Innovations for migratory bird monitoring along the East Atlantic Flyway (FLYWAY)

Following a request from the Dutch Ministry of Agriculture, Nature and Food Quality (LNV) and its counterparts in Germany and Denmark

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1. SUMMARY

1.1 Why monitoring?

Coastal waterbirds and the wetlands they inhabit are an essential component of worldwide biodiversity. Across the globe, migratory waterbirds share a few, general routes between breeding grounds and non-breeding grounds encompassing general global flyways across continents. An important flyway between Europe and Africa, used by millions of waterbirds, is the East Atlantic Flyway, which coarsely connects the Arctic region between NE Canada and Siberian Russia with the European and African west coast.

Many international treaties and conventions are targeting the conservation of biodiversity and ecosystems. To ensure an early detection of worrisome population trends of waterbird species and define important sites for these species, national governments and site managers need reliable monitoring data. Clearly, for appropriate decisions about potential conservation measures information about population trends and sizes is essential.

After the designation of the Wadden Sea as a World Heritage site in 2009, the Wadden Sea Flyway Initiative (WSFI) was established in 2012, which initiated an integrated monitoring programme of coastal waterbirds in 2013 together with Wetlands International and BirdLife International. The goals of this integrated monitoring programme along the East Atlantic Flyway are to (1) estimate the size and distribution of flyway populations and to detect trends herein (abundance monitoring). Additional goals are to (2) gain insight into the causes that explain changes in waterbird numbers and distribution, i.e. through monitoring of reproduction and survival (vital rate monitoring), and (3) assess pressures at sites along the flyway (environmental monitoring).

1.2 Current methodology

During annual surveys and extra triennial simultaneous campaigns it is aimed to cover almost all relevant wetlands along the flyway, to a large extent relying on experienced volunteers. These counts are conducted in January, when there is generally little migratory movement of birds. Large colonial-breeding waterbirds are (also) counted during the breeding season (e.g. Koffijberg et al. 2022). The products of the current abundance monitoring are (reliable estimates of) the total number of birds per species or population and changes over time therein, as well as (changes) in geographical distribution. These data are used to choose sites to assign (an extra) conservation status and to signal the need for, design, evaluate the effect of conservation measures following (inter)national treaties and laws.

The estimation of vital rates (reproduction and survival) is currently hardly implemented in the monitoring programme. However, other research groups have set-up and are conducting several studies in which vital rates are estimated for a number of species (Rakhimberdiev et al. 2015, e.g. Lok et al. 2015, 2017, Reneerkens et al. 2020). Annual survival is mostly estimated using mark-recapture analyses based on observational data of individually colour-marked birds. Reproductive success can be measured at different stages (incubation, chick rearing, post-fledging) through detailed observations at the breeding grounds or by assessing proportions of juveniles (in observed groups or catches) at migration and wintering sites.

Environmental variables including human pressures are monitored by asking local waterbird counters and site managers to fill in questionnaires about the state of the habitat

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and the presence or absence of human pressures at the sites that they know. Correlating pressures with local abundance or vital rates can give insights into which environmental pressures may be responsible for changes in waterbird populations so that policy and conservation can act correspondingly.

1.3 Shortcomings

The success of the monitoring of coastal waterbirds along the East Atlantic Flyway depends on clear objectives, consistent methodology, a minimization of sources of error and a long-term continuation. However, documenting the conservation status of flyway populations and the sites they use is a true challenge and, inevitably, there are shortcomings to the current monitoring. To start with, there is often uncertainty about the geographical boundaries of flyway populations and the degree of co-occurrence of subspecies that cannot be distinguished in the field, which has obvious consequences for the determination of population sizes. This problem will likely increase because of Climate induced changes in distribution may additionally add uncertainty about the geographical boundaries of flyway populations. The abundance monitoring by field observers estimating the number of birds at sites is subject to inaccuracy due to several logistical and natural factors. At the flyway-level, incomplete coverage (sites and suitable habitat that remain unobserved during counts) are a cause of inaccuracy. Particularly for the African part of the flyway, observer capacity and availability of equipment (optical equipment, field guides, fuel for cars and boats) as well as continuity of experienced observers continues to be a challenge. Locally, a main issue in counting birds is the reliability of the counts. Especially when flocks of waterbirds are large and contain several similar-sized species, there is a considerable error in the estimates of group sizes resulting in lower reliability of the flyway population-size estimates. Consistent underestimation can also be problematic. For instance, during high tide, some shorebird species roost hidden in mangroves.

The monitoring of vital rates mainly suffers from the fact that this is only done for a few species, often for a short period and not systematically embedded in the flyway monitoring scheme. Systematic monitoring of population-level reproductive output is currently only performed for geese and swans, based on observations of the number of juveniles within families. For most other waterbird species, flyway-wide estimates of annual reproductive success are methodologically more challenging to obtain and are often still lacking.

The current method of monitoring environmental pressures via questionnaires is suboptimal due to their qualitative and subjective nature as well as limits of detectability. Objective, reproducible and quantitative analyses are needed to help disentangle global and local effects of the environment on bird populations.

The monitoring results currently have insufficient impact on the policy level, probably as a result of insufficient communication and translation of results to policy makers and because the outcomes of analyses are usually and inevitably often published when e.g. population declines are already going on for considerable time.

1.4 Possible solutions

The rapid and ongoing development of monitoring techniques, statistical analyses, computational power of computers, access to satellite imagery, as well as the fast development of machine learning techniques could be helpful to increase the accuracy of the

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current monitoring. We identified many techniques, currently not (optimally) embedded in the flyway monitoring, that could likely result in large improvements.

Individual tracking of birds, colour-ringing, genetic and isotopic methods will help to describe (changes in) species-specific flyway boundaries and connectivity between sites.

Abundance monitoring can benefit from power analyses to identify at which frequency and at which sites waterbird monitoring should take place to reach the desired time frame that statistically significant (negative) trends can be detected. The accuracy of counts can be improved with remote sensing techniques, especially drones, on high tide roosts, which are already successful when used to count colony-breeding waterbirds. Nonetheless, there are limitations in the use of drones that need to be overcome first, such as disturbing birds, species recognition, and the limited area that can be covered. Observations of individual colour-marked waterbirds can also be used to estimate bird numbers.

