientific journals, to translate the answers of the questions into evidence-based management conservation recommendations, with a decision-making perspective; and (2) through communication targeting the society, with attractive and summarised formats (videos and films, presentations, newsletters, social media posts, posters and flyers, radio spots, among others) focusing on conveying a few key messages deriving from the monitoring data captured within the research papers an conservation reports, and aiming at changing the perspective of the general public and of target stakeholders like funders and governmental institutions. There are issues in the real world. For examples, funding for the science is often taken for granted, especially leading to lack of investments in high quality data analysis and interpretation. What is usually poorly programmed also is the step that translates solid scientific knowledge into products that inform the general public (and this includes most managers and all policy makers) or even better, appeals to their imagination. It is our strong recommendation to give more attention to both the science and the imagination in the future.

10. An exercise budgeting required resources to implement tracking into monitoring

For the purpose of exemplifying an implementation of tracking into monitoring schemes, we made a budgeting exercise for three representative species taken from the priority species list (Annex 2), which we present bellow in Table 1. Note however that in this table, only costs related to the equipment and field work are included. Budgeting for the implementation of tracking into monitoring schemes must account for various expenses beyond the costs associated with acquiring, deploying, and maintaining tracking devices; the required resources span over many other categories. In this section we discuss the different costs that need to be considered.

Tracking devices vary in price depending on the size, battery life, and functionality required for different bird species (Gould *et al.* 2024). Small and lightweight devices are essential for tracking smaller birds without impeding their natural behaviour, which often increases the cost. Additionally, the recurring costs of data transmission and device maintenance should be included in the budget, as well as one-off costs related to the acquisition of supporting equipment to download the data from the tags, like (mobile or stationary) antennas and receivers.

Fieldwork expenses are another major consideration and include travel costs for researchers to access remote breeding, stopover, and non-breeding residency sites across multiple countries in the flyway. Accommodation and subsistence costs for field teams can be unpredictably and highly variable, especially in remote or high-cost regions. The project also needs to budget for the equipment and supplies necessary for capturing and tagging birds, such as mist nets, cannon nets, bait, and tagging materials (including metal and colour rings, and ringing material). Safety equipment for field personnel, including first aid kits and communication devices, is essential to ensure the safety and efficiency of field operations. Personnel costs are easier to budget, and encompass salaries for field researchers, technicians, and data analysts, as well as potential stipends for local collaborators and volunteers.

Data management and curation is also a critical component of tracking projects. Budgeting for data managing software, database management systems, and potentially cloud storage solutions, including cyber security, is necessary to handle the large volumes of data generated by tracking devices. The costs of training for researchers and data managers in using these tools should be considered.

Among the most relevant, but often underfunded parts of this process is data analysis, interpretation, and scientific reporting. The massive amounts of data collected will need to be handled by highly skilled researchers, that will try to answer the different questions by thoroughly analysing the data and preparing manuscripts with the results for publication. This will require funding for the human resources needed for this, and also time to allow a proper analysis and interpretation of the data, and publication of the outputs. Effective communication and dissemination of research findings are essential for conservation impact. Budget allocations for publishing results in open-access mode in scientific journals, creating outreach materials, and attending conferences to present findings are important to ensure that the data informs conservation strategies and policies. Similarly, the translation of the obtained results to management needs to be conducted by qualified personnel, who will ensure that the results of the research are boiled down to conservation recommendations. Not less important is including feedback to local communities and institutions that participated in data collection, and an engagement to presenting the results in comprehensible ways to these stakeholders and society sectors needs financial investment but has massive returns at a longer term.

Capacity building is crucial to achieve data equity at a flyway scale and improves data quality and quantity by ensuring local ownership of monitoring schemes. This requires long term investment from the implementation consortium, with different forms of capacity building needed, including training in field methodologies to local stakeholders, field courses to students and protected area professionals, and higher-level engagement by promoting master and PhD degrees for local students and local researchers. Raising capacity locally in all stages of tracking projects, from design to data collection, analysis, interpretation and publication, requires significative financial investments, but has been proven critical to achieve successful conservation (Şekercioĝlu 2012, Schmeller *et al.* 2017, Lucrezi *et al.* 2019).

11. Final considerations

Bird counts have been and continue to be a powerful tool for monitoring waterbird populations, providing vital information for conservation efforts (Moussy *et al.* 2022). Nevertheless, they represent one among several data types that are required to support a truly effective flyway conservation. In this work we introduce the different types of knowledge needed for this purpose, and the types of data that need to be collected to build such varied knowledge. While recognizing the value of count data, we analyse in detail *why* and *how* count data in isolation are limited and insufficient to monitor bird populations, aiming at ensuring their flyway-wide conservation. Focusing on tracking data, we offer sustained arguments on how this data type can address the limitations of count-data and propose a framework with clear steps for a roadmap to combine tracking and count data into an integrated monitoring scheme. The proposed framework can be applied to all flyways of the world, and although this review is focused on coastal waterbirds as a case study, the concepts discussed and presented are not limited to this study system, being applicable to any bird group.

Among the most important considerations for an integrated monitoring set up is the need to recognize the importance of long-term commitments and necessary investments for both tracking and count efforts at flyway scales. The lack of continuous funding or long-term involvement and commitment of institutions and stakeholders to tracking efforts aiming at improving monitoring is one of the main impediments hampering the building of the required knowledge blocks. This is frequently due to the current way funding streams for research and conservation are organized at global and local scales, which are insufficient to sustain long-term efforts. Designing and implementing the roadmap proposed here requires a change in the way these investments are perceived.

In this work we present arguments to promote the integration of tracking into current and future monitoring settings. However, we feel the need to call attention to the fact that careful and informed species selection for a wider tracking effort is not only useful to help direct efforts, but also a tool to avoid the temptation of “tracking everything that moves”. Fitting tracking devices onto birds involves significant risks and disturbance to individuals, sites, and populations (Bowlin *et al.* 2010, Weiser *et al.* 2015, Lameris *et al.* 2018, Geen *et al.* 2019, Pakanen *et al.* 2020). There is therefore an ethical component regarding the trade-offs between disturbing birds and learning from their movements. In this sense, only the most adequate species (see section 9 and 10, and Annex 2) should be considered for tagging, and mass disturbance of all species for tracking are rarely beneficial, with few exceptions related to local scale projects with minimal tag effects (e.g. Bijleveld et al. 2022). Moreover, moving forward, we believe there is a need to reinforce studies assessing the impact of tracking devices and trapping practices on bird individuals and populations, particularly focused on species and tracking devices for which there is a lack of evidence on this regard. Such call has been made by Lameris & Kleyheeg (2017), which showed that the increase in the number of waterbirds tracking studies in the scientific literature was not accompanied by an increase of reports on impacts of tracking on individuals and populations. Ensuring that tracking practices follow strict ethical rules is essential to build trust among all stakeholders in an integrated monitoring framework, as well as from the society in general. (Lameris & Kleyheeg 2017) offer an excellent framework for standardizing the reporting of methods in primary tracking studies and standardized protocols to measure effects of tracking devices on waterbirds.

With the advancement of new technologies and diversification of the offer of tracking devices in the market, prices begin to significantly decrease, making the technology more accessible for researchers. Nevertheless, the avenue of the inclusion of tracking into flyway scale monitoring will also potentially promote an increase in the regional inequity, particularly regarding the access to tracking technologies and the skill set required to integrate them into monitoring programs. This is due to financial capacity, and historical conservation and research context being vastly different among low- and high-income regions of the world (Nuñez *et al.* 2019, Soares *et al.* 2023). Regional inequity in knowledge production and access is by now widely known within the scientific community (Nuñez *et al.* 2021). Metrics comparing low- and high-income regions in subjects like the number of publications, access to key ecology journals, or the number of collaborations and co-authorships, are a testimony of this inequity (Gui *et al.* 2019, Nuñez *et al.* 2019, 2021). Flyway conservation is by definition global, in the sense that it relies on knowledge from different parts of the world (Nuñez *et al.* 2021), which are interconnected by the migratory movement of birds. But it is also local, as understanding local environmental conditions and pressures is essential to frame or answer ecological questions about migration and about population trends (Aubin *et al.* 2020). True understanding of these global ecological patterns can only come when data collection and availability is balanced along the flyway (Nuñez *et al.* 2021), which in turn, is only possible if local knowledge generation, led by local-based research, is strong enough in all regions of the flyway (Aubin *et al.*

2020, Soares *et al.* 2023). This concept, to which we refer to as “Glocal Ecology”, should be at the heart of the integrated monitoring framework proposed here.

Table 1. Estimated costs of flyway scale tracking for 3 representative species selected from Table S3 in Annex 2 of the report.

Study system	Gaps/Questions	Tracking system type	Tracking system cost (one-off)	Tracking system cost (annual)	Sample size	Number of sites	Field work	Catching equipment	Team	Salary personnel	Total per year	Total one off
Common Tern	Missing imortant sites	Interlink Nano (https://interrex-tracking.com/nano/; or GPS-GSM without solar pannel (https://www.gm-tracking.com/lightest-gpsgsm-5g-hqbg0603-product/)	5000	1000	20	2	10000	5000	2	9000	96000	15000
	Connectivity											
	Seasonality											
	Distributional range changes/Flyway boundaries											
	Poorly covered species											
	Demographic structure/age-sex spatial-temporal segregation											
	Population structure/Mixed-populations or sub-species											
	Function of the sites	ATLAS	20000	60	100	2	15000	5000	2	9000	78000	45000
	Turn-over at sites											
Bar-tailed godwit	Missing imortant sites	GPS-GSM (https://www.gm-tracking.com/global-tracking-hqbg1205-with-acc-sensor-product/; https://interrex-tracking.com/mini/ ; https://druid.tech/products/debut-series/debut-mini/)	0	1200	20	3	25000	7500	5	9000	282000	7500
	Connectivity											
	Seasonality											
	Distributional range changes/Flyway boundaries											
	Poorly covered species											
	Population structure/Mixed-populations or sub-species											
	Demographic structure/age-sex spatial-temporal segregation											
	Function of the sites	ATLAS	20000	60	100	2	30000	7500	5	9000	162000	47500

	Turn-over at sites											
Sanderling	Missing imortant sites	Interlink Ultra (https://interrex-tracking.com/ultra/; https://druid.tech/products/customized-solutions/ultra/)	5000	1500	20	3	25000	7500	5	9000	300000	22500
	Connectivity											
	Seasonality											
	Distributional range changes/Flyway boundaries											
	Poorly covered species											
	Demographic structure/age-sex spatial-temporal segregation											
	Function of the sites	ATLAS	20000	60	100	2	30000	7500	5	9000	162000	47500
	Turn-over at sites											

Note 1: *Prices are rough estimates in Euro. This budget is made with a flyway scale approach in mind. There is also local scale endevours that should be considered, for which similar questions can be addressed using different tracking methods and technologies, and even different study systems*

Note 2: Explanation of columns
Study system: example of 3 representative study systems to calulate resources needed for tracking
Gaps/Questions: Related to section 8 of the report
Tracking system: Type of tracking device adequate for the species and for the gaps/questions to be addressedd
Tracking system cost (one-off): unit price of support equipment for tracking devices (antennas and other infrastrucutural costs)
Tracking system cost (annual): unit price of tracking devices (including recurrent data costs)
Sample size: recomended number of birds to track annually in each site
Number of sites: number of sites where count is being conducted in the flyway where trackers will also be deployed
Field work/catching: expensesincluing field trip costs like travel, accomodation, food, licenses, access
Team: number of people required in catching teams
Salary personnel: salary costs per team member per catching expedition (assuming a consultancy daily rate of 600 eur and 15 days of field work per site per year)
Total per year: Calculated as: (Tracking system cost (annual) x *Sample size* x *Number of sites) + (Field work/catching* x *Number of sites) + (Team* x *Salary personnel* x *Number of sites)*
Total one-off: Calculated as: (Tracking system (one-off) x *Number of sites) + Catching equipment*

12. References

Albanese, G. & Davis, C.A. 2015. Characteristics within and around stopover wetlands used by migratory shorebirds: Is the neighborhood important? *Condor* **117**: 328–340.

Allen, A.M., Jongejans, E., van de Pol, M., Ens, B.J., Frauendorf, M., van der Sluijs, M. & de Kroon, H. 2022. The demographic causes of population change vary across four decades in a long-lived shorebird. *Ecology* **103**.

Altenburg, W., Engelmoer, M., Mes, R. & Piersma, T. 1982. *Wintering waders on the Banc d'Arguin, Mauritania. Report of the Netherlands Ornithological Mauritanian Expedition 1980*.

Amano, T., Székely, T., Koyama, K., Amano, H. & Sutherland, W.J. 2010. A framework for monitoring the status of populations: An example from wader populations in the East Asian-Australasian flyway. *Biol Conserv* **143**: 2238–2247.

Aubin, I., Cardou, F., Boisvert-Marsh, L., Garnier, E., Strukelj, M. & Munson, A.D. 2020. Managing data locally to answer questions globally: The role of collaborative science in ecology. *Journal of Vegetation Science* **31**: 509–517.

Baillie, S.R., Robinson, R.A., Clark, J.A. & Redfern, C.P.F. 2009. From individuals to flyways: The future of marking birds for conservation. *Ringing and Migration* **24**: 155–161.

Baker, A.J., González, P.M., Piersma, T., Niles, L.J., De Lima Serrano Do Nascimento, I., Atkinson, P.W., Clark, N.A., Minton, C.D.T., Peck, M.K. & Aarts, G. 2004. Rapid population decline in red knots: Fitness consequences of decreased refuelling rates and late arrival in Delaware Bay. *Proceedings of the Royal Society B: Biological Sciences* **271**: 875–882.

Bakker, W., Ens, B.J., Dokter, A., van der Kolk, H.J., Rappoldt, K., van de Pol, M., Troost, K., van der Veer, H.W., Bijleveld, A.I., van der Meer, J., Oosterbeek, K., Jongejans, E. & Allen, A.M. 2021. Connecting foraging and roosting areas reveals how food stocks explain shorebird numbers. *Estuar Coast Shelf Sci* **259**: 107458.

Bart, J. 2005. Monitoring the abundance of bird populations. *Auk* **122**: 15–25.

Barton, M.G., Martay, B., Hereward, H.F.R., P.-H.J.W., Robinson, R.A., Scott, S.E. & Williams, J.M. 2023. *Climate change and migratory species: a review of impacts, conservation actions, indicators and ecosystem services. Part 2 – Conserving migratory species in the face of climate change*.

Basso, E., Ruiz, J., Linscott, J.A., Senner, N.R., Weegman, M., Ballard, B. & Navedo, J.G. 2024. Movement ecology during non-breeding season in a long-distance migratory shorebird: are space use and movement patterns sex-biased? *Behav Ecol Sociobiol* **78**: 67.