Vital rates (the probabilities to reproduce and/or survive) can be measured in different ways. The colour-ringing of waterbirds and observations of individually colour-marked birds along the flyway can be extended to more species to assess temporal and spatial variation in their survival probabilities. The longer such projects run in a standardised way, the more powerful they become. Assessing the annual variation in the percentage of juvenile birds in counts and catches of coastal waterbirds (especially shorebirds) will be of much value to assess variation in reproductive rates. Importantly, integrative population models can be used to a much larger extent in coastal waterbirds and are powerful because they allow detailed estimation of vital rates that are not assessed in the field, but deduced by the model based on other vital rates. Recently developed molecular methods to estimate age of individuals, in contrast to the age classes (juvenile versus “one-year or older”) will provide much more detail into population matrix models and allow for more detailed analysis of age-dependent vital rates and, as such, result in more precise estimates of e.g. population dynamics.

Environmental monitoring can relatively easily also include the collection of quantitative data, even at the scale of the entire flyway, by remote sensing using satellite imagery. Many relevant proxies of environmental pressures can be measured at a useful spatiotemporal scale. For example, the extent of mudflats, the number of human constructions, and the timing of snowmelt can all be reliably measured. Such environmental monitoring would be a large step forward improving the early warning function of the monitoring. However, linking such measurements mechanistically to bird abundance is complicated because of time lags between stressors and bird numbers or by carry-over effects (stressors causing a change in abundance elsewhere) and compensatory mechanisms, such as buffer effects.

Tracking individual birds by use of transmitters or loggers, can better link bird behaviour to assess (changes in) habitat quality. Tracking devices and on-the-ground ecological studies are, however, expensive, requiring large investments to carry out such work as an integrated part of the monitoring along the flyway.

1.5 Conclusions and recommendations

In summary, many novel methods and techniques are available but differ in their costs and benefits, their potential impact on improving the current waterbird monitoring and the time required for them to become available. Ultimately, choices about whether, and which, innovative techniques should be adopted, need to be made in relation to information needs

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and resources available. Our assessment highlights several improvements with a high impact and urgency that can be applied:

(1) the current abundance monitoring can benefit from (relatively simple) power analyses, re-sampling techniques and/or simulations to indicate how the current monitoring scheme can become more reliable with adjustments in frequency and site selection. Additionally, the adoption of new methods to correct for missing values in the dataset (imputation) will make the analyses of waterbird abundance monitoring more efficient, powerful and reliable. Densities of individually marked birds could be used to estimate numbers. Counts from planes or large high-flying drones would increase the accuracy of counts. Better instructions, training of observers and the development of clearer monitoring protocols could easily increase the long-term commitment and reliability of counts in areas where there is no long-standing history with counting birds.

(2) There is a large need to integrate the long-term monitoring of vital rates of a few selected key species that represent specific habitats and life histories into the current scheme. Estimates of seasonal or annual survival and population-level annual reproductive output can be measured for these species and used in integrative population models to indicate where and when in a life cycle and along the flyway population growth is limited.

(3) There is a large potential to use satellite imagery to remotely sense the environment. We highly recommended to use old and new methods simultaneously for some period to enable evaluation and validation of both methods and the extent to which they affect the outcomes. Some techniques can already easily be implemented (e.g. remote sensing of habitat, estimates of vital rates, counts of colony-breeding birds by use of drones), while other techniques require pilot studies to obtain the necessary knowledge and gain experience of how to reliably adopt and implement these techniques into the current monitoring. E.g., pilot studies of the suitability of using drones to count waterbirds at high tide roosts and to estimate coastal waterbird densities at low tide will be useful. Also, the suitability of individual tracking of birds in combination with measurements of habitat quality as a monitoring tool on flyway scale needs more study. Ultimately to understand population trends and to offer options for management measures, the combined use of bird counts, colour-ring schemes, individual tracking of habitat use and integrated population models will be very powerful.

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2. INTRODUCTION

2.1 Occasion

After the designation of the Wadden Sea as a World Heritage site in 2009, the Wadden Sea Flyway Initiative (WSFI) was established in 2012 which initiated an integrated monitoring programme in 2013 (Boere and van Roomen 2011, van Roomen et al. 2013). The Wadden Sea Flyway initiative, involves partnerships between governments, non-governmental organizations, and other stakeholders to address challenges faced by migratory birds depending on the Wadden Sea, during their annual routines along their joint migrations. In cooperation with Wetlands International and Birdlife International, the initiative started an integrated monitoring scheme which aimed for the assessment of waterbird numbers, monitoring of vital rates and of pressures and potential threats to waterbird populations along the flyway. The aim of the monitoring scheme is to get reliable information about the total population sizes of these coastal waterbirds, to monitor changes in their population sizes and to gain a better insight into which conservation measures are needed and how to best implement them. Since 2013, in a large international effort, annual counts of coastal waterbirds are carried out in January and once in three years a "total count' is organized along the East Atlantic coasts of Europe and Africa, the so-called East Atlantic Flyway. During the counts, observers also collect information about conditions of the habitat, human activities and possible threats to waterbirds and their habitat. After each total count, a Flyway Assessment Report is produced in which the conservation status of relevant flyway populations and their sites are described (van Roomen et al. 2015, 2018, 2022). Now that we are marking the first ten years of this monitoring, and given the inevitable uncertainties surrounding the estimates and difficulties to assess threats to waterbird populations across a vast geographic area, it is useful to evaluate the current programme and asses possible improvements. The development of monitoring techniques has been fast in recent decades (Lahoz-Monfort and Magrath 2021, Fig. 1), and taking stock of these may help to improve the current methodology.

We were fortunate that the European Commission's Directorate General for Structural Reform Support (DG REFORM), following the request from the Ministry of Agriculture, Nature and Food Quality of the Netherlands, also on behalf of counterparts in Denmark and Germany, awarded the Coastal & Marine Union (EUCC) to support the development of the project entitled "*Innovations for migratory bird monitoring along the East Atlantic Flyway*" (original name *Digitalizing Monitoring of the East Atlantic Flyway*"). EUCC We were included in this project on request of EUCC and we were asked to produce a report describing current methodology and shortcomings (Background Analyses) and to give an overview of possible innovations and improvements (State of Play Assessment).

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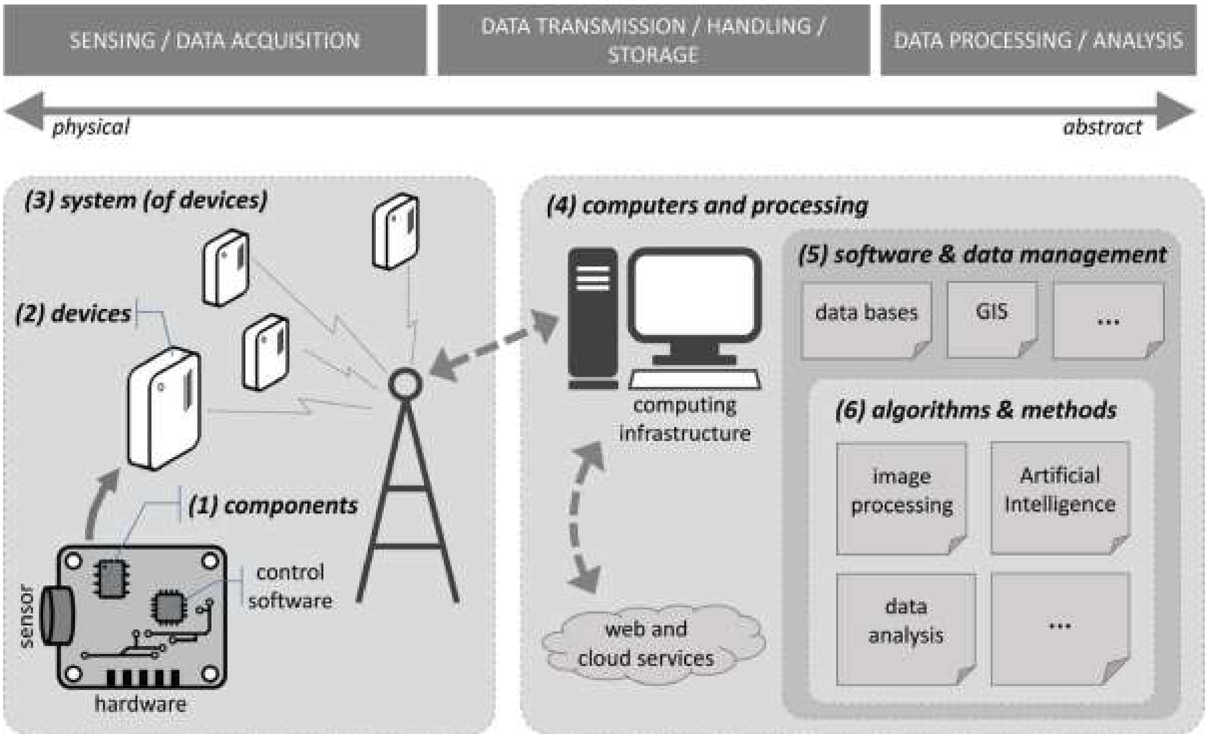

Figure 1. Technology that aids the monitoring of the natural world has advanced rapidly during the last decades, with developments along the entire pipeline from sensing via data transmission to data processing and analyses. From (Lahoz-Monfort and Magrath 2021).

2.2 Methods and outline report

We conducted a review of the scientific literature, summarizing possibilities for improving the current monitoring scheme. This process was aided by overview reports from external experts, who included unpublished information and best expert advice about certain themes: the use of drones to count birds (Rasmussen et al. 2023), monitoring of habitats and anthropogenic pressures via remote sensing, especially using satellite imagery (Kersten et al. 2023), the use of individual tracking of coastal waterbirds for monitoring purposes (Henriques et al. 2024) and advise on statistical improvements of current monitoring (Godeau et al. 2024). Furthermore, we consulted leading experts in various fields and methods during a two-day workshop on 20-21 November 2024 in Wilhelmshaven, Germany (Hofmann & Ferreira 2024). Next to presentations on the topics of the overview reports, the workshop hosted speakers on additional topics such as the information needs for policy and site management, estimating vital rates through colour-mark programmes, the need of detailed knowledge of foraging ecology and food resources for coastal waterbirds, remote sensing of the Arctic, capacity building of observers and possible ways of integrating data into information systems. The knowledge collected during the workshop and pilot studies has been incorporated in this report too.

In this report we outline why monitoring is needed, which types of monitoring exist and which information is required by policy makers and site managers (chapter 3). Then we outline how the monitoring of waterbirds and its habitat along the East Atlantic Flyway is currently conducted (chapter 4) and what the main shortcomings are (chapter 5). Based on the review of the literature, the review reports and the workshop we outline possible solutions in chapters

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6-9. We start with a chapter on improving our knowledge of the geographical definitions of flyway populations which is central to the monitoring along the east Atlantic Flyway (chapter 6). We then address improvements to abundance monitoring (chapter 7), vital rate monitoring (chapter 8) and environmental habitat monitoring (chapter 9). In chapter 10, we discuss the need of an integrated approach of the monitoring and the possibilities and problems in explaining changes in bird numbers. Also possible ways of organizing and governance of such a monitoring programme are addressed. In Chapter 11 we summarise our finding, draw conclusions and give recommendations for the future of coastal waterbird monitoring along the East Atlantic Flyway.

2.3 Acknowledgements

We thank the Dutch government, and Karst Jaarsma in particular, for requesting, also on behalf of the German and Danish governments, DG Reform to fund the project of which compiling this background analysis and state of play assessment is part. EU DG Reform (Cristoph Klockenbring, in particular) is greatly acknowledged for funding, guiding and practically supporting the project. We greatly acknowledge the EUCC (Maria Ferreira and Jane Hofmann) for support and guidance. The report has much benefited from the much appreciated feed-back on an earlier draft by the steering group and the advisory board. All authors of pilot (desk) studies (Thomas Bregnballe, Laura Dami, Pierre Defos du Rau, Elie Gaget, Nader Gebril, Ugoline Godeau, Mohamed Henriques, Thomas Eske Holm, Anna Kersten, Simeon Lisovski, Georg Nehls, Lars Maltha Rasmussen, Marc Schnurawa, Bennett Stolze, Julika Voss) are acknowledged for their useful input. We wish to thank many colleagues for input and discussions, during the Wilhelmshaven workshop.