Belo, J.R., Dias, M.P., Jara, J., Almeida, A., Morais, F., Silva, C., Valadeiro, J. & Alves, J.A. 2023. Synchronous Declines of Wintering Waders and High-Tide Roost Area in a Temperate Estuary: Results of a 10-Year Monitoring Programme. *Waterbirds* **45**: 141–149.

Berger-Tal, O. & Lahoz-Monfort, J.J. 2018. Conservation technology: The next generation. *Conserv Lett* **11**.

Bernd-Ulrich Meyburg, Paul W. Howey, Christiane Meyburg & Klaus Dietrich Fiuczynski. 2011. Two complete migration cycles of an adult Hobby tracked by satellite. *British Birds* **104**: 2–15.

Bernhardt, J.R. & Leslie, H.M. 2013. Resilience to Climate Change in Coastal Marine Ecosystems. *Ann Rev Mar Sci* **5**: 371–392.

Bijleveld, A.I., van Maarseveen, F., Denissen, B., Dekinga, A., Penning, E., Ersoy, S., Gupte, P.R., de Monte, L., ten Horn, J., Bom, R.A., Toledo, S., Nathan, R. & Beardsworth, C.E. 2022. WATLAS: high-throughput and real-time tracking of many small birds in the Dutch Wadden Sea. *Animal Biotelemetry* **10**.

BirdLife International. 2016. Important Bird and Biodiversity Areas (IBAs).

BirdLife International. 2018. Global IBA Criteria - BirdLife International Data Zone.

Boere, G.C., Galbraith, C. a, Stroud, D. a, Colquhoun, I., Scott, D. a & Underhill, L.G. 2006. *Waterbirds around the world: a global overview of the conservation, management and research of the world's waterbird flyways*, First (C. A. G. and D. A. S. G.C. Boere, ed). The Stationery Office Limited, Edinburgh.

Bom, R.A., Conklin, J.R., Verkuil, Y.I., Alves, J.A., de Fouw, J., Dekinga, A., Hassell, C.J., Klaassen, R.H.G., Kwarteng, A.Y., Rakhimberdiev, E., Rocha, A., ten Horn, J., Tibbitts, T.L., Tomkovich, P.S., Victor, R. & Piersma, T. 2022. Central-West Siberian-breeding Bar-tailed Godwits (Limosa lapponica) segregate in two morphologically distinct flyway populations. *Ibis* **164**: 468–485.

Bom, R.A., Piersma, T., Alves, J.A. & Rakhimberdiev, E. 2024. Global temperature homogenization can obliterate temporal isolation in migratory animals with potential loss of population structure. *Glob Chang Biol* **30**.

Börger, L. 2016. Stuck in motion? Reconnecting questions and tools in movement ecology.

Bouten, W., Baaij, E.W., Shamoun-Baranes, J. & Camphuysen, K.C.J. 2013. A flexible GPS tracking system for studying bird behaviour at multiple scales. *J Ornithol* **154**: 571–580.

Bowlin, M.S., Henningsson, P., Muijres, F.T., Vleugels, R.H.E., Liechti, F. & Hedenström, A. 2010. The effects of geolocator drag and weight on the flight ranges of small migrants. *Methods Ecol Evol* **1**: 398–402.

Boyd, H. & Piersma, T. 2001. Changing balance between survival and recruitment explains population trends in red knots Calidris canutus islandica wintering in Britain, 1969-1995. *Ardea* **89**: 301–317.

Bridge, E.S., Thorup, K., Bowlin, M.S., Chilson, P.B., Diehl, R.H., Fléron, R.W., Hartl, P., Roland, K., Kelly, J.F., Robinson, W.D. & Wikelski, M. 2011. Technology on the move: Recent and forthcoming innovations for tracking migratory birds. *Bioscience* **61**: 689–698.

Brlík, V., Šilarová, E., Škorpilová, J., Alonso, H., Anton, M., Aunins, A., Benkö, Z., Biver, G., Busch, M., Chodkiewicz, T., Chylarecki, P., Coombes, D., de Carli, E., del Moral, J.C., Derouaux, A., Escandell, V., Eskildsen, D.P., Fontaine, B., Foppen, R.P.B., Gamero, A., Gregory, R.D., Harris, S., Herrando, S., Hristov, I., Husby, M., Ieronymidou, C., Jiquet, F., Kålås, J.A., Kamp, J., Kmecl, P., Kurlavičius, P., Lehikoinen, A., Lewis, L., Lindström, Å., Manolopoulos, A., Martí, D., Massimino, D., Moshøj, C., Nellis, R., Noble, D., Paquet, A., Paquet, J.Y., Portolou, D., Ramírez, I., Redel, C., Reif, J., Ridzoň, J., Schmid, H., Seaman, B., Silva, L., Soldaat, L., Spasov, S., Staneva, A., Szép, T., Florenzano, G.T., Teufelbauer, N., Trautmann, S., van der Meij, T., van Strien, A., van Turnhout, C., Vermeersch, G., Vermouzek, Z., Vikstrøm, T., Voříšek, P., Weiserbs, A. & Klvaňová, A. 2021. Long-term and large-scale multispecies dataset tracking population changes of common European breeding birds. *Sci Data* **8**.

Brochard, C., Spaans, B., Prop, J. & Piersma, T. 2002. Use of individual colour-ringing to estimate annual survival in male and female Red Knot Calidris canutus islandica: a progress report for 1998–2001. *Wader Study Group Bulletin* **99**: 54–56.

Burton, N. & Blew, J. 2008. *Population status of waders wintering on Europe's non-estuarine coasts*.

Burton, N.H.K., Musgrove, A.J. & Rehfisch, M.M. 2004. Tidal variation in numbers of waterbirds: How frequently should birds be counted to detect change and do low tide counts provide a realistic average? *Bird Study* **51**: 48–57.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., A.Wardle, D., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S. & Naeem, S. 2012. Biodiversity loss and its impact on humanity. *Nature* **489**: 326–326.

Carneiro, C., Gunnarsson, T.G. & Alves, J.A. 2019. Faster migration in autumn than in spring: seasonal migration patterns and non-breeding distribution of Icelandic whimbrels *Numenius phaeopus islandicus*. *J Avian Biol* **50**.

Carrascal, L.M., Seoane, J. & Palomino, D. 2008. Bias in density estimations using strip transects in dry open-country environments in the Canary Islands. *Anim Biodivers Conserv* **31**: 45–50.

Catry, T., Alves, J. a., Andrade, J., Costa, H., Dias, M.P., Fernandes, P., Leal, A., Lourenço, P.M., Martins, R.C., Moniz, F., Pardal, S., Rocha, A., Santos, C.D., Encarnação, V. & Granadeiro, J.P. 2011. Long-term declines of wader populations at the Tagus estuary, Portugal: a response to global or local factors? *Bird Conserv Int* **21**: 438–453.

Catry, T., Alves, J.A., Gill, J.A., Gunnarsson, T.G. & Granadeiro, J.P. 2012. Sex promotes spatial and dietary segregation in a migratory shorebird during the non-breeding season. *PLoS One* **7**.

Chan, Y.-C., Brugge, M., Tibbitts, T.L., Dekinga, A., Porter, R., Klaassen, R.H.G. & Piersma, T. 2016. Testing an attachment method for solar-powered tracking devices on a long-distance migrating shorebird. *J Ornithol* **157**: 277–287.

Chan, Y.C., Chan, D.T.C., Tibbitts, T.L., Hassell, C.J. & Piersma, T. 2023. Site fidelity of migratory shorebirds facing habitat deterioration: insights from satellite tracking and mark-resighting. *Mov Ecol* **11**.

Chan, Y.C., Peng, H.B., Han, Y.X., Chung, S.S.W., Li, J., Zhang, L. & Piersma, T. 2019a. Conserving unprotected important coastal habitats in the Yellow Sea: Shorebird occurrence, distribution and food resources at Lianyungang. *Glob Ecol Conserv* **20**.

Chan, Y.C., Tibbitts, T.L., Lok, T., Hassell, C.J., Peng, H.B., Ma, Z., Zhang, Z. & Piersma, T. 2019b. Filling knowledge gaps in a threatened shorebird flyway through satellite tracking. *Journal of Applied Ecology* **56**: 2305–2315.

Chen, S., Zhang, Y., Xu, C., Cao, L., Huang, Z.Y.X., Li, C., Chen, B.J.W., Lu, C., Xu, W., Song, Y. & de Boer, W.F. 2022. Neighbourhood threats: landscape context and anthropogenic changes can trigger waterbird population collapse. *Landsc Ecol* **37**: 3141–3158.

Chen, Y., Dong, J., Xiao, X., Zhang, M., Tian, B., Zhou, Y., Li, B. & Ma, Z. 2016. Land claim and loss of tidal flats in the Yangtze Estuary. *Sci Rep* **6**.

Chen, Y., Yu, Y. tung, Meng, F., Deng, X., Cao, L. & Fox, A.D. 2021. Migration routes, population status and important sites used by the globally threatened Black-faced Spoonbill (Platalea minor): a synthesis of surveys and tracking studies. *Avian Res* **12**.

Clemens, R.S., Rogers, D.I., Hansen, B.D., Gosbell, K., Minton, C.D.T., Straw, P., Bamford, M., Woehler, E.J., Milton, D.A., Weston, M.A., Venables, B., Weller, D., Hassell, C., Rutherford, B., Onton, K., Herrod, A., Studds, C.E., Choi, C.Y., Dhanjal-Adams, K.L., Murray, N.J., Skilleter, G.A. & Fuller, R.A. 2016. Continental-scale decreases in shorebird populations in Australia. *Emu* **116**: 119–135.

Conklin, J.R., Reneerkens, J., Verkuil, Y.I., Tomkovich, P.S., Palsbøll, P.J. & Piersma, T. 2016. Low genetic differentiation between greenlandic and siberian sanderling populations implies a different phylogeographic history than found in red knots. *J Ornithol* **157**: 325–332.

Conklin, J.R., Verkuil, Y.I., Battley, P.F., Hassell, C.J., ten Horn, J., Johnson, J.A., Tomkovich, P.S., Baker, A.J., Piersma, T. & Fontaine, M.C. 2022. Global flyway evolution in red knots Calidris canutus and genetic evidence for a Nearctic refugium. *Mol Ecol* **31**: 2124–2139.

Davidson, N., Bryant, D. & Boere, G. 1999. Conservation uses of ringing data: Flyway networks for waterbirds. *Ringing and Migration* **19**: S83–S94.

de Boer, A.P., Vansteelant, W.M.G. & Piersma, T. 2024. Primary moult of Eurasian Spoonbills Platalea leucorodia leucorodia in the Wadden Sea in relation to age, breeding and migration. *Ardea. in press*.

Dick, W.J.A., Piersma, T. & Prokosch, P. 1987. Spring migration of the Siberian Knots Calidris canutus canutus: results of a co-operative Wader Study Group project. *Ornis Scandinavica* **18**: 5–16.

Dodd, S.L. & Colwell, M.A. 1996. Seasonal variation in diurnal and nocturnal distributions of nonbreeding shorebirds at North Humboldt Bay, California. *Condor* **98**: 196–207.

Doney, S.C., Ruckelshaus, M., Emmett Duffy, J., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J., Rabalais, N.N., Sydeman, W.J. & Talley, L.D. 2012. Climate Change Impacts on Marine Ecosystems. *Ann Rev Mar Sci* **4**: 11–37.

Donohue, I., Petchey, O.L., Kéfi, S., Génin, A., Jackson, A.L., Yang, Q. & O'Connor, N.E. 2017. Loss of predator species, not intermediate consumers, triggers rapid and dramatic extinction cascades. *Glob Chang Biol* **23**: 2962–2972.

Duijns, S., van Gils, J.A., Spaans, B., ten Horn, J., Brugge, M. & Piersma, T. 2014. Sex-specific winter distribution in a sexually dimorphic shorebird is explained by resource partitioning. *Ecol Evol* **4**: 4009–4018.

Eren, S., Beaulieu, A., Piersma, T. & Crockford, N. 2024. Flyways Beyond Migratory Pathways: The Case of Waterbird Conservation. *Conservation and Society*, doi: 10.4103/cs.cs_109_22.

Eriksson, B.K., van der Heide, T., van de Koppel, J., Piersma, T., van der Veer, H.W. & Olff, H. 2010. Major changes in the ecology of the wadden sea: Human impacts, ecosystem engineering and sediment dynamics. *Ecosystems* **13**: 752–764.

Exo, K.M., Hillig, F. & Bairlein, F. 2019. Migration routes and strategies of Grey Plovers (Pluvialis squatarola) on the East Atlantic Flyway as revealed by satellite tracking. *Avian Res* **10**.

Fei, X.U., Liu, G. & Yali, S.I. 2017. Local temperature and El Niño Southern Oscillation influence migration phenology of East Asian migratory waterbirds wintering in Poyang, China. *Integr Zool* **12**: 303–317.

Fijn, R.C., Hiemstra, D., Phillips, R.A. & Van Der Winden, J. 2013. Arctic Terns Sterna paradisaea from the Netherlands migrate record distances across three oceans to Wilkes Land, East Antarctica. *Ardea* **101**: 3–12.

Finger, T.A., Afton, A.D., Schummer, M.L., Petrie, S.A., Badzinski, S.S., Johnson, M.A., Szymanski, M.L., Jacobs, K.J., Olsen, G.H. & Mitchell, M.A. 2016. Environmental factors influence lesser scaup migration chronology and population monitoring. *Journal of Wildlife Management* **80**: 1437–1449.

Frederiksen, M., Fox, A.D., Madsen, J. & Colhoun, K. 2001. Estimating the Total Number of Birds Using a Staging Site. *J Wildl Manage* **65**: 282.

Fuller, M.R. & Mosher., J.A. 1987. Raptor Survey Techniques. In: *Raptor Management Techniques Manual* (B. G. Pendleton, B. A. Millsap, K. W. Cline, & D. M. Bird, eds), pp. 37–65. National Wildlife Federation, Washington DC.

Fuller, R.J. & Langslow, D.R. 1984. Estimating numbers of birds by point counts: how long should counts last? *Bird Study* **31**: 195–202.