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3. THE EAST ATLANTIC FLYWAY AND ANNUAL CYCLE OF WATERBIRDS

Worldwide, migratory birds use a few general global flyways across continents. Flyways can be considered general routes shared by many species between breeding grounds and non-breeding grounds, typically including staging sites. They can be defined as “The entire range of a migratory bird species (or groups of related species or distinct populations of a single species) through which it moves on an annual basis from the breeding grounds to non-breeding areas, including intermediate resting and feeding places as well as the area within which the birds migrate.” (Boere and Stroud 2006). A clear definition of the borders of flyways used by species or populations, enables estimates of flyway population sizes, and suitable international protection. Flyways can be useful units for conservation, and are, for example, used by the Ramsar convention (Bridgewater and Kim 2021a, b), where sites are considered to require sufficient protection if at least 1% of a flyway population of one or more waterbird species uses that site during a part of the annual cycle.

In this report, we deal with the East Atlantic Flyway, which is the combination of breeding, staging and wintering areas of waterbirds along the entire Atlantic coast from Europe to southern Africa, used by waterbirds that breed in in northeast Canada, Greenland, Svalbard, Fennoscandia and Siberia (van Roomen et al. 2022, Fig. 2). The coastal waterbirds that are considered and being monitored (chapter 5) include shorebirds, gulls, terns, ducks, geese, herons, egrets, grebes, spoonbills and cormorants but most research is done on shorebirds and geese.

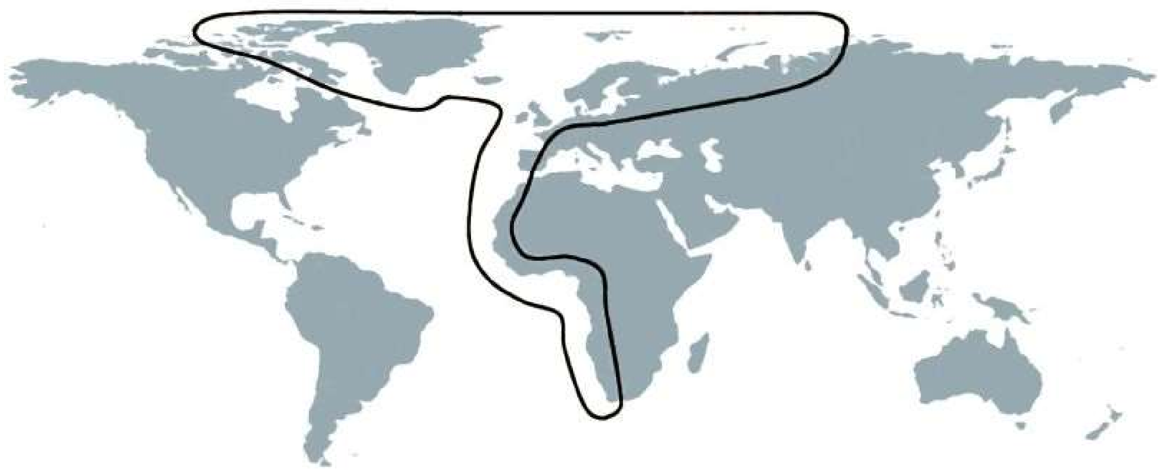

Figure 2. The boundaries of the East Atlantic Flyway. Species-specific flyways can deviate from this generalised delineation.

Migratory coastal waterbirds move a lot within an annual cycle and the timing of such movements differs between (sub)species. In general, the overall concentration of migratory waterbirds moves within an annual cycle between the southern and northern regions within the East Atlantic Flyway (Figs. 2-3). During the summer (May-July) most waterbirds are in their northern breeding grounds, after which during southward migration (July-September) birds are on the move to their winter destinations and can be found, sometimes in large concentrations,

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at staging sites where the birds (re)fuel for the remainder of their journey southward. Between October- February, most waterbirds will be relatively stationary at their wintering grounds along the coasts of Europe and Africa or in inland wetlands. In March-May they prepare for northward migration again and can be seen at staging sites, which are often, but not necessarily, the same sites that are used during southward migration. The annual migration of waterbirds means that the different countries along the East Atlantic Flyway host different number of birds at different times of the year. Some wetlands, occasionally shared by several countries, along the East Atlantic Flyway are particularly relevant because particularly large numbers of waterbirds of many species occur there at different times of the year (i.e. such sites are often used to overwinter and play a crucial role as a staging site too).

Figure 3. A general overview of an annual cycle of a typical coastal waterbird, which reproduces in the summer in (usually) northern regions and winters in more southern regions and migrates between winter and breeding locations in spring and fall. Not all coastal waterbirds migrate; e.g. European Oystercatchers often breed and overwinter in the same general region.

The Wadden Sea is, arguably, the most essential intertidal area within the East Atlantic Flyway, where annually millions of waterbirds find food and safety to stage, winter and/or moult (Boere 1976, van de Kam et al. 2004). The central location of the Wadden Sea, makes it an essential hub, used by significant proportions of almost any coastal waterbird population using the East Atlantic Flyway. Still, local changes of any site along the flyway may have negative consequences for flyway populations. Clearly, the number of birds in the Wadden Sea is not only affected by the conditions in the Wadden Sea, but also elsewhere along the flyway .

Monitoring and conservation of waterbirds along the East Atlantic Flyway is important in the light of the global decline of biodiversity. Migratory waterbirds are essential components of global biodiversity (Bauer and Hoye 2014), but only 9% of 1451 migratory bird species are adequately covered by protected areas across all stages of their annual cycle (Runge et al. 2015). This indicates the difficulties of international nature conservation of migratory species (Wilcove and Wikelski 2008). The world has already lost significant amounts of wetland areas,

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mainly due to agriculture and urbanization, with the most serious losses in Europe, the United States and China (Hu et al. 2017, Fluet-Chouinard et al. 2023). The global situation is especially worrying for long-distance migratory shorebirds, which show consistent steep population declines (Rosenberg et al. 2019, Smith et al. 2023). Hence, to halt and reverse the declines, conservation of migratory animals need to be improved (Jetz et al. 2007, Wilcove and Wikelski 2008, Allen and Singh 2016), particularly for waterbirds relying on wetlands.

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4. DATA NEEDS FOR THE CONSERVATION OF COASTAL WATERBIRDS

The conservation of migratory waterbirds is complicated by the inter-connectedness of many wetlands and other habitat, such as the Arctic tundra, that migratory waterbirds rely during their lives (Runge et al. 2015). Migratory waterbirds are influenced by multiple factors that can easily be separated by thousands of kilometres across international borders. Taking this spatial connectiveness into account is complicated, yet essential for an effective conservation (Martin et al. 2007). As an illustration, the conservation of an essential site such as the Wadden Sea (van de Kam et al. 2004, Reneerkens et al. 2005, van Roomen et al. 2022), will not guarantee the conservation of the flyway populations of waterbirds, if they are facing significant threats elsewhere along the flyway. Threats in the Wadden Sea are, at the same time, likely to impact a large number of flyway populations due to its central position and importance to many populations using the East Atlantic Flyway. The combined effect of international treaties and laws, national legislation and regional conservation should result in effective conservation of flyway populations. Data on the status of and threats to coastal waterbird population across these three different levels should help policy makers to fulfill their obligations and nature managers to take the most effective conservation actions.

Changes in waterbird population sizes are described by data collected through monitoring schemes, which typically indicate whether populations are stable, decline or increase. As such they are a first essential step towards conservation ("monitoring" Fig. 4). A second function of monitoring waterbird populations and their habitat, is to evaluate what might cause changes in waterbird population and which conservation actions will be effective ("assessment" in Fig. 4). This involves monitoring vital rates (survival, reproduction and dispersal), as well as environmental variables (e.g. increased human pressure such as hunting, or habitat destruction) that may be expected to result in changes in abundance via changes in vital rates. National and international legislation aims to maintain (water)bird populations in a favourable conservation status, and monitoring is needed to evaluate this status. International legislation, national legislation and local conservation action require different types of data.

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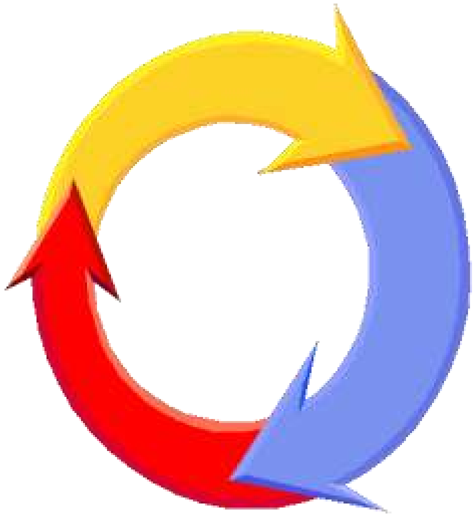

Figure 4. A simple policy cycle showing how monitoring coastal waterbird abundance ("monitoring") should lead to testable hypotheses about the cause of changes in waterbird abundance, which can be assessed ("assessment") by monitoring of vital rates and the environment, which –if necessary– should lead to "management action" (conservation). The effect of management action can subsequently be monitored again.

4.1 International treaties and conventions

The conservation of flyway populations of waterbirds can only be efficiently addressed, if it is based on the best available knowledge in conjunction with international policies by all countries involved within a flyway. Next to several national and European laws and agreements, the Ramsar Convention on Wetlands of International Importance and the African Eurasian Waterbird Agreement has been of great importance for international conservation of wetlands and waterbirds (Ramsar Convention Bureau 1990, Boere and Rubec 2009, Boere and Piersma 2012, Bridgewater and Kim 2021b). An essential component of the Ramsar convention is the recognition of internationally important wetlands that require conservation if they hold 1% of a flyway population of a waterbird population. Clearly, such designations are only possible by regular monitoring of numbers at sites and along the entire flyway.

The Ramsar convention is an international biodiversity convention focusing on the wise use of wetlands. As such, he Ramsar Convention provides a solid basis for the conservation of migratory waterbirds (Stroud and Davidson 2021, Bridgewater and Kim 2021a, b). Several subsequent conventions such as the United Nations Environment Programme's Convention on Migratory Species (CMS), and the Biodiversity Convention included criteria for the conservation of migratory birds based on the Ramsar criteria. It is these criteria that make knowledge of the number of waterbirds and the changes in their abundance so important, even though there is considerable discussion about its current effectiveness (Bridgewater and Kim 2021b, Navedo and Piersma 2023).

For an area to obtain Ramsar status based on waterbirds, one of two specific criteria need to be fulfilled: (1) if it regularly supports 20,000 or more waterbirds, and (2) if it regularly

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supports 1% of the individuals in a population of one species or subspecies of waterbird." In addition, (3) if it supports species at a critical stage in their life cycles or provides refuge during adverse conditions. Up to 2500 sites worldwide have been designated because they fulfil (at least) one of the two specific criteria for waterbirds (Stroud and Davidson 2021). Turnover of individuals, especially during migration periods, will lead to more waterbirds using particular wetlands than are counted at any one point in time, such that the importance of such a wetland for supporting waterbird populations will often be greater than is apparent from simple census information.

Clearly, site designation and conservation status based on the presence of significant numbers of waterbirds is only possible with up-to-date knowledge about (local) population sizes and population trends of waterbirds. Long-term monitoring allows evaluation of which and how many waterbirds occur at a given site at a given time. The sum of counts at sites along the East Atlantic Flyway provide estimates of overall population size of each species. Based on the fraction of the total population estimate, the numbers counted at each site are used for assessing whether a wetland should be considered internationally important because it regularly supports 1% of the individuals in a population of one species or subspecies of waterbird (van Roomen et al. 2022).

The African-Eurasian Waterbird Agreement (AEWA) is an independent intergovernmental treaty developed under the auspices of the CMS. The goal of the agreement is to coordinate efforts to conserve bird species migrating between European and African nations. The AEWA is dedicated to conserve migratory waterbirds and their habitats. It area covered by the agreement includes the entire East Atlantic Flyway. All countries that have joined the Agreement are legally bound to undertake the measures specified by AEWA to warrant the conservation of migratory waterbirds within their national boundaries. Next to species and habitat protection, these include research and monitoring (Agreement on the Conservation of African-Eurasian Migratory Waterbirds (AEWA) 2022). Treaties such as AEWA and CMS require solid data on coastal waterbird population fluctuations and the causes of such fluctuations. National governments that have signed treaties such AEWA and the Ramsar convention, require monitoring data of coastal waterbirds. With such data they can evaluate whether the habitats and/or bird species that they have agreed to protect following these agreements, are sufficiently protected or whether conservation management is needed.