Gauld, J.G., Silva, J.P., Atkinson, P.W., Record, P., Acácio, M., Arkumarev, V., Blas, J., Bouten, W., Burton, N., Catry, I., Champagnon, J., Clewley, G.D., Dagys, M., Duriez, O., Exo, K.M., Fiedler, W., Flack, A., Friedemann, G., Fritz, J., Garcia-Ripolles, C., Garthe, S., Giunchi, D., Grozdanov, A., Harel, R., Humphreys, E.M., Janssen, R., Kölzsch, A., Kulikova, O., Lameris, T.K., López-López, P., Masden, E.A., Monti, F., Nathan, R., Nikolov, S., Oppel, S., Peshev, H., Phipps, L., Pokrovsky, I., Ross-Smith, V.H.,

Saravia, V., Scragg, E.S., Sforzi, A., Stoynov, E., Thaxter, C., Van Steelant, W., van Toor, M., Vorneweg, B., Waldenström, J., Wikelski, M., Žydelis, R. & Franco, A.M.A. 2022. Hotspots in the grid: Avian sensitivity and vulnerability to collision risk from energy infrastructure interactions in Europe and North Africa. *Journal of Applied Ecology* **59**: 1496–1512.

Geen, G.R., Robinson, R.A. & Baillie, S.R. 2019. Effects of tracking devices on individual birds – a review of the evidence.

Gherardi-Fuentes, C., Ruiz, J., Verdugo, C. & Navedo, J.G. 2020. Male-biased adult sex ratio in non-breeding areas of an extreme long-distance migratory shorebird population. *Acta Oecologica* **105**.

Gibson, D., Chaplin, M.K., Hunt, K.L., Friedrich, M.J., Weithman, C.E., Addison, L.M., Cavalieri, V., Coleman, S., Cuthbert, F.J., Fraser, J.D., Golder, W., Hoffman, D., Karpanty, S.M., Van Zoeren, A. & Catlin, D.H. 2018. Impacts of anthropogenic disturbance on body condition, survival, and site fidelity of nonbreeding Piping Plovers. *Condor* **120**: 566–580.

Gill, J.A., Norris, K., Potts, P.M., Gunnarsson, T.G., Atkinson, P.W. & Sutherland, W.J. 2001. The buffer effect and large-scale population regulation in migratory birds. *Nature* **412**: 436–438.

Gill, R.E., Piersma, T., Hufford, G., Servranckx, R. & Riegen, A. 2005. Crossing the ultimate ecological barrier: evidence for an 11 000-km-long nonstop flight from Alaska to New Zealand and Eastern Australia by bar-tailed godwits. *Condor* **107**: 1–20.

Gill, R.E., Tibbitts, T.L., Douglas, D.C., Handel, C.M., Mulcahy, D.M., Gottschalck, J.C., Warnock, N., McCaffery, B.J., Battley, P.F. & Piersma, T. 2009. Extreme endurance flights by landbirds crossing the Pacific Ocean: Ecological corridor rather than barrier? *Proceedings of the Royal Society B: Biological Sciences* **276**: 447–457.

Godet, L., Jaffre, M. & Devictor, V. 2011. Waders in winter: long-term changes of migratory bird assemblages facing climate change. *Biol Lett* **7**: 714–717.

Gould, L.A., Manning, A.D., McGinness, H.M. & Hansen, B.D. 2024. A review of electronic devices for tracking small and medium migratory shorebirds.

Granadeiro, J.P., Dias, M.P., Martins, R.C. & Palmeirim, J.M. 2006. Variation in numbers and behaviour of waders during the tidal cycle: implications for the use of estuarine sediment flats. *Acta Oecologica* **29**: 293–300.

Granadeiro, J.P., Santos, C.D., Dias, M.P. & Palmeirim, J.M. 2007. Environmental factors drive habitat partitioning in birds feeding in intertidal flats: Implications for conservation. *Hydrobiologia* **587**: 291–302.

Gregory, R.D., Gibbons, D.W. & Donald, P.F. 2004. Bird census and survey techniques. *Quality* **6**: 17–56.

Gui, Q., Liu, C. & Du, D. 2019. Globalization of science and international scientific collaboration: A network perspective. *Geoforum* **105**: 1–12.

Guilford, T., Åkesson, S., Gagliardo, A., Holland, R.A., Mouritsen, H., Muheim, R., Wiltschko, R., Wiltschko, W. & Bingman, V.P. 2011. Migratory navigation in birds: New opportunities in an era of fast-developing tracking technology.

Gunnarsson, T.G., Gill, J.A., Potts, P.M., Atkinson, P.W., Croger, R.E., Gélinaud, G., Gardarsson, A. & Sutherland, W.J. 2005. Estimating population size in Black-tailed Godwits Limosa limosa islandica by colour-marking. *Bird Study* **52**: 153–158.

Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O'Hara, C., Scarborough, C. & Selkoe, K.A. 2019. Recent pace of change in human impact on the world's ocean. *Sci Rep* **9**.

Hansen, B.D., Fuller, R.A., Watkins, D., Rogers, D.I., Clemens, R.S., Newman, M., Woehler, E.J., Weller, D.R., Hansen, B.D., Watkins, R.A., Rogers, D., Clemens, D.I., Newman, R.S. & Weller, E.J. 2016. *Revision of the East Asian-Australasian Flyway Population Estimates for 37 listed Migratory Shorebird Species*.

Harley, C.D.G., Hughes, A.R., Hultgren, K.M., Miner, B.G., Sorte, C.J.B., Thornber, C.S., Rodriguez, L.F., Tomanek, L. & Williams, S.L. 2006. The impacts of climate change in coastal marine systems. *Ecol Lett* **9**: 228–241.

Harrison, A.-L., Stenzel, C., Anderson, A., Howell, J., Lanctot, R.B., Aikens, M., Aldabe, J., Berigan, L.A., Bêty, J., Blomberg, E., Bosi de Almeida, J., Boyce, A.J., Bradley, D.W., Brown, S., Carlisle, J., Cheskey, E., Christie, K., Hipfner, M., Johnson, J.A., Johnson, L., Kempenaers, B., Knaga, P., Kwon, E., Lagassé, B.J., Stantial, M.L., Taylor, A.R., Valcu, M., Wehtje, W., Winn, B. & Wunder, M.B. n.d. *The collective application of shorebird tracking data to conservation*.

Hebblewhite, M. & Haydon, D.T. 2010. Distinguishing technology from biology: A critical review of the use of GPS telemetry data in ecology.

Henriques, M., Belo, J.R., Sá, J., Monteiro, H., Alves, J.A., Piersma, T., Dodman, T. & Roomen, M. van. 2022. The Bijagós Archipelago: a key area for waterbirds of the East Atlantic Flyway. In: *East Atlantic Flyway Assessment 2020: The status of coastal waterbird populations and their sites* (M. van Roomen, G.

Citegetse, O. Crowe, T. Dodman, W. Hagemeijer, K. Meise, & H. Schekkerman, eds), pp. 81–93. Wadden Sea Flyway Initiative, Wetlands International, BirdLife International, Wilhelmshaven, Germany; Wageningen, The Netherlands; Cambridge, United Kingdom.

Henriques, M., Piersma, T., Vansteelant, W., de Goeij, P. & Lok, T. 2024. *A place and a time for everything: Eurasian Spoonbills divide spring and summer activities across different areas in the eastern Wadden Sea.*

Hofmeyr, S.D., Symes, C.T. & Underhill, L.G. 2014. Secretarybird Sagittarius serpentarius population trends and ecology: Insights from South African citizen science data. *PLoS One* **9**.

International, W. 2012. Annual IWC Count Totals: African-Eurasian Waterbird Census.

IUCN. 2023. The IUCN Red List of Threatened Species. Version 2022-2.

Iverson, A.R., Schaefer, J.L.B., Skalos, S.M. & Hawkins, C.E. 2023. Global positioning system (GPS) and platform transmitter terminal (PTT) tags reveal fine-scale migratory movements of small birds: A review highlights further opportunities for hypothesis-driven research. *Ornithological Applications* **125**.

Iwamura, T., Fuller, R.A. & Possingham, H.P. 2014. Optimal Management of a Multispecies Shorebird Flyway under Sea-Level Rise. *Conservation Biology* **28**: 1710–1720.

Iwamura, T., Possingham, H.P., Chadès, I., Minton, C., Murray, N.J., Rogers, D.I., Treml, E.A. & Fuller, R.A. 2013. Migratory connectivity magnifies the consequences of habitat loss from sea-level rise for shorebird populations. *Tohoku Journal of Experimental Medicine* **230**.

Jackson, M. V., Fuller, R.A., Gan, X., Li, J., Mao, D., Melville, D.S., Murray, N.J., Wang, Z. & Choi, C.Y. 2021. Dual threat of tidal flat loss and invasive Spartina alterniflora endanger important shorebird habitat in coastal mainland China. *J Environ Manage* **278**: 111549.

Jeroen Reneerkens, Abdelaziz Benhoussa, Helen Boland, Mark Collier, Kirsten Grond, Klaus Günther, Gunnar Thor Hallgrimsson, Jannik Hansen, Włodzimierz Meissner, Brecht de Meulenaer, Yaa Ntiamoa-Baidu, Theunis Piersma, Martin Poot, Marc van Roomen, Ron W. Summers, Pavel S. Tomkovich & Les G. Underhill. 2009. Sanderlings using African–Eurasian flyways: a review of current knowledge. *Wader Study Group Bulletin* **116**: 2–22.

Johnson, F.A., Zimmerman, G.S., Jensen, G.H., Clausen, K.K., Frederiksen, M. & Madsen, J. 2020. Using integrated population models for insights into monitoring programs: An application using pink-footed geese. *Ecol Modell* **415**.

Joo, R., Picardi, S., Boone, M.E., Clay, T.A., Patrick, S.C., Romero-Romero, V.S. & Basille, M. 2020. A decade of movement ecology. Available at: http://arxiv.org/abs/2006.00110.

Joo, R., Picardi, S., Boone, M.E., Clay, T.A., Patrick, S.C., Romero-Romero, V.S. & Basille, M. 2022. Recent trends in movement ecology of animals and human mobility.

Jourdan, C., Fort, J., Pinaud, D., Delaporte, P., Gernigon, J., Guenneteau, S., Jomat, L., Lelong, V., Lemesle, J.C., Robin, F., Rousseau, P. & Bocher, P. 2021. Highly diversified habitats and resources influence habitat selection in wintering shorebirds. *J Ornithol* **162**: 823–838.

Katzner, T.E. & Arlettaz, R. 2020. Evaluating Contributions of Recent Tracking-Based Animal Movement Ecology to Conservation Management.

Kempenaers, B. & Valcu, M. 2017. Breeding site sampling across the Arctic by individual males of a polygynous shorebird. *Nature* **541**: 528–531.

Koleček, J., Reif, J., Šálek, M., Hanzelka, J., Sottas, C. & Kubelka, V. n.d. Global population trends in shorebirds: migratory behaviour makes species at risk. , doi: 10.1007/s00114-021-01717-1/Published.

Kölzsch, A., Müskens, G.J.D.M., Szinai, P., Moonen, S., Glazov, P., Kruckenberg, H., Wikelski, M. & Nolet, B.A. 2019. Flyway connectivity and exchange primarily driven by moult migration in geese. *Mov Ecol* **7**.

Kuang, F., Coleman, J.T., Hassell, C.J., Leung, K.S.K., Maglio, G., Ke, W., Cheng, C., Zhao, J., Zhang, Z. & Ma, Z. 2020. Seasonal and population differences in migration of Whimbrels in the East Asian-Australasian Flyway. *Avian Res* **11**.

Lahoz-Monfort, J.J. & Magrath, M.J.L. 2021. A Comprehensive Overview of Technologies for Species and Habitat Monitoring and Conservation.

Lamb, J.S., Cooper-Mullin, C., Gilliland, S.G., Berlin, A.M., Bowman, T.D., Boyd, W.S., De La Cruz, S.E.W., Esler, D., Evenson, J.R., Flint, P., Lepage, C., Meattey, D.E., Osenkowski, J.E., Paton, P.W.C., Perry, M.C., Rosenberg, D., Savard, J.P.L., Savoy, L., Schamber, J., Ward, D.H., Takekawa, J.Y. & McWilliams, S.R. 2024. Evaluating conservation units using network analysis: a sea duck case study. *Front Ecol Environ*, doi: 10.1002/fee.2648.

Lameris, T.K. & Kleyheeg, E. 2017. Reduction in adverse effects of tracking devices on waterfowl requires better measuring and reporting.

Lameris, T.K., Müskens, G.J.D.M., Kölzsch, A., Dokter, A.M., Van der Jeugd, H.P. & Nolet, B.A. 2018. Effects of harness-attached tracking devices on survival, migration, and reproduction in three species of migratory waterfowl. *Animal Biotelemetry* **6**.

Lehnen, S.E. & Krementz, D.G. 2005. Turnover Rates of Fall-Migrating Pectoral Sandpipers in the Lower Mississippi Alluvial. **69**: 671–680.

Lei, J., Jia, Y., Zuo, A., Zeng, Q., Shi, L., Zhou, Y., Zhang, H., Lu, C., Lei, G. & Wen, L. 2019. Bird satellite tracking revealed critical protection gaps in East Asian–Australasian flyway. *Int J Environ Res Public Health* **16**.

Lewis, M. 2016. AEWA at Twenty: An Appraisal of the African-Eurasian Waterbird Agreement and Its Unique Place in International Environmental Law. *Journal of International Wildlife Law & Policy* **19**: 22–61.

Li, J., Hughes, A.C. & Dudgeon, D. 2019. Mapping wader biodiversity along the East Asian-Australasian flyway. *PLoS One* **14**.

Lislevand, T., Briedis, M., Heggøy, O. & Hahn, S. 2017. Seasonal migration strategies of Common Ringed Plovers *Charadrius hiaticula*. *Ibis* **159**: 225–229.

Lisovski, S., Gosbell, K., Christie, M., Hoye, B.J., Klaassen, M., Stewart, I.D., Taysom, A.J. & Minton, C. 2016. Movement patterns of Sanderling (Calidris alba) in the East Asian-Australasian Flyway and a comparison of methods for identification of crucial areas for conservation. *Emu* **116**: 168–177.

Lisovski, S., Gosbell, K., Minton, C. & Klaassen, M. 2021. Migration strategy as an indicator of resilience to change in two shorebird species with contrasting population trajectories. *Journal of Animal Ecology* **90**: 2005–2014.

Lok, T., Hassell, C.J., Piersma, T., Pradel, R. & Gimenez, O. 2019. Accounting for heterogeneity when estimating stopover duration, timing and population size of red knots along the Luannan Coast of Bohai Bay, China. *Ecol Evol* **9**: 6176–6188.

Lok, T., Overdijk, O. & Piersma, T. 2015. The cost of migration: Spoonbills suffer higher mortality during trans-Saharan spring migrations only. *Biol Lett* **11**.

Lok, T., Overdijk, O., Tinbergen, J.M. & Piersma, T. 2011. The paradox of spoonbill migration: Most birds travel to where survival rates are lowest. *Anim Behav* **82**: 837–844.