4.2 National legislation

Countries differ in their legislation to protect nature, but many European wetlands within the East Atlantic Flyway are designated as a Natura 2000 protected area ("Special Protected Area"), which together form a network of protected nature areas to ensure the long-term sustainability of habitats and species. EU countries set site-specific conservation objectives which will determine the type of management that is required. Management includes measures to avoid the deterioration of natural habitats and the habitats of species as well as significant disturbance of the species for which the areas have been designated. For each Special Protected Area within Natura 2000, there are site-specific "conservation objectives", such as the annual average number of breeding or non-breeding waterbird species which the national government has the obligation to conserve. This implies that active management should take place to maintain or expand the population size and the habitat quality for those species. By conducting long-term monitoring of breeding and non-breeding

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coastal waterbirds in these Special Protected Areas, it can be assesses whether conservation objectives are being achieved. All countries that sign up to the Multilateral Environmental Agreements and other forms of international cooperation (see 4.1), which next to the Ramsar Convention and AEWA include the Abidjan Convention (focussing on the Atlantic coast of Africa) and the Convention on Biological Diversity (CBD), embrace, internationally agreed standards for biodiversity management in their countries. The implementation of many resolutions and action plans included in these agreements calls for proper national-level monitoring.

4.3 Information needs to better manage sites

Site managers or land owners are responsible for the maintenance of the natural values of their sites, following the (inter)national laws and agreements that they are bound to via their national governments. For site managers, it will be especially relevant to also know the causes of observed population fluctuations. Local site-specific causes should be disentangled from causes from elsewhere (e.g. through carry-over effects, see 6.3) or that act at a larger spatial scale than the scale of the site, and cannot be directly influenced by local conservation management. Evidence-based knowledge will enable site managers to adjust management to mitigate or avoid factors responsible for population declines. Furthermore, if correctly monitored (i.e. including control sites, sufficient sample sizes etc) the effect of specific conservation action can be evaluated (Fig. 4).

Two wetlands along the East Atlantic Flyway are designated as UNESCO world heritage; the Banc d'Arguin (Mauritania) and the Wadden Sea (Netherlands, Germany and Denmark). The World heritage Committee (WHC) provided this status among other factors because of their relevance for a large number of coastal waterbirds relying on both sites (McInnes et al. 2017). One of the prerequisites of the WHC for the designation of the Wadden Sea are that countries strengthen their cooperation on management and research activities with other countries along the East Atlantic Flyway which play a significant role in conserving migratory species along these flyways. To maintain the status as a World Heritage, nations are obliged to periodically report about the state of conservation of the designates sites. For such reports, reliable knowledge of the status of the waterbird populations at these sites, as well as factors that may negatively affect the value of the sites, is needed.

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5. CURRENT METHODOLOGY

The aims of the integrated monitoring along the East Atlantic Flyway are (1) to assess waterbird abundance (population sizes, trends and distribution), (2) to monitor environmental conditions (including pressures and conservation measures) at the sites used by waterbirds and (3) to monitor vital rates (reproduction and survival) for a selection of populations (Fig. 5). Vital rate monitoring increases our understanding of the processes causing changes in numbers and distributions, as it links environmental pressures and conservation measures to bird abundance (Reneerkens 2022, Fig. 4).

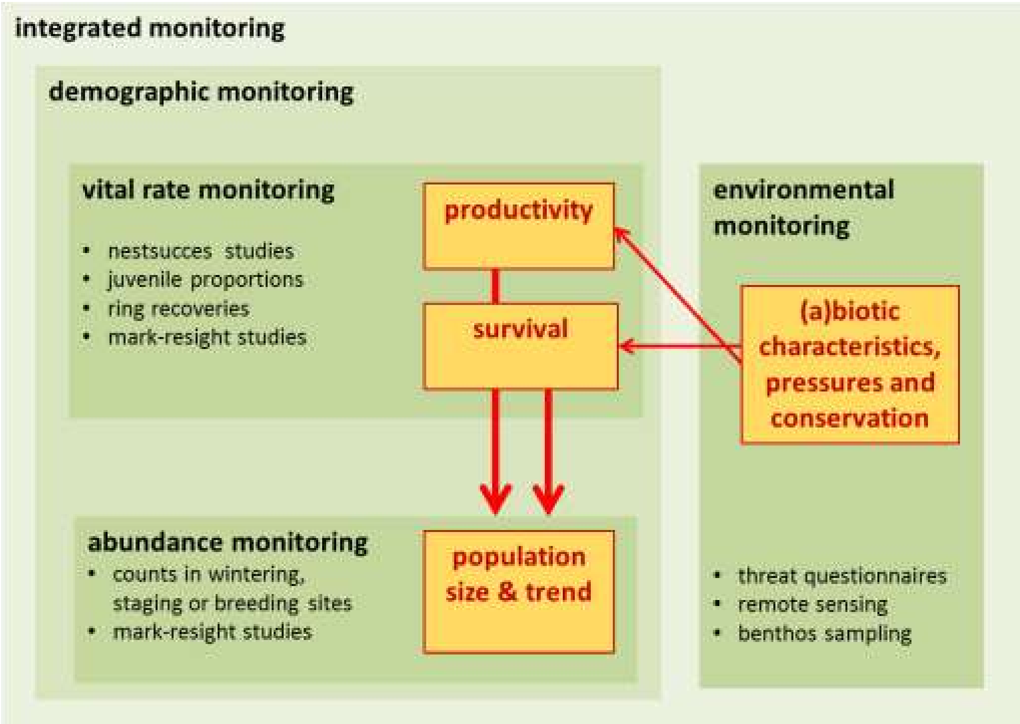

Figure 5. Different components of the integrated monitoring of coastal waterbirds along the east Atlantic Flyway and their relations to each other (from van Roomen et al. 2013).

5.1 Species and flyway populations

Several criteria have been applied in the decision about which species and populations should be included in the East Atlantic Flyway monitoring (van Roomen et al. 2013). One criterion is that (sub)species and populations for which the Wadden Sea is designated as a Special Protected Area in the Natura 2000 framework should be included. A second criterion is that populations which occur to a large extent at the same wintering sites as those used by populations that also occur in the Wadden Sea, should be included. A third criterion is that the populations included should largely be confined to coastal sites of the East Atlantic Flyway.

Until present, population trends for 83 populations from 66 species can be analysed based on the flyway monitoring. This represents a large selection of species and populations occurring in significant numbers in the Wadden Sea. The population trends of these species present significant indicators for the quality of both wetlands and habitats within the coastal

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East Atlantic Flyway (van Roomen et al. 2022). Within most waterbird species, distinct subspecies or biogeographical defined populations exists (following the African Eurasian Waterbird Agreement and Ramsar Convention taxonomy and definitions) with population-specific flyways. These flyway populations are the focus of the flyway monitoring. For example, the *canutus* subspecies of Red Knot winters in West Africa, whereas the *islandica* subspecies winters in West Europe (Davidson and Piersma 1992). They both make use of the Wadden Sea at different times of the year and are included as two different populations in the flyway monitoring.

5.2 Abundance monitoring

The goals of the abundance monitoring are threefold: to determine total population sizes per waterbird flyway population, to determine temporal trends in population sizes, and to identify the distribution within the East Atlantic Flyway. The monitoring focuses primarily on coastal estuarine sites but inland sites are also included when focal populations occur there. The monitoring includes all countries where the selected waterbird populations occur in important numbers depending on the distribution during wintering, migration or breeding. Sixteen European and twenty African coastal countries participate in the flyway counts in January. In most European countries monitoring is conducted at nearly all sites that contain substantial waterbird populations, but this is not yet the case for most African countries. Counts are simultaneously conducted at the different sites along the flyway to avoid double counting or missing birds (if the same birds are counted twice or missed if they move between sites or countries in the time interval between counts if they would not occur simultaneously).

A good spatial coverage is needed to avoid underestimates of population sizes and/or biased temporal trends (e.g. if only sites would be visited where the population size of a certain species is decreasing). For most waterbird populations the midwinter period (January) is the most suitable for this kind of monitoring as the targeted species then occur concentrated at relatively a few sites and when there is typically little migratory movement of birds, avoiding that changes in numbers are caused by redistributions rather than changes in population size.

In most European countries a long tradition exists of annually counting waterbirds in January, covering most of important sites. This is less the case for many African countries. In most African countries resources (manpower and finances) are lacking to cover all important wetlands on an annual basis. There are positive exceptions, with e.g. Ghana where the entire coast has been surveyed since 1986 (Ntiamoa-Baidu 1991, Ntiamoa-Baidu and Gordon 2000, Ntiamoa-Baidu et al. 2014). Based on both tradition and the availability of resources it was decided for the East Atlantic Flyway monitoring to annually conduct counts in January at many sites in Europe and in, at least, a selection of sites in Africa. Every three years a 'total count' takes place with a complete spatial coverage (van Roomen et al. 2013). An initial 'total' count along the flyway was conducted in 2014 (van Roomen et al. 2015). After that first total count it was decided to standardly organise total counts every three years, and a second was organised in 2017 (van Roomen et al. 2018), a third count in 2020 (van Roomen et al. 2022) and the fourth simultaneous count was conducted in 2023.

Coastal waterbirds are usually counted during high tide when they congregate at high tide roosts, but at some sites in Africa, counts have to be carried out during low tide as waterbirds roost in mangroves at high tide where they remain invisible behind leaves and

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cannot be counted. Local volunteers and professionals use binoculars and telescopes to count or estimate the number of birds present for each species observed. Some waterbird species are easier and more reliable to count during the breeding season than during the midwinter count, as they form aggregated breeding colonies, such as many species of gulls and terns. The population size estimates and trends for these species are therefore based on counts during the breeding season, which necessitates the inclusion of other countries and sites in the monitoring programme (van Roomen et al. 2022).

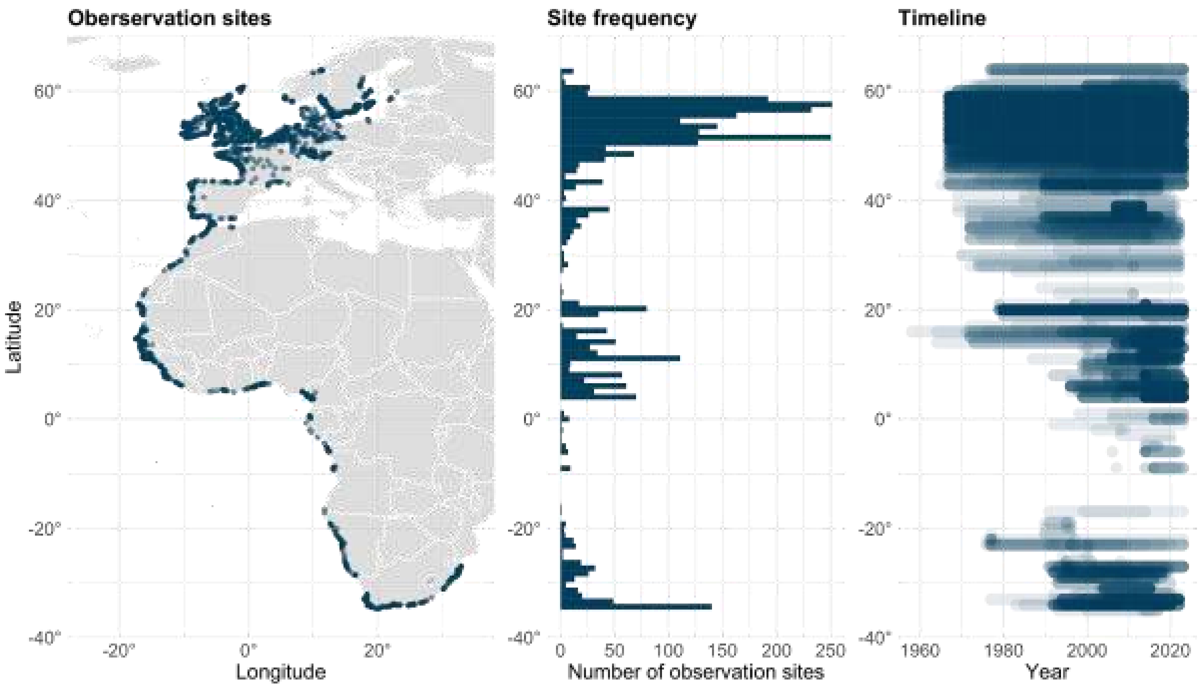

Figure 6. Locations along the East Atlantic Flyway where coastal waterbirds have been counted ("Observation sites"), the number of sites ("site frequency") and the years during which counts were conducted ("Timeline") per latitude degree (from (Stolze and Lisovski 2023).