Lok, T. & Piersma, T. n.d. Sex-specific rhythm of nest attendance and foraging range in a colony-breeding waterbird. *Revised MS*.

Lok, T., van der Geest, M., Bom, R.A., de Goeij, P., Piersma, T. & Bouten, W. 2023. Prey ingestion rates revealed by back-mounted accelerometers in Eurasian spoonbills. *Animal Biotelemetry* **11**.

Lok, T., Veldhoen, L., Overdijk, O., Tinbergen, J.M. & Piersma, T. 2017. An age-dependent fitness cost of migration? Old trans-Saharan migrating spoonbills breed later than those staying in Europe, and late breeders have lower recruitment. *Journal of Animal Ecology* **86**: 998–1009.

Long, J.A. & Nelson, T.A. 2013. A review of quantitative methods for movement data.

Loonstra, A.H.J., Piersma, T. & Reneerkens, J. 2016. Staging Duration and Passage Population Size of Sanderlings in the Western Dutch Wadden Sea. *Ardea* **104**: 49–61.

Lucrezi, S., Esfehani, M.H., Ferretti, E. & Cerrano, C. 2019. The effects of stakeholder education and capacity building in marine protected areas: A case study from southern Mozambique. *Mar Policy* **108**.

Maclean, I.M.D., Austin, G.E., Rehfisch, M.M., Blew, J., Crowe, O., Delany, S., Devos, K., Deceuninck, B., Günther, K., Laursen, K., Van Roomen, M. & Wahl, J. 2008. Climate change causes rapid changes in the distribution and site abundance of birds in winter. *Glob Chang Biol* **14**: 2489–2500.

Madsen, J., Tjørnløv, R.S., Frederiksen, M., Mitchell, C. & Sigfússon, A.T. 2014. Connectivity between flyway populations of waterbirds: Assessment of rates of exchange, their causes and consequences. *Journal of Applied Ecology* **51**: 183–193.

Månsson, J., Liljebäck, N., Nilsson, L., Olsson, C., Kruckenberg, H. & Elmberg, J. 2022. Migration patterns of Swedish Greylag geese Anser anser—implications for flyway management in a changing world. *Eur J Wildl Res* **68**.

Martay, B., Macphie, K.H., Bowgen, K.M., Pearce-Higgins J.W., Robinson, R.A., Scott, S.E. & Williams, J.M. 2023. *Climate change and migratory species: a review of impacts, conservation actions, indicators and ecosystem services. Part 1 – Impacts of climate change on migratory species*.

Martín, B., Delgado, S., de la Cruz, A., Tirado, S. & Ferrer, M. 2015. Effects of human presence on the long-term trends of migrant and resident shorebirds: Evidence of local population declines. *Anim Conserv* **18**: 73–81.

Martínez-Curci, N.S., Isacch, J.P., D'Amico, V.L., Rojas, P. & Castresana, G.J. 2020. To migrate or not: drivers of over-summering in a long-distance migratory shorebird. *J Avian Biol* **51**.

Martins, R.C., Catry, T., Rebelo, R., Pardal, S., Palmeirim, J.M. & Granadeiro, J.P. 2016. Contrasting estuary-scale distribution of wintering and migrating waders: the potential role of fear. *Hydrobiologia* **768**: 211–222.

Mathot, K.J., Piersma, T. & Elner, R.W. 2018. Shorebirds as Integrators and Indicators of Mudflat Ecology. *Mudflat Ecology* 309–338.

Mathot, K.J., Smith, B.D. & Elner, R.W. 2007. LATITUDINAL CLINES IN FOOD DISTRIBUTION CORRELATE WITH DIFFERENTIAL MIGRATION IN THE WESTERN SANDPIPER. *Ecology* **88**: 781–791.

McDuffie, L.A., Christie, K.S., Taylor, A.R., Nol, E., Friis, C., Harwood, C.M., Rausch, J., Laliberte, B., Gesmundo, C., Wright, J.R. & Johnson, J.A. 2022. Flyway-scale GPS tracking reveals migratory routes and key stopover and non-breeding locations of lesser yellowlegs. *Ecol Evol* **12**.

Méndez, V., Alves, J.A., Gill, J.A. & Gunnarsson, T.G. 2018. Patterns and processes in shorebird survival rates: a global review.

Michel, G., Nightingale, J., Beal, M., Bernard, A., Dias, M.P. & Alves, J.A. 2024. *Global review of shorebird tracking publications: Gaps and priorities for research and conservation*.

Morrick, Z.N., Lilleyman, A., Fuller, R.A., Bush, R., Coleman, J.T., Garnett, S.T., Gerasimov, Y.N., Jessop, R., Ma, Z., Maglio, G., Minton, C.D.T., Syroechkovskiy, E. & Woodworth, B.K. 2022. Differential population trends align with migratory connectivity in an endangered shorebird. *Conserv Sci Pract* **4**.

Moussy, C., Burfield, I.J., Stephenson, P.J., Newton, A.F.E., Butchart, S.H.M., Sutherland, W.J., Gregory, R.D., McRae, L., Bubb, P., Roesler, I., Ursino, C., Wu, Y., Retief, E.F., Udin, J.S., Urazaliyev, R., Sánchez-Clavijo, L.M., Lartey, E. & Donald, P.F. 2022. A quantitative global review of species population monitoring.

Mu, T., Cai, S., Peng, H., Hassell, C.J., Boyle, A., Zhang, Z., Piersma, T. & Wilcove, D.S. 2022. Evaluating staging habitat quality to advance the conservation of a declining migratory shorebird, Red Knot *Calidris canutus*. *Journal of Applied Ecology* **59**: 2084–2093.

Murn, C. & Holloway, G.J. 2016. Using areas of known occupancy to identify sources of variation in detection probability of raptors: taking time lowers replication effort for surveys. *R Soc Open Sci* **3**: 160368.

Murray, N.J., Marra, P.P., Fuller, R.A., Clemens, R.S., Dhanjal-Adams, K., Gosbell, K.B., Hassell, C.J., Iwamura, T., Melville, D., Minton, C.D.T., Riegen, A.C., Rogers, D.I., Woehler, E.J. & Studds, C.E. 2018. The large-scale drivers of population declines in a long-distance migratory shorebird. *Ecography* **41**: 867–876.

Nagy, S. & Langendoen, T. 2020. Flyway trend analyses based on data from the African-Eurasian Waterbird Census from the period of 1967-2018. *Online publication. Wetlands International, Wageningen, The Netherlands. URL: http://iwc. test. wetlands. org/index. php/aewatrends8*.

Navedo, J.G. & Piersma, T. 2023. Do 50-year-old Ramsar criteria still do the best possible job? A plea for broadened scientific underpinning of the global protection of wetlands and migratory waterbirds. *Conserv Lett* **16**.

Navedo, J.G. & Ruiz, J. 2020. Oversummering in the southern hemisphere by long-distance migratory shorebirds calls for reappraisal of wetland conservation policies. *Glob Ecol Conserv* **23**: e01189.

Newton, A., Icely, J., Cristina, S., Perillo, G.M.E., Turner, R.E., Ashan, D., Cragg, S., Luo, Y., Tu, C., Li, Y., Zhang, H., Ramesh, R., Forbes, D.L., Solidoro, C., Béjaoui, B., Gao, S., Pastres, R., Kelsey, H., Taillie, D., Nhan, N., Brito, A.C., de Lima, R. & Kuenzer, C. 2020. Anthropogenic, Direct Pressures on Coastal Wetlands.

Newton, I. 2007. *The Migration Ecology of Birds*.

Nichols, J.D., Hines, J.E., Sauer, J.R., Fallon, F., Fallon, J. & Heglund, P.J. 2000. A double-observer approach for estimating detection probability and abundance from avian point counts. *Auk* **117**: 393–408.

Nightingale, J., Gill, J.A., Þórisson, B., Potts, P.M., Gunnarsson, T.G. & Alves, J.A. 2023. Conservation beyond boundaries: using animal movement networks in protected area assessment. *Anim Conserv* **26**: 753–765.

Niles, L.J., Burger, J., Porter, R.R., Dey, A.D., Minton, C.D.T., Gonzalez, P.M., Baker, A.J., Fox, J.W. & Gordon, C. 2010. First results using light level geolocators to track Red Knots in the Western Hemisphere show rapid and long intercontinental flights and new details of migration pathways. *Wader Study Group Bulletin* **117**: 123–130.

Ntiamoa-Baidu, Y., Nuoh, A.A., Reneerkens, J. & Piersma, T. 2014. Population increases in non-breeding sanderlings in ghana indicate site preference. *Ardea* **102**: 131–137.

Nuñez, M.A., Barlow, J., Cadotte, M., Lucas, K., Newton, E., Pettorelli, N. & Stephens, P.A. 2019. Assessing the uneven global distribution of readership, submissions and publications in applied ecology: Obvious problems without obvious solutions.

Nuñez, M.A., Chiuffo, M.C., Pauchard, A. & Zenni, R.D. 2021. Making ecology really global. *Trends Ecol Evol* **36**: 766–769.

O'Connor, C.M., Norris, D.R., Crossin, G.T. & Cooke, S.J. 2014. Biological carryover effects: Linking common concepts and mechanisms in ecology and evolution. *Ecosphere* **5**.

Oudman, T., Goeij, P. De, Piersma, T. & Lok, T. 2017. Colony-Breeding Eurasian Spoonbills in the Netherlands: Local Limits to Population Growth with Expansion into New Areas. *Ardea* **105**: 113–124.

Oudman, T., Schekkerman, H., Kidee, A., Van Roomen, M., Camara, M., Smit, C., Horn, J. Ten, Piersma, T. & El-Hacen, E.H.M. 2020. Changes in the waterbird community of the Parc National du Banc d'Arguin, Mauritania, 1980-2017. *Bird Conserv Int* **30**: 618–633.

Overdijk, O. & Navedo, J.G. 2012. A massive spoonbill stopover episode: Identifying emergency sites for the conservation of migratory waterbird populations. *Aquat Conserv* **22**: 695–703.

Pakanen, V.M., Jaakkonen, T., Saarinen, J., Rönkä, N., Thomson, R.L. & Koivula, K. 2018. Migration strategies of the Baltic dunlin: rapid jump migration in the autumn but slower skipping type spring migration. *J Avian Biol* **49**.

Pakanen, V.M., Rönkä, N., Robert Leslie, T., Blomqvist, D. & Koivula, K. 2020. Survival probability in a small shorebird decreases with the time an individual carries a tracking device. *J Avian Biol* **51**.

Pienkowski, M.W., Lloyd, C.S. & Minton, C.D.T. 1979. Seasonal and migrational weight changes in dunlins. *Bird Study* **26**: 134–148.

Piersma, T. 2007. Using the power of comparison to explain habitat use and migration strategies of shorebirds worldwide. In: *Journal of Ornithology*.

Piersma, T. 2012. What is habitat quality? Dissecting a research portfolio on shorebirds. In: *Birds and Habitat: Relationships in Changing Landscapes* (R. Fuller, ed), pp. 383–407.

Piersma, T. & Davidson, N. 1992. The migrations and annual cycles of five subspecies of knots in perspective. *Wader Study Group Bulletin* **64**: 187–197.

Piersma, T. & Jukema, J. 1990. Budgeting the flight of a long-distance migrant: changes in nutrient reserve levels of bar-tailed godwits at successive spring staging sites. *Ardea* **78**: 315–337.

Piersma, T., Lok, T., Chen, Y., Hassell, C.J., Yang, H.Y., Boyle, A., Slaymaker, M., Chan, Y.C., Melville, D.S., Zhang, Z.W. & Ma, Z. 2016. Simultaneous declines in summer survival of three shorebird species signals a flyway at risk. *Journal of Applied Ecology* **53**: 479–490.

Piersma, T., Prokosch, P. & Bredin, D. 1992. The migration system of Afro-Siberian Knots Calidris canutus canutus. *Wader Study Group Bulletin* **64**: 52–63.

Piersma, T., Verkuil, Y. & Tulp, I. 1994. *Resources for Long-Distance Migration of Knots Calidris canutus islandica and C. c. canutus: How Broad Is the Temporal Exploitation Window of Benthic Prey in the Western and Eastern Wadden Sea?*

Piironen, A., Fox, A.D., Kampe-Persson, H., Skyllberg, U., Therkildsen, O.R. & Laaksonen, T. 2023. When and where to count? Implications of migratory connectivity and nonbreeding distribution to population censuses in a migratory bird population. *Popul Ecol* **65**: 121–132.

Pimm, S.L., Alibhai, S., Bergl, R., Dehgan, A., Giri, C., Jewell, Z., Joppa, L., Kays, R. & Loarie, S. 2015. Emerging Technologies to Conserve Biodiversity.

Rakhimberdiev, E., Duijns, S., Karagicheva, J., Camphuysen, C.J., Dekinga, A., Dekker, R., Gavrilov, A., ten Horn, J., Jukema, J., Saveliev, A., Soloviev, M., Tibbitts, T.L., van Gils, J.A., Piersma, T., van Loon, A., Wijker, A., Keijl, G., Levering, H., Jan Visser, Heemskerk, L., Knijnsberg, L., van Roomen, M., Ruiters, P., Admiraal, P., Veldt, P., Reijnders, R. & Beentjes, W. 2018. Fuelling conditions at staging sites can mitigate Arctic warming effects in a migratory bird. *Nat Commun* **9**.

Rakhimberdiev, E., Saveliev, A., Piersma, T. & Karagicheva, J. 2017. FLightR: an r package for reconstructing animal paths from solar geolocation loggers.

Rakhimberdiev, E., Verkuil, Y.I., Saveliev, A.A., Väisänen, R.A., Karagicheva, J., Soloviev, M.Y., Tomkovich, P.S. & Piersma, T. 2011. A global population redistribution in a migrant shorebird detected with continent-wide qualitative breeding survey data. *Divers Distrib* **17**: 144–151.

Ramo, C., Aguilera, E., Figuerola, J., Mãnez, M. & Green, A.J. 2013. Long-term population trends of colonial wading birds breeding in doñana (Sw Spain) in relation to environmental and anthropogenic factors. *Ardeola* **60**: 305–326.

Ramo, C., Amat, J.A., Nilsson, L., Schricke, V., Rodríguez-Alonso, M., Gómez-Crespo, E., Jubete, F., Navedo, J.G., Masero, J.A., Palacios, J., Boos, M. & Green, A.J. 2015. Latitudinal-related variation in wintering population trends of greylag geese (Anser Anser) along the atlantic flyway: A response to climate change? *PLoS One* **10**.