Population sizes are currently assessed by conducting simultaneous counts in January in as many as possible sites, to get total estimates per country when all potential sites have been counted. Adding up the numbers from each country will ultimately lead to estimates of total flyway population sizes. As in most countries not all potential sites are counted, a variety of methods is used to estimate the totals per country, ranging from using the total counted numbers to adding missed birds based on expert judgement to various analytical methods to estimate totals (Frost et al. 2021, Wetlands International 2021, van Roomen et al 2022). In a selection of populations the estimate is based on country estimates of breeding bird numbers in which the number of breeding pairs is multiplied by 3 (parents plus the average of one young). The estimate of breeding bird numbers per country is also based on various methods (total coverage of breeding pairs in rare species, atlases, a variety of extrapolation methods).

The population trends, as calculated within the East Atlantic Flyway monitoring, are based on analyses of a selection of sites with relatively good coverage over the years. Many

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European sites have a sufficient temporal coverage for this purpose, but this is less often the case for African sites. However, care is taken that the most important African sites (i.e. those holding largest numbers of birds) are included. Despite a careful selection of sites with good coverage, missing counts occur frequently and imputing of missing values need to be applied to prevent biased estimates of trends. For the trend calculations software TRIM is used which is developed for the analyses of time series of counts with missing values and is based on loglinear Poisson regression (van Strien et al. 2004). In the overall analyses, a stepwise approach is used in which site and national trends are calculated followed by flyway-level trends. Estimates from years for which thresholds of the degree of imputation were passed, are removed from the analyses (van Roomen et al. 2011a, Nagy and Langendoen 2020).

5.3 Vital rate monitoring

Waterbirds are generally long-lived species and their population size may not be sufficiently responsive to changes in the environment to provide early warnings of upcoming changes in abundance (Forslund and Pärt 1995, Hockey et al. 1998). Vital rates, such as breeding productivity (Thorup and Koffijberg 2016)and survival are expected to be much more responsive to changes in the environment (Piersma and Lindström 2004) and they have the potential to translate environmental factors into changes in population size (Fig. 5, but see 6.2.4). Currently, vital rates are estimated in a number of coastal waterbird species (van Roomen et al. 2011b), but monitoring vital rates is not implemented as an integrated part of the current East Atlantic flyway monitoring.

5.4 Environmental monitoring

Data collection on the habitat quality of sites and the threats faced by waterbirds is needed to understand what may explain (local) population trends in order to formulate appropriate hypotheses on how such environmental factors may impact vital rates and eventually changes in (local) population size. Knowledge of threats across the flyway will also help to understand changes at flyway scale. This information is gathered through questionnaires completed by local observers, site managers and national coordinators (Dodman et al. 2018, Crowe et al. 2022).

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6. SHORTCOMINGS IN CURRENT FLYWAY MONITORING

6.1 Uncertain population-specific flyway boundaries

Although there seems to be a reasonable consensus concerning the geographic limits and the interconnections between breeding, stop-over, and wintering sites for several flyway populations (Delany et al. 2009), even for common waterbird species this knowledge is often incomplete and/or based on assumptions. Most problematic is the recognition of subspecies or sub-groups of bird populations that show consistently different connectivity from another sub-group that cannot be distinguished based on plumage characteristics or morphology. For example, boundaries of population-specific flyways are unclear for the *totanus* subspecies of Common Redshank *Tringa totanus*, breeding in N Europe and those of continental W Europe (van Roomen et al. 2011b). Similar unclarity exists about the extent of mixing of *psammodromus* and *tundrae* Common Ringed Plovers *Charadrius dubius* in W Africa (Thies et al. 2018), between the Nearctic and Palearctic breeding populations of Ruddy Turnstone *Arenaria interpres* (Engelmoer and Roselaar 1998), or the extent to which Sanderlings breeding in Greenland or Siberia mix in in the non-breeding season (Reneerkens et al. 2009, Conklin et al. 2016).

This limited knowledge for many populations impedes the evaluation of their status. Furthermore, climate change and other factors may result in changes in both breeding and non-breeding distributions, affecting the flyway's geographic boundaries (Maclean et al. 2008, Tombre et al. 2019, Lameris et al. 2021, Madsen et al. 2023) and this is expected to accelerate under the current rate at which the global climate is changing (Walther et al. 2002, Root et al. 2003, Parmesan and Yohe 2003). Individual waterbirds can change their distribution within the known boundaries of a (sub)species, but the boundaries can change too leading to the contraction, expansion or directional shift of the flyway distribution. A documented example is the disappearance of the *canutus* subspecies of Red Knots from southern Africa, where now West Africa is the southern limit of the species flyway distribution (Summers et al. 2011). This can complicate the interpretation of flyway trends if some of the wintering birds completely move out of the censused area (cf. Rakhimberdiev et al. 2011) or if different flyway populations overlap and mix increasingly, eventually perhaps leading to previously distinct populations (re)merging into one (Conklin et al. 2022, Bom et al. 2024).

6.2 Shortcomings in abundance monitoring

The reliable detection of population sizes and the short- and long-term changes thereof is essential for appropriate decisions about potential conservation measures. However, waterbird monitoring by field observers estimating the number of birds at sites is subject to inaccuracy due to several logistical and natural factors. Counts or estimates of bird numbers will normally differ from the true flock or population size, and the (absolute and percentual) error will vary with species and population sizes. Furthermore, given the size of the flyway and the long-term, it is inevitable that there will be missing data (i.e. when sites are occasionally not visited for counts). Temporal or spatial differences in the proportion of birds counted can, for these reasons, be misinterpreted as differences in population size.

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6.2.1 Imperfect monitoring design

The design of the monitoring scheme, including methodology, spatial coverage and survey frequency, can introduce biases if not appropriately chosen to represent the entire populations that use the flyway. The statistical process of good design is considered a critical component of any successful monitoring program, but calculations of statistical power to detect trends are often overlooked (Lindenmayer and Likens 2010). Thus, starting with good hypotheses (Yoccoz