Ramsar Convention. 2014. *The Ramsar Sites Criteria: The nine criteria for identifying Wetlands of International Importance*.

Rappoldt, C., Kersten, M. & Smit, C. 1985. Errors in large-scale shorebird counts. *Ardea* **73**: 13–24.

Reese, G.C. & Skagen, S.K. 2017. Modeling nonbreeding distributions of shorebirds and waterfowl in response to climate change. *Ecol Evol* **7**: 1497–1513.

Reneerkens, J. 2022. Demographic monitoring along the East-Atlantic Flyway: a case study on Sanderlings using international citizen science. In: *East Atlantic Flyway Assessment 2020.The status of coastal waterbird populations and their sites.* Wadden Sea Flyway Initiative p/a CWSS, Wilhelmshaven, Germany.

Reneerkens, J., Versluijs, T.S.L., Piersma, T., Alves, J.A., Boorman, M., Corse, C., Gilg, O., Hallgrimsson, G.T., Lang, J., Loos, B., Ntiamoa-Baidu, Y., Nuoh, A.A., Potts, P.M., ten Horn, J. & Lok, T. 2020. Low fitness at low latitudes: Wintering in the tropics increases migratory delays and mortality rates in an Arctic breeding shorebird. *Journal of Animal Ecology* **89**: 691–703.

Robinson, O.J., Ruiz-Gutierrez, V., Reynolds, M.D., Golet, G.H., Strimas-Mackey, M. & Fink, D. 2020. Integrating citizen science data with expert surveys increases accuracy and spatial extent of species distribution models. *Divers Distrib* **26**: 976–986.

Robinson, W.D., Bowlin, M.S., Bisson, I., Shamoun-Baranes, J., Thorup, K., Diehl, R.H., Kunz, T.H., Mabey, S. & Winkler, D.W. 2010. Integrating concepts and technologies to advance the study of bird migration.

Rodrigues, M.S., Araújo, P.M., Silva, J.P., Abad-Gómez, J.M., Rodrigues, P.C., Ramos, J.A. & Alves, J.A. 2023. Habitat selection and ontogeny of habitat use by juvenile Eurasian Spoonbill Platalea leucorodia revealed by GPS tracking. *Bird Conserv Int* **33**.

Rogers, D.I., Yang, H.Y., Hassell, C.J., Boyle, A.N., Rogers, K.G., Chen, B., Zhang, Z.W. & Piersma, T. 2010. Red Knots (Calidris canutus piersmai and C. c. rogersi) depend on a small threatened staging area in Bohai Bay, China. *Emu* **110**: 307–315.

Rogers, K.G.; & Piersma, T. 2005. Monitoring vital rates of migrant shorebird populations. *Ardea* **93**: 65–77.

Rönkä, N., Pakanen, V.M., Pauliny, A., Thomson, R.L., Nuotio, K., Pehlak, H., Thorup, O., Lehikoinen, P., Rönkä, A., Blomqvist, D., Koivula, K. & Kvist, L. 2021. Genetic differentiation in an endangered and strongly philopatric, migrant shorebird. *BMC Ecol Evol* **21**.

Roodbergen, M., Klok, C. & Schekkerman, H. 2008. The ongoing decline of the breeding population of Black-tailed Godwits Limosa l. limosa in the Netherlands is not explained by changes in adult survival. *Ardea* **96**: 207–218.

Rosa, S., Palmeirim, J.M. & Moreira, F. 2003. Factors Affecting Waterbird Abundance and Species Richness in an Increasingly Urbanized Area of the Tagus Estuary in Portugal. *Waterbirds* **26**: 226.

Sala, E. & Knowlton, N. 2006. Global Marine Biodiversity Trends. *Annu Rev Environ Resour* **31**: 93–122.

Sandercock, B.K. 2006. Estimation of Demographic Parameters from Live-Encounter Data: a Summary Review. *Journal of Wildlife Management* **70**: 1504–1520.

Scarpignato, A.L., Huysman, A.E., Jimenez, M.F., Witko, C.J., Harrison, A.L., Seavy, N.E., Smith, M.A., Deppe, J.L., Wilsey, C.B. & Marra, P.P. 2023. Shortfalls in tracking data available to inform North American migratory bird conservation. *Biol Conserv* **286**.

Schmaltz, L.E., Jelle Loonstra, A.H., Wymenga, E., Hobson, K.A. & Piersma, T. 2018. Quantifying the non-breeding provenance of staging Ruffs, Philomachus pugnax, using stable isotope analysis of different tissues. *J Ornithol* **159**: 191–203.

Schmeller, D., Henle, K., Loyau, A., Besnard, A. & Henry, P.-Y. 2012a. Bird-monitoring in Europe – a first overview of practices, motivations and aims. *Nat Conserv* **2**: 41–57.

Schmeller, D.S., Böhm, M., Arvanitidis, C., Barber-Meyer, S., Brummitt, N., Chandler, M., Chatzinikolaou, E., Costello, M.J., Ding, H., García-Moreno, J., Gill, M., Haase, P., Jones, M., Juillard, R., Magnusson, W.E., Martin, C.S., McGeoch, M., Mihoub, J.B., Pettorelli, N., Proença, V., Peng, C., Regan, E., Schmiedel, U., Simaika, J.P., Weatherdon, L., Waterman, C., Xu, H. & Belnap, J. 2017. Building capacity in biodiversity monitoring at the global scale.

Schmeller, D.S., Henle, K., Loyau, A., Besnard, A. & Henry, P.Y. 2012b. Bird-monitoring in Europe - A first overview of practices, motivations and aims.

Schummer, M.L., Afton, A.D., Badzinski, S.S., Petrie, S.A., Olsen, G.H. & Mitchell, M.A. 2018. Evaluating the waterfowl breeding population and habitat survey for scaup. *Journal of Wildlife Management* **82**: 1252–1262.

Schwartz, M.W., Cook, C.N., Pressey, R.L., Pullin, A.S., Runge, M.C., Salafsky, N., Sutherland, W.J. & Williamson, M.A. 2018. Decision Support Frameworks and Tools for Conservation.

Schwemmer, P., Güpner, F., Adler, S., Klingbeil, K. & Garthe, S. 2016. Modelling small-scale foraging habitat use in breeding Eurasian oystercatchers (Haematopus ostralegus) in relation to prey distribution and environmental predictors. *Ecol Modell* **320**: 322–333.

Scott, I., Mitchell, P.I. & Evans, P.R. 1994. Seasonal changes in body mass, body composition and food requirements in wild migratory birds. *Proceedings of the Nutrition Society* **53**: 521–531.

Şekercioĝlu, Ç.H. 2012. Promoting community-based bird monitoring in the tropics: Conservation, research, environmental education, capacity-building, and local incomes.

Senner, N.R., Conklin, J.R. & Piersma, T. 2015. An ontogenetic perspective on individual differences.

Shamoun-Baranes, J., Leyrer, J., Van Loon, E., Bocher, P., Robin, F., Meunier, F. & Piersma, T. 2010. Stochastic atmospheric assistance and the use of emergency staging sites by migrants. In: *Proceedings of the Royal Society B: Biological Sciences*, pp. 1505–1511. Royal Society.

Simmons, R.E., Kolberg, H., Braby, R. & Erni, B. 2015. Declines in migrant shorebird populations from a winter-quarter perspective. *Conservation Biology* **29**: 877–887.

Smith, P.A., Smith, A.C., Andres, B., Francis, C.M., Harrington, B., Friis, C., Morrison, R.I.G., Paquet, J., Winn, B. & Brown, S. 2023. Accelerating declines of North America's shorebirds signal the need for urgent conservation action. *Ornithological Applications* **125**.

Snell, K.R.S., Frederiksen, M. & Bregnballe, T. 2021. Differential spatial migration programmes are both sex and age specific for migratory great cormorants. *J Ornithol* **162**: 1075–1085.

Soares, L., Cockle, K.L., Inzunza, E.R., Ibarra, J., Miño, C.I., Zuluaga, S., Bonaccorso, E., Ríos-Orjuela, J.C., Montaño-Centellas, F.A., Freile, J.F., Echeverry-Galvis, M.A., Bonaparte, E.B., Diele-Viegas, L.M., Speziale, K., Cabrera-Cruz, S.A., Acevedo-Charry, O., Velarde, E., Lima, C.C., Ojeda, V.S., Fontana, C.S., Echeverri, A., Lambertucci, S.A., Macedo, R.H., Esquivel, A., Latta, S.C., Ruvalcaba-Ortega, I., Alves, M.A.S., Santiago-Alarcon, D., Bodrati, A., González-García, F., Fariña, N., Martínez-Gómez, J.E., Ortega-Álvarez, R., Montellano, M.G.N., Ribas, C.C., Bosque, C., Di Giacomo, A.S., Areta, J.I., Emer, C., Valdés, L.M., González, C., Rebollo, M.E., Mangini, G., Lara, C., Pizarro, J.C., Cueto, V.R., Bolaños-Sittler, P.R., Ornelas, J.F., Acosta, M., Cenizo, M., Marini, M.Â., Vázquez-Reyes, L.D., González-Oreja, J.A., Bugoni, L., Quiroga, M., Ferretti, V., Manica, L., Grande, J.M., Rodríguez-Gómez, F., Diaz, S., Büttner, N., Mentesana, L., Campos-Cerqueira, M., López, F.G., Guaraldo, A.C., MacGregor-Fors, I., Aguiar-Silva, F.H., Miyaki, C.Y., Ippi, S., Mérida, E., Kopuchian, C., Cornelius, C., Enríquez, P.L., Ocampo-Peñuela, N., Renton, K., Salazar, J.C., Sandoval, L., Sandoval, J.C., Astudillo, P.X., Davis, A.O., Cantero, N., Ocampo, D., Humberto, O., Gomez, M., Borges, S.H., Cordoba-Cordoba, S., Pietrek, A.G., de Araújo, C.B., Fernández, G., de la Cueva, H., Marcos, J., Capurucho, G., Gutiérrez-Ramos, N.A., Ferreira, A., Costa, L.M., Soldatini, C., Madden, H.M., Santillán, M.A., Jiménez-Uzcátegui, G., Jordan, E.A., Freitas, G.H.S., Pulgarin, P.C.R., Almazán-Núñez, R.C., Altamirano, T., Gomez, M.R., Velazquez, M.C., Irala, R., Gandoy, F.A., Trigueros, A.C., Ferreyra, C.A., Albores-Barajas, Y., Tellkamp, M., Oliveira, C.D., Weiler, A., del Coro Arizmendi, M., Tossas, A.G., Zarza, R., Serra, G., Villegas-Patraca, R., Di Sallo, F.G., Valentim, C., Noriega, J.I., García, G.A., de la Peña, M.R., Fraga, R.M. & Martins, P.R. 2023. Neotropical ornithology: Reckoning with historical assumptions, removing systemic barriers, and reimagining the future.

Spaans, B., Van Kooten, L., Cremer, J., Leyrer, J. & Piersma, T. 2011. Densities of individually marked migrants away from the marking site to estimate population sizes: A test with three wader populations. *Bird Study* **58**: 130–140.

Stroud, D.A., Davidson, N.C., West, R., Scott, D.A., Haanstra, L., Thorup, O., Ganter, B. & Delany, S. 2004. Status of migratory wader populations in Africa and Western Eurasia in the 1990s. *International Wader Studies* **15**: 1–259.

Studds, C.E., Kendall, B.E., Murray, N.J., Wilson, H.B., Rogers, D.I., Clemens, R.S., Gosbell, K., Hassell, C.J., Jessop, R., Melville, D.S., Milton, D.A., Minton, C.D.T., Possingham, H.P., Riegen, A.C., Straw, P., Woehler, E.J. & Fuller, R.A. 2017. Rapid population decline in migratory shorebirds relying on Yellow Sea tidal mudflats as stopover sites. *Nat Commun* **8**: 1–7.

Summers, R.W., Foster, S., Swann, B. & Etheridge, B. 2012. Local and global influences on population declines of coastal waders: Purple Sandpiper Calidris maritima numbers in the Moray Firth, Scotland. *Estuar Coast Shelf Sci* **102–103**: 126–132.

Sutherland, W.J., Alves, J.A., Amano, T., Chang, C.H., Nicholas, C., Finlayson, C.M.A.X., Gill, J.A., Jr, R.E.G., González, P.M., Gunnarsson, T.G., Kleijn, D., Spray, C.J. & Székely, T. 2012. Review Article A horizon scanning assessment of current and potential future threats to migratory shorebirds. *Ibis* **154**: 663–679.

Thomas, L. 1996. Monitoring Long-Term Population Change: Why are there so Many Analysis Methods? *Ecology* **77**: 49–58.

Thompson, W.L. 2002. Towards Reliable Bird Surveys: Accounting for Individuals Present But Not Detected. *Auk* **119**: 18.

UNEP/CMS Secretariat. 2009. A bird's eye view on flyways: A brief tour by the Convention on the Conservation of Migratory Species of Wild Animals. 68 pages.

van de Kam, J., Ens, B., Piersma, T. & Zwarts, L. 2004. *Shorebirds: An ilustrated behavioural ecology* (S. J. Moore & P. F. Battley, eds). KNNV Publishing, Utrecht.

Van Den Hout, P.J., Piersma, T., Ten Horn, J., Spaans, B. & Lok, T. 2017a. Individual shifts toward safety explain age-related foraging distribution in a gregarious shorebird. *Behavioral Ecology* **28**: 419–428.

Van Den Hout, P.J., Piersma, T., Ten Horn, J., Spaans, B. & Lok, T. 2017b. Individual shifts toward safety explain age-related foraging distribution in a gregarious shorebird. *Behavioral Ecology* **28**: 419–428.

van Roomen, M., Citegetse, G., Crowe, O., Dodman, T., Hagemeijer, W., Meise, K. & Schekkerman, H. 2022. *East Atlantic Flyway assessment 2020: The status of coastal waterbird populations and their sites* (M. van Roomen, G. Citegetse, O. Crowe, T. Dodman, W. Hagemeijer, K. Meise, & H. Schekkerman, eds). Wadden Sea Flyway Initiative, Wetlands International, BirdLife International, Wilhelmshaven, Germany; Wageningen, The Netherlands; Cambridge, United Kingdom.

van Roomen, M., Delany, S. & Scherkkerman, H. 2013a. Integrated monitoring of coastal waterbird populations along the East Atlantic Flyway.

van Roomen, M., Delany, S. & Scherkkerman, H. 2013b. Integrated monitoring of coastal waterbird populations along the East Atlantic Flyway.

Verhoeven, M.A., Loonstra, A.H.J., McBride, A.D., Both, C., Senner, N.R. & Piersma, T. 2021. Migration route, stopping sites, and non-breeding destinations of adult Black-tailed Godwits breeding in southwest Fryslân, The Netherlands. *J Ornithol* **162**: 61–76.

Verkuil, Y.I., Karlionova, N., Rakhimberdiev, E.N., Jukema, J., Wijmenga, J.J., Hooijmeijer, J.C.E.W., Pinchuk, P., Wymenga, E., Baker, A.J. & Piersma, T. 2012. Losing a staging area: Eastward redistribution of Afro-Eurasian ruffs is associated with deteriorating fuelling conditions along the western flyway. *Biol Conserv* **149**: 51–59.

Verkuil, Y.I., Wijmenga, J.J., Hooijmeijer, J.C.E.W. & Piersma, T. 2010. Spring migration of ruffs philomachus pugnax in fryslân: estimates of staging duration using resighting data. *Ardea* **98**: 21–33.

Vervoort, R., Schmaltz, L.E., Hooijmeijer, J.C.E.W., Verkuil, Y.I., Kempenaers, B. & Piersma, T. 2022. Within- and between-Year Variation in the Presence of Individually Marked Ruff Calidris pugnax at a Stopover Site during Northward Migration. *Ardea* **110**.

VonBank, J.A., Collins, D.P., Ellis, K.S., Donnelly, J.P. & Knetter, J.M. 2023. Movement dynamics influence population monitoring and adaptive harvest management strategies in migratory birds. *Glob Ecol Conserv* **48**.

Wauchope, H.S., Shaw, J.D., Varpe, Ø., Lappo, E.G., Boertmann, D., Lanctot, R.B. & Fuller, R.A. 2017. Rapid climate-driven loss of breeding habitat for Arctic migratory birds. *Glob Chang Biol* **23**: 1085–1094.

Weiser, E.L., Lanctot, R.B., Brown, S.C., Alves, J.A., Battley, P.F., Bentzen, R., Bêty, J., Bishop, M.A., Boldenow, M., Bollache, L., Casler, B., Christie, M., Coleman, J.T., Conklin, J.R., English, W.B., River Gates, H., Gilg, O., Giroux, M.A., Gosbell, K., Hassell, C., Helmericks, J., Johnson, A., Katrínardóttir, B., Koivula, K., Kwon, E., Lamarre, J.F., Lang, J., Lank, D.B., Lecomte, N., Liebezeit, J., Loverti, V., McKinnon, L., Minton, C., Mizrahi, D., Nol, E., Pakanen, V.M., Perz, J., Porter, R., Rausch, J., Reneerkens, J., Rönkä, N., Saalfeld, S., Senner, N., Sittler, B., Smith, P.A., Sowl, K., Taylor, A., Ward, D.H., Yezerinac, S. & Sandercock, B.K. 2015. Effects of geolocators on hatching success, return rates, breeding movements, and change in body mass in 16 species of Arctic-breeding shorebirds. *Mov Ecol* **4**.

Weiser, E.L., Lanctot, R.B., Brown, S.C., Gates, H.R., Bentzen, R.L., Bêty, J., Boldenow, M.L., English, W.B., Franks, S.E., Koloski, L., Kwon, E., Lamarre, J.F., Lank, D.B., Liebezeit, J.R., McKinnon, L., Nol, E., Rausch, J., Saalfeld, S.T., Senner, N.R., Ward, D.H., Woodard, P.F. & Sandercock, B.K. 2018. Environmental and ecological conditions at Arctic breeding sites have limited effects on true survival rates of adult shorebirds. *Auk* **135**: 29–43.

Weiser, E.L., Lanctot, R.B., Brown, S.C., Gates, H.R., Bêty, J., Boldenow, M.L., Brook, R.W., Brown, G.S., English, W.B., Flemming, S.A., Franks, S.E., Gilchrist, H.G., Giroux, M.A., Johnson, A., Kendall, S., Kennedy, L. V., Koloski, L., Kwon, E., Lamarre, J.F., Lank, D.B., Latty, C.J., Lecomte, N., Liebezeit, J.R., McGuire, R.L., McKinnon, L., Nol, E., Payer, D., Perz, J., Rausch, J., Robards, M., Saalfeld, S.T., Senner, N.R., Smith, P.A., Soloviev, M., Solovyeva, D., Ward, D.H., Woodard, P.F. & Sandercock, B.K. 2020. Annual adult survival drives trends in Arctic-breeding shorebirds but knowledge gaps in other vital rates remain. *Condor* **122**.

Weithman, C., Gibson, D., Hunt, K., Friedrich, M., Fraser, J., Karpanty, S. & Catlin, D. 2017. Senescence and carryover effects of reproductive performance influence migration, condition, and breeding propensity in a small shorebird. *Ecol Evol* **7**: 11044–11056.

Wetlands International. 2021. *Flyway trend analyses based on data from the Asian Waterbird Census from the period of 1987-2020*.

Wetlands International. 2023. International Waterbird Census.

Williams, B.A., Watson, J.E.M., Beyer, H.L., Klein, C.J., Montgomery, J., Runting, R.K., Roberson, L.A., Halpern, B.S., Grantham, H.S., Kuempel, C.D., Frazier, M., Venter, O. & Wenger, A. 2022. Global rarity of intact coastal regions. *Conservation Biology* **36**.

Williams, H.J., Taylor, L.A., Benhamou, S., Bijleveld, A.I., Clay, T.A., de Grissac, S., Demšar, U., English, H.M., Franconi, N., Gómez-Laich, A., Griffiths, R.C., Kay, W.P., Morales, J.M., Potts, J.R., Rogerson, K.F., Rutz, C., Spelt, A., Trevail, A.M., Wilson, R.P. & Börger, L. 2020. Optimizing the use of biologgers for movement ecology research.

Yu, Y.T. & Swennen, C. 2004. Habitat use of the Black-faced Spoonbill. *Waterbirds* **27**: 129–134.

Zeileis, A., Kleiber, C. & Jackman, S. 2008. Regression models for count data in R. *J Stat Softw* **27**: 1–25.

Zhang, S.D., Ma, Z., Choi, C.Y., Peng, H.B., Bai, Q.Q., Liu, W.L., Tan, K., Melville, D.S., He, P., Chan, Y.C., Van Gils, J.A. & Piersma, T. 2018. Persistent use of a shorebird staging site in the Yellow Sea despite severe declines in food resources implies a lack of alternatives. *Bird Conserv Int* **28**: 534–548.

Zhu, B.R., Verhoeven, M.A., Loonstra, A.H.J., Sanchez-Aguilar, L., Hassell, C.J., Leung, K.K.S., Lei, W., Zhang, Z. & Piersma, T. 2021a. Identification of breeding grounds and annual routines of the newly discovered bohaii subspecies of Black-tailed Godwits. *Emu* **121**: 292–302.

Zhu, B.R., Verkuil, Y.I., Conklin, J.R., Yang, A., Lei, W., Alves, J.A., Hassell, C.J., Dorofeev, D., Zhang, Z. & Piersma, T. 2021b. Discovery of a morphologically and genetically distinct population of Black-tailed Godwits in the East Asian-Australasian Flyway. *Ibis* **163**: 448–462.

Ziolkowski, D., Lutmerding, M., Aponte, V.I. & Hudson, M.-A.R. 2022. 2022 Release - North American Breeding Bird Survey Dataset (1966-2021).

Zwarts, L. 1988. Numbers and distribution of coastal waders in Guinea-Bissau. *Ardea* **76**: 42–55.

Zwarts, L., Hulscher, J.B., Koopman, K., Piersma, T. & Zegers, P.M. 1996. Seasonal and Annual Variation in Body Weight, Nutrient Stores and Mortality of Oystercatchers Haematopus ostralegus. *Ardea* **84A**: 327–356.

Zwarts, L. & Piersma, T. 1990. How important is the Banc d'Arguin Mauritania as a temporary staging area for waders in spring? *Ardea* **78**: 113–122.

2017. *National Census Reports East Atlantic Africa 2017. Results of waterbird and wetland monitoring in the East Atlantic Flyway* (G. Agblonon, C. Nsabagasani, T. Langendoen, & M. van Roomen, eds). Common Wadden Sea Secretariat, Programme Rich Wadden Sea, Wetlands International & BirdLife International.

Annexes

Annexes to report *Towards an improved flyway monitoring: A heuristic framework to integrate count and tracking data*

Annex 1 Further details on the selection of tracking technology and device fitting

Wildlife tracking is a critical tool for understanding animal movement and behavior, providing essential information for conservation efforts. While various tracking methods exist, electronic tracking devices have revolutionized the field by offering detailed insights into animal movements, migration patterns and space use at unprecedented scales. However, selecting the appropriate tracking technology can be challenging, especially for small to medium-sized migratory shorebirds due to their size and weight constraints.

1. Tracking technology

The ideal tracking device for waterbirds, particularly for small shorebirds, would be lightweight, durable, have a long battery life, allow for remote data download, be easy to attach, and provide high spatiotemporal resolution data at a low cost. However, while current technology is already achieving this ideal for larger-sized birds like geese, this is still pretty much under development for smaller (i.e., <500 g; (Iverson *et al.* 2023) species, due to limitations in power supply weight and the need for frequent, high-resolution location fixes over extended periods (Iverson *et al.* 2023, Gould *et al.* 2024).

An effective choice of device depends on the application's purpose. Platform Transmitter Terminal (PTT) Doppler devices are suitable for long-distance tracking due to their smaller size and lighter weight (around 2g), but they offer lower resolution location data (250m-1500m) and are expensive (~ $4450+ USD; Table S1; https://www.microwavetelemetry.com/avian_transmitter_pricing) (Gould *et al.* 2024). Global Positioning System (GPS) devices are better suited for tracking smaller-scale movements as they provide higher resolution data (down to 5m) and are often more cost-effective (ranging $1000 – $3000 USD; Table S1), but they tend to be heavier (starting at 3g+, but often ca. 5g+; https://www.gm-tracking.com/products/) (Gould *et al.* 2024). GPS devices can be further categorized into satellite GPS devices, which allow for remote data download, and GPS short-range download (SRD) devices, which require the bird to be within a certain range of a receiver station for data retrieval (Gould *et al.* 2024). Satellite GPS devices are ideal for long-range studies but can be expensive, while GPS SRD devices are more affordable but limited by their range (see Table S1 and S2). Other options include radio telemetry and light-level geolocators. Radio telemetry, especially automated systems like MOTUS and ATLAS, are lightweight, inexpensive, and widely used for bird movement studies, but they require the bird to be within the vicinity of a receiver and are limited to specific geographic areas. Light-level geolocators are the lightest and cheapest option, but they offer the lowest spatial resolution data and require recapturing the bird to retrieve the data (Bridge *et al.* 2011, Guilford *et al.* 2011, Iverson *et al.* 2023, Gould *et al.* 2024). Table S2, extracted from (Gould *et al.* 2024), offers a detailed description on different tracking devices.

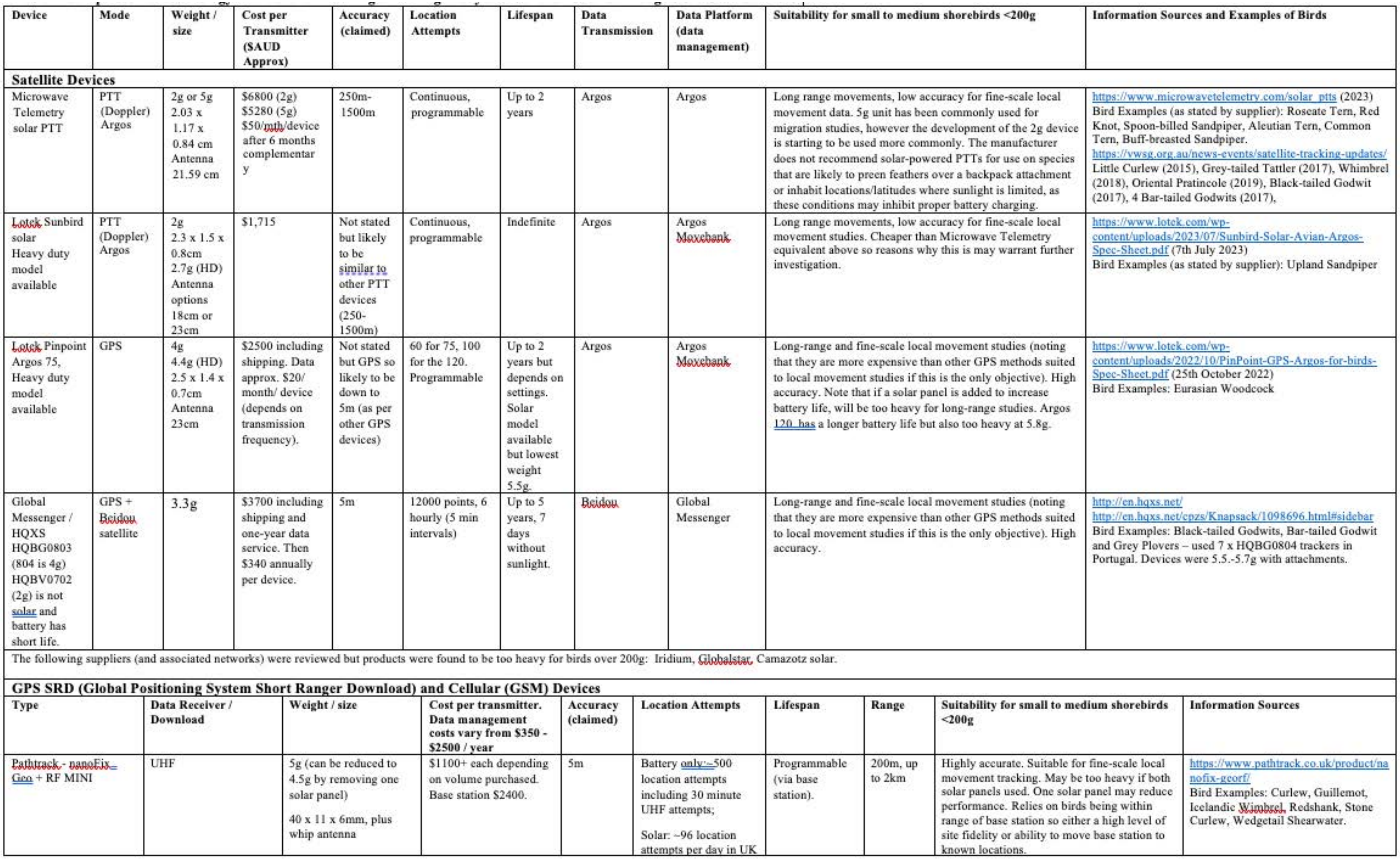
The plannification of new tracking efforts need to have very solid foundations set on previous experiences and on the knowledge accumulated on the course of the last two decades of expansion of tracking studies in the waterbird domain (Bridge *et al.* 2011, Guilford *et al.* 2011, Michel *et al.* 2024). A recent review by Iverson et al. (2023) found that 61% of studies on small birds (<500g) used PTT tags, followed by 22% using GPS-transmitters and 19% using GPS-archival tags. The authors also found that PTT tags had the highest success rate (85%) compared to GPS-transmitters (50%) and GPS-archival tags (17.5%). Another recent study by Michel et al. (2024) found that VHF radio tags were the most common type of tracking device used in the early period of shorebird tracking (1982-2009), but GPS transmitters have become the most popular choice since 2018.

2. Device fitting and deployment

Attaching tracking devices to birds also requires careful consideration. The method of attachment should minimize negative impacts on the animal's welfare and behavior. While invasive methods were used in the past (Geen *et al.* 2019), external attachments like leg loop harnesses or full body harnesses (chest harnesses) made with soft, degradable materials are now preferred (Gould *et al.* 2024). The choice of attachment method depends on the bird's morphology, behavior, and the study duration. Full body harnesses can be used for birds with compact body shapes, like Red Knots *Calidris canutus*, but they may interfere with their preening behavior due to their long bills(Chan *et al.* 2016). Leg-loop harnesses are suitable for long-legged shorebirds but may not be appropriate for species with no external knee, which is again the case for Red Knots (Chan *et al.* 2016). Materials used for harnesses include Teflon, nylon, Dacron, beading elastic, and surgical silicone tubing (Lameris *et al.* 2018, Gould *et al.* 2024). Teflon, nylon, and Dacron are not elastic and may cause abrasion or restrict movement if not fitted properly. Beading elastic is more flexible and can accommodate changes in body size, but it is less durable. Surgical silicone is a more permanent option but may be heavier. The choice of material depends on the study duration and the bird's behavior and morphology. For instance, Teflon ribbon has been used successfully in leg-loop harnesses for small and medium-sized birds without adverse effects, while beading elastic has been used in Latham's Snipe tracking studies with tags and harnesses lasting for over a year (Gould *et al.* 2024). Iverson et al. (2023) and Michel et al. (2024) reported in their reviews that most studies used harnesses to attach tags to birds, with only a few using internal implants or feather mounts. The tag load used in these studies typically ranged from 0.5% to 5% of the bird's body mass, with most studies using tag loads of less than 3%.

In addition to choosing and fitting the device, data management is another consideration that needs to be taken into account. There are a number of platforms available to manage data from tracking devices. Some are manufacturer-specific, like the Ecotopia app used for Druid GPS Bluetooth tags (https://druid.tech/ecotopia/), while others are multi-user platforms like CLS ARGOS (https://telemetry.groupcls.com), which is used by various device manufacturers like Lotek (https://www.lotek.com) and Microwave Telemetry (https://www.microwavetelemetry.com/home). The Motus Wildlife Tracking System (https://motus.org) is a collaborative network that uses coordinated automated radio telemetry and has its own data management platform. Finally, Movebank (https://www.movebank.org/cms/movebank-main) is a freely accessible platform that allows researchers to manage, share, analyze, and archive animal movement and biologging data from various tracking methods. It also collaborates with ARGOS and Motus to offer integrated data management solutions, and it is becoming increasingly popuar among researchers. Although only 27.2% of publications reviews by (Michel *et al.* 2024) reported archiving tracking data in repositories, this practice has been increasing over time.

Table S1. Comparison of technology available for tracking small migratory shorebird birds under 200g as of November 2023. Extracted from Gould et al. (2024).



Device	**Mode**	**Weight / size**	**Cost per Transmitter (SAUD Approx)**	**Accuracy (claimed)**	**Location Attempts**	**Lifespan**	**Data Transmission**	**Data Platform (data management)**	**Suitability for small to medium shorebirds <200g**	**Information Sources and Examples of Birds**
Satellite Devices										
Microwave Telemetry solar PTT	PTT (Doppler) Argos	2g or 5g 2.03 x 1.17 x 0.84 cm Antenna 21.59 cm	$6800 (2g) $5280 (5g) $50/mth/device after 6 months complementary	250m-1500m	Continuous, programmable	Up to 2 years	Argos	Argos	Long range movements, low accuracy for fine-scale local movement data. 5g unit has been commonly used for migration studies, however the development of the 2g device is starting to be used more commonly. The manufacturer does not recommend solar-powered PTTs for use on species that are likely to preen feathers over a backpack attachment or inhabit locations/latitudes where sunlight is limited, as these conditions may inhibit proper battery charging.	https://www.microwavetelemetry.com/solar_ptts (2023) Bird Examples (as stated by supplier): Roseate Tern, Red Knot, Spoon-billed Sandpiper, Aleutian Tern, Common Tern, Buff-breasted Sandpiper. https://vwsg.org.au/news-events/satellite-tracking-updates/ Little Curlew (2015), Grey-tailed Tattler (2017), Whimbrel (2018), Oriental Pratincole (2019), Black-tailed Godwit (2017), 4 Bar-tailed Godwits (2017),
Lotek Sunbird solar Heavy duty model available	PTT (Doppler) Argos	2g 2.3 x 1.5 x 0.8cm 2.7g (HD) Antenna options 18cm or 23cm	$1,715	Not stated but likely to be similar to other PTT devices (250-1500m)	Continuous, programmable	Indefinite	Argos	Argos Movebank	Long range movements, low accuracy for fine-scale local movement studies. Cheaper than Microwave Telemetry equivalent above so reasons why this is may warrant further investigation.	https://www.lotek.com/wp-content/uploads/2023/07/Sunbird-Solar-Avian-Argos-Spec-Sheet.pdf (7th July 2023) Bird Examples (as stated by supplier): Upland Sandpiper
Lotek Pinpoint Argos 75, Heavy duty model available	GPS	4g 4.4g (HD) 2.5 x 1.4 x 0.7cm Antenna 23cm	$2500 including shipping. Data approx. $20/ month/ device (depends on transmission frequency).	Not stated but GPS so likely to be down to 5m (as per other GPS devices)	60 for 75, 100 for the 120. Programmable	Up to 2 years but depends on settings. Solar model available but lowest weight 5.5g.	Argos	Argos Movebank	Long-range and fine-scale local movement studies (noting that they are more expensive than other GPS methods suited to local movement studies if this is the only objective). High accuracy. Note that if a solar panel is added to increase battery life, will be too heavy for long-range studies. Argos 120 has a longer battery life but also too heavy at 5.8g.	https://www.lotek.com/wp-content/uploads/2022/10/PinPoint-GPS-Argos-for-birds-Spec-Sheet.pdf (25th October 2022) Bird Examples: Eurasian Woodcock
Global Messenger / HQXS HQBG0803 (804 is 4g) HQBV0702 (2g) is not solar and battery has short life.	GPS + Beidou satellite	3.3g	$3700 including shipping and one-year data service. Then $340 annually per device.	5m	12000 points, 6 hourly (5 min intervals)	Up to 5 years, 7 days without sunlight.	Beidou	Global Messenger	Long-range and fine-scale local movement studies (noting that they are more expensive than other GPS methods suited to local movement studies if this is the only objective). High accuracy.	http://en.hqxs.net/ http://en.hqxs.net/cpzs/Knapsack/1098696.html#sidebar Bird Examples: Black-tailed Godwits, Bar-tailed Godwit and Grey Plovers – used 7 x HQBG0804 trackers in Portugal. Devices were 5.5.-5.7g with attachments.

The following suppliers (and associated networks) were reviewed but products were found to be too heavy for birds over 200g: Iridium, Globalstar, Camazotz solar.

GPS SRD (Global Positioning System Short Ranger Download) and Cellular (GSM) Devices

Type	**Data Receiver / Download**	**Weight / size**	**Cost per transmitter. Data management costs vary from $350 - $2500 / year**	**Accuracy (claimed)**	**Location Attempts**	**Lifespan**	**Range**	**Suitability for small to medium shorebirds <200g**	**Information Sources**
Pathtrack - nanoFix Geo + RF MINI	UHF	5g (can be reduced to 4.5g by removing one solar panel) 40 x 11 x 6mm, plus whip antenna	$1100+ each depending on volume purchased. Base station $2400.	5m	Battery only: ~500 location attempts including 30 minute UHF attempts; Solar: ~96 location attempts per day in UK	Programmable (via base station).	200m, up to 2km	Highly accurate. Suitable for fine-scale local movement tracking. May be too heavy if both solar panels used. One solar panel may reduce performance. Relies on birds being within range of base station so either a high level of site fidelity or ability to move base station to known locations.	https://www.pathtrack.co.uk/product/nanofix-georf/ Bird Examples: Curlew, Guillemot, Icelandic Wimbrel, Redshank, Stone Curlew, Wedgetail Shearwater.

					summer (48 if only one panel used).				
Telemetry Solutions Nano backpacks	UHF (long-range drone mounted receiver)	5g	$1210 each plus $1500 for base station Software is $85 and app is free.	5m	Programmable	36 days max (depends on settings).	30km (drone mounted).	All too heavy except for one GPS device which was 5g and uses UHF (long range) download via drone base stations. Uses Iridium satellite network. Battery operated (not solar) and therefore only had a lifespan of 36 days (max). Base station has 2 days battery life. Works best in open sunny conditions.	www.telemetrysolutions.com Bird Examples: Shearwater, Caspian tern – many species.
Lotek PinPoint VHF 75 & Pinpont Commander (receiver)	VHF	3g	PinPoint VHF 75: $1,715 Commander: $1,415	5m	90 to 5,500 (dependent on model and schedules)	Not specified but battery operated.	800m - 1km	Highly accurate. Suitable for fine-scale local movement tracking. Relies on birds being within range of base station so either a high level of site fidelity or ability to move base station to known locations. Solar VHF models are available, but these are 6g+. GoTel GSP Solar which use cellular networks are also available but lightest of these are 6.6g and only use 2G network. 3G and 5G network enabled tags are available but are 18g+	https://www.lotek.com/wp-content/uploads/2023/06/PinPoint-GPS-VHF-for-birds-Spec-Sheet.pdf Bird Examples: No small wader birds, only Barred Owl, Turkeys. https://www.lotek.com/products/gotel-gps/ Supported by Motus which is a large-scale network of receivers and associated data sharing platform https://motus.org/about/
Pathtrack - nanoFix Geo + RF MINI	UHF	5g (can be reduced to 4.5g by removing one solar panel) 40 x 11 x 6mm, plus whip antenna	$1100+ each depending on volume purchased. Base station $2400.	5m	Battery only ~500 location attempts including 30 minute UHF attempts; Solar: ~96 location attempts per day in UK summer (48 if only one panel used).	Programmable (via base station).	200m, up to 2km	Highly accurate. Suitable for fine-scale local movement tracking. May be too heavy if both solar panels used. One solar panel may reduce performance. Relies on birds being within range of base station so either a high level of site fidelity or ability to move base station to known locations.	https://www.pathtrack.co.uk/product/nanofix-georf/ Bird Examples: Curlew, Guillemot, Icelandic Wimbrel, Reshank, Stone Curlew, Wedgetail Shearwater.
Telemetry Solutions Nano backpacks	UHF (long-range drone mounted receiver)	5g	$1210 each plus $1500 for base station Software is $85 and app is free.	5m	Programmable	36 days max (depends on settings).	30km (drone mounted).	All too heavy except for one GPS device which was 5g and uses UHF (long range) download via drone base stations. Uses Iridium satellite network. Battery operated (not solar) and therefore only had a lifespan of 36 days (max). Base station has 2 days battery life. Works best in open sunny conditions.	www.telemetrysolutions.com Bird Examples: Shearwater, Caspian tern, Sharp-tailed Grouse – many species.
Ecotone Alle 60, Alle 100 (solar available)	UHF	4.5g, 6g	$100ea plus base station ($1500)	5m	Programmable	~500 GPS fixes for the 60 and ~1000 for the 100. Up to 3 months depending on programming	100m	Accurate. Light. Relies on birds being within range of base station so either a high level of site fidelity or ability to move base station to known locations.	https://www.northstarst.com/products/alle-60/ https://www.northstarst.com/products/alle-100/ Bird Examples: No small wader birds. Superb Parrots
Interrex Druid NANO Solar	Bluetooth	3.7g (available in larger sizes)	$150ea plus base station ($1500).	5m	Fully charged battery 100 GPS positions under optimal satellite view. Solar keeps battery charged (assuming enough sunlight)	Programmable. Up to 890 GPS fixes per day. 460 days at default setting (1 hour intervals)	150m (phone), up to 1.5km (receiver).	Accurate. Light. Suitable for local movement tracking. Relies on birds being within range of base station so need a high level of site fidelity or ability to move base station to known locations.	https://interrex-tracking.com/ Bird Examples: Latham's Snipe https://lathamssnipeproject.wordpress.com/news/
Interrex Druid ULTRA	5G network	3.6g	$1000ea	5m	Programmable	Programmable. Up to 2 years depending on settings.	Anywhere in 5G network	Accurate. Light. Relies on bird being in the range of a 5G network for data upload. New to market and not widely tested.	https://interrex-tracking.com/ Bird Examples: Little Tern. Not widely tested.

Automated Radiotracking. Note that this only presents the largest networks. There are numerous species-specific smaller scale projects.

Type	Data Receiver / Download	Weight / size	Cost excl data management costs vary	Accuracy (claimed)	Location Attempts	Lifespan	Range	Suitability for small to medium shorebirds <200g	Information Sources

			from $350 - $2500 / year						
ATLAS (Advanced Tracking and Localization of Animals in real-life Systems)	UHF	Down to 0.8g	$200ea plus base stations (~$100) plus set up costs (may be several thousand if over a large area).	5m	Don't store data so need a high number of receivers evenly spaced (need 3 receivers / tag to get signal).	Not specified. Glued on to birds so up to several months but can be reused if retrieved.	8-15km (if receiver very high or drone-mounted)	Birds need to be within range of receivers. Need many receivers for birds that travel within a known area. Need minimum of 3 receivers. Better options available unless it is being set up as a large-scale study e.g. Wadden Sea.	https://methodsblog.com/2022/06/21/atlas-a-regional-scale-tracking-system/ As at 2022, there were 6 ATLAS systems worldwide with over 50 species tracked. Example: Dutch Wadden Sea Project (WATLAS) – 26 receivers in 2021 covering 1326km: https://methodsblog.com/2022/06/21/atlas-a-regional-scale-tracking-system/ Birds tracked: Red Knots, Sanderlings, Bar-tailed Godwits, and Common Terns
MOTUS Automated Radio Telemetry Network	Two types of tags used. Nanotags tags use amplitude modulationor AM, whereas CTT tags use frequency modulationor FM. VHF 160mHz and UHF 435mHz	Down to 0.15g	Varies depending on type	1-15 kms.	Don't store data.	Varies but often glued.	15km but varies with frequency.	Collaborative network: Uses NanoTags™ manufactured by Lotek Wireless Inc, and LifeTag™, PowerTag™, and HybridTag™ manufactured by Cellular Tracking Technologies (CTT). The two tags use fundamentally different transmission and coding systems. Need birds to stay within range of receivers which are mostly in the northern hemisphere. Map can be found at: https://motus.org/data/receiversMap Current network 750 receivers and growing. Can create a receiver 'fence' or grid of 'fences' over a geographic area so any tagged animal passing through it will get detected.	https://motus.org/telemetry/ Examples: Bar-tailed Godwit, Dowitchers, Stilts, Sandpipers, Knots (many different species).

Table S2. Description, advantages and limitations of technology used for obtaining movement data from migratory shorebirds under 200g. Extracted from Gould et al. (2024)

Type	Description	Advantages	Limitations
GPS Satellite (Solar or non-rechargeable battery). Remote data download.	Location data recorded via GPS receiver using satellites. Relayed to central data store or internet connected computer (wi-fi or cellular data). Location plotted on map (5, 6). Lifespan depends on settings - very frequent readings drain battery power whereas longer intervals between readings use less power. Solar recharges battery.	Accurate (down to 5m) and useful for studies that require fine scale movement data. Frequent data readings. Records speed and altitude. 24-hour data. Low human interference required once affixed. On board storage. High download options.	Too heavy (5g+) for birds under 200g (especially with solar panel). Expensive (~A$1000+ depending on device).
Doppler (PTT)	Transmit data via satellite systems which estimate position using the Doppler effect, the shift in wavelength of a transmitted radio frequency signal between an overhead satellite and a ground-based component which calculates PTT positions. Raw data processed to extract transmitted information (2, 6). Data downloaded directly from carriers. Argos is the primary global provider of animal satellite data transmission, but there are others such as Iridium.	Light (down to 2g). Low human interference required once affixed. Data can be obtained remotely from anywhere on earth over a relatively long time-period (e.g. two years or more).	Expensive (~A$5000+). Lower accuracy than GPS (250m -1500m compared with 5m for GPS). Better suited to global migration studies where fine scale movement data is not critical. No on-board storage. Minimal download options.
GPS UHF or VHF SRD (Short range download). Battery or solar.	GPS devices receive signals from at least three satellites (often many more) simultaneously to determine position to within metres. The devices store this data which is then transmitted using Bluetooth, cellular network, UHF or VHF. Receiver stations may be installed or internet-enabled devices such as smart phones may be used with or without relay hubs.	Accurate (down to 5m). Light (down to 2.0g) Tags inexpensive (~A$200ea). Receivers more expensive but long life (~A$1200). High on-board data storage.	Need receiver or cellular network in a compatible frequency to download data. Can be mounted on drones to increase range. Animal has to be within the vicinity of one or more receiver stations for data to be downloaded (17, 23). High labour if numerous receivers are required. High risk of loss if birds leave area. In some countries like Australia, certain frequencies clash with emergency services frequencies and can't be used.
Automated Radio Telemetry (e.g. MOTUS, ATLAS)	Radio-tracking with automated receivers, such as those associated with the Motus network or ATLAS, in combination with digitally coded tags (which contain a special code that uniquely identifies the device) enable many birds to be tracked continuously and simultaneously across broad landscapes. Motus supports two types of uniquely coded radio transmitters and has been deployed in more than 850 receiving stations across 28 countries on 6	Light. Tags range in size from ~0.2 g to ~2.6 g, Accurate (down to 5m) but depends on number of receivers. Inexpensive (price varies but generally A$200 or less). Lifespans vary from 20 days to many years depending on the model.	Birds need to be in the vicinity of a receiver (<1km) and these networks are limited to specific geographic areas (mostly in the northern hemisphere). Limited by the strength of the signal emitted by the tag.

	continents (24). ATLAS comprises six systems in four different countries (25)	Widely used for bird movement studies.	Configuration and location of receivers needs to be considered if being set up independent of an existing network. Need to ensure tag transmission frequency matches that of the receiver.
Manual Radiotracking	VHF tags transmit a VHF radio signal which can be detected from the ground or air by a radio receiver in the form of a hand-held antenna. This enables researchers to locate and track the radio-tagged animal in real time.	Light (<3g). Inexpensive. Can be glued on (short term deployment).	Low accuracy – general location only. Need to be within the vicinity of the tag (<100m) High labour. More accurate technologies are now available at a comparable cost.
Light Level Geolocation	Record light-level in lux that can be used with time and data-stamp to estimate the coordinates of an animal's location. Can also be fitted with temperature and salinity loggers (2, 26, 27). Many different types available.	Light (<1g). Inexpensive (<A$150) Very small (can be mounted on leg flags).	Need to re-capture animal to retrieve data. Very low accuracy (kilometres) and requires detailed data calculations to determine locations.
Biologging	Biologging is a broad term that refers to the use of different technologies to learn about animal behaviour. Examples include camera traps (video and still) to record foraging behaviour, or accelerometers to measure energy budgets. Often used in conjunction with tracking technology to provide insight into behaviour.	Variety of techniques that can complement other tracking technologies. Wide variety of options available. Can provide detailed insights into animal behaviour.	Not used as a tracking technology in isolation. Not broadly applicable – generally used for a very specific purpose.

Annex 2: Considerations on the selection of priority species for an integrated flyway monitoring in the East Atlantic Flyway

1. Priority species at a gloal level

Michel et al. (2024) conducted a comprehensive review of the scientific literature on shorebird tracking studies at a global scale to assess the current state of knowledge and identify gaps and priorities for future research and conservation efforts. The study encompassed 353 publications covering 73 shorebird species from five families, revealing significant disparities in data availability across species and regions. The research highlighted a bias towards migratory species and those of intermediate body size, with over half of the shorebird species lacking any tracking publications. Geographic disparities were also evident, with data availability concentrated in temperate regions and migratory routes passing through wealthier countries, while the Global South remained largely understudied. The take away of this is that there are currently an implicit bias on our knowledge of the different flyways due to this disparity, which qualifies as a significant gap that needs to be addressed even for species that are well covered by tracking studies.

The study by (Michel *et al.* 2024) also identified 13 priority species for future tracking research based on their conservation needs, lack of existing data, and the potential of tracking to inform conservation actions (see Table 4 of Michel *et al.* 2024). These species are primarily found in the East Asia/Australasia flyway and South America, highlighting the need for increased research efforts in these regions. The priority species identified were: Imperial Snipe (*Gallinago imperialis)*, Australian Painted Snipe (*Rostratula australis*), Spotted Greenshank (*Tringa guttifer*), Sulawesi Woodcock (*Scolopax celebensis*), Diademed Plover (*Phegornis mitchellii*), Hooded Plover (*Thinornis cucullatus*), Malaysian Plover (*Charadrius peronii*), White-faced Plover (*Charadrius dealbatus*), Asian Dowitcher (*Limnodromus semipalmatus*), Curlew Sandpiper (*Calidris ferruginea*), Fuegian Snipe (*Gallinago stricklandii*), Javan Woodcock (*Scolopax saturata*), and Slender-billed Curlew (*Numenius tenuirostris*). Of these, the Spotted Greenshank, White-faced Plover, Asian Dowitcher, Curlew Sandpiper, and Slender-billed Curlew are found in the East Atlantic Flyway. The authors emphasized the importance of coordinated efforts among researchers and conservation actors to strategically deploy tracking devices and archive data in accessible repositories to maximize the impact of shorebird tracking studies. The study's findings serve as a call to action for the research community to prioritize data collection and sharing to address the conservation challenges faced by shorebirds globally, together with the conservation community and managers of the areas these birds depend on.

2. Priority species for the East Atlantic Flyway

Creating comprehensive lists for priority waterbird species based on the East Atlantic Flyway involves thorough analysis of scientific literature and data on knowledge gaps specifically targetting this region. Although (Michel *et al.* 2024) makes very strong advancements in providing this information, it is offered at a global scale. In addition, the conservation status used in the prioritization of species is also assessed at a global, including populations of all flyways. Nevertheless, based on current knowledge on population trends in the flyway as of 2020 (van Roomen *et al.* 2022), we made an exercise to highlight a list of species of conservation priority in the East Atlantic Flyway.

Using as guidance the priority species selection criteria presented in section 10, Step 3 of the report, we offer in Table S3 a list of 11 potential priority species to implement tracking combined with count data for an improved monitoring set up in the East Atlantic Flyway. The list only includes species that we consider that are possible to track safely, i.e., without significantly impacting the survival and behaviour of the individuals and of the population, and species that are logistically accessible for catching and for recovering data from the tags. The list was build in such way that it includes a variety of species responding to the key criteria of species selection, namely (1) species that can serve as sentinels of change in their environments, (2) species representing different habitats, behaviours, size classes, behaviours, diets, migratory patterns, and range distribution (coverage) in the flyway, (3) species representing different conservation status and trends in the Flyway, and (4) species representing both study systems we already have longer term data and experience on, which serve as the best for monitoring changes reliably on their environment, and study systems on which very little information exists yet, qualifying as a priority for the knowledge gaps on their ecology and on the habitats they use. Note that the proportion of Scolopacidae shorebirds in the list is quite high, mirroring their conservation priority, as they suffer the highest declines among all waterbirds in the East Atlantic Flyway (van Roomen *et al.* 2022), and also the accumulated experience tracking these species in the last decade (Michel *et al.* 2024).

Table S3. List of proposed priority species to develop an integrated monitoring set up combining counts and tracking data in the East Atlantic Flyway. All species are already assumed to be possible to track logistically and in terms of the individuals and population safety.

Species	Family	Weight (grams, min - max)	Max. Tracking device weigth	EAF coverage	EAF S-trend	Habitat	Diet	Existing ecological knowledge	Existing tracking expertise	Knowledge gap level	Num. populations in EAF
Brent goose	Anatidae	800 - 1510	24	Arctic - North Spain	Stable	Coastal saltmarsh Seagrass Grassland	Grass / seagrass	High	High	Low	3
Eurasian spoonbill	Threskiornithidae	1130 - 1960	34	North West Europe - Mauritania	Strong increase	Coastal Estuaries Wetlands	Fish / shrimp	Medium	Medium	Medium	2
Common tern	Laridae	113 - 144	3.5	Scandinavia/South Siberia - South Africa	Stable	Coastal Subtidal	Fish	Medium	Low	Medium	3
Eurasian oystercatcher	Haematopodidae	465 - 640	14	North European / Iceland - West Africa	Moderate decline	Variable	Variable	High	Medium	Medium	1
Grey plover	Charadriidae	200 - 290	6	Arctic - Guinea golf	Moderate decline	Intertidal	Macrozoobenthos	Medium	Medium	High	1
Sanderling	Scolopacidae	46 - 73	1.5-1.7	Arctic - South Africa	Stable	Sandy coasts Sandy intertidal flats	Macrozoobenthos - Crustaceans	Medium	Low	High	2+
Curlew sandpiper	Scolopacidae	49 - 79	1.5-1.7	Arctic - Golf of Guinea	Strong decline	Intertidal	Macrozoobenthos	Low	Low	High	1
Red Knot	Scolopacidae	120 - 158	3.5	Arctic - South Africa	Moderate decline	Intertidal	Macrozoobenthos - Bivalves	High	Low	Medium	2
Bar-tailed godwit	Scolopacidae	244 - 360	7	Arctic - South Africa	Moderate decline	Intertidal	Macrozoobenthos - Polychaetes	High	Medium	Medium	2
Whimbrel	Scolopacidae	355 - 522	10.5	Arctic - South Africa	Stable	Intertidal Grass meadows	Macrozoobenthos - Crustaceans	High	Medium	Medium	2 or 3
Black-tailed godwits	Scolopacidae	240 - 360	7	West Europe - West Africa	Declining	Intertidal Rice fields Grass meadows	Variable	High	High	Medium	2

References in Annexes 1 and 2

Bridge, E.S., Thorup, K., Bowlin, M.S., Chilson, P.B., Diehl, R.H., Fléron, R.W., Hartl, P., Roland, K., Kelly, J.F., Robinson, W.D. & Wikelski, M. 2011. Technology on the move: Recent and forthcoming innovations for tracking migratory birds. Bioscience 61: 689–698.

Chan, Y.-C., Brugge, M., Tibbitts, T.L., Dekinga, A., Porter, R., Klaassen, R.H.G. & Piersma, T. 2016. Testing an attachment method for solar-powered tracking devices on a long-distance migrating shorebird. J Ornithol 157: 277–287.

Geen, G.R., Robinson, R.A. & Baillie, S.R. 2019. Effects of tracking devices on individual birds – a review of the evidence.

Gould, L.A., Manning, A.D., McGinness, H.M. & Hansen, B.D. 2024. A review of electronic devices for tracking small and medium migratory shorebirds.

Guilford, T., Åkesson, S., Gagliardo, A., Holland, R.A., Mouritsen, H., Muheim, R., Wiltschko, R., Wiltschko, W. & Bingman, V.P. 2011. Migratory navigation in birds: New opportunities in an era of fast-developing tracking technology.

Iverson, A.R., Schaefer, J.L.B., Skalos, S.M. & Hawkins, C.E. 2023. Global positioning system (GPS) and platform transmitter terminal (PTT) tags reveal fine-scale migratory movements of small birds: A review highlights further opportunities for hypothesis-driven research. Ornithological Applications 125.

Lameris, T.K., Müskens, G.J.D.M., Kölzsch, A., Dokter, A.M., Van der Jeugd, H.P. & Nolet, B.A. 2018. Effects of harness-attached tracking devices on survival, migration, and reproduction in three species of migratory waterfowl. Animal Biotelemetry 6.

Michel, G., Nightingale, J., Beal, M., Bernard, A., Dias, M.P. & Alves, J.A. 2024. Global review of shorebird tracking publications: Gaps and priorities for research and conservation.

van Roomen, M., Citegetse, G., Crowe, O., Dodman, T., Hagemeijer, W., Meise, K. & Schekkerman, H. 2022. East Atlantic Flyway assessment 2020: The status of coastal waterbird populations and their sites (M. van Roomen, G. Citegetse, O. Crowe, T. Dodman, W. Hagemeijer, K. Meise, & H. Schekkerman, eds). Wadden Sea Flyway Initiative, Wetlands International, BirdLife International, Wilhelmshaven, Germany; Wageningen, The Netherlands; Cambridge, United Kingdom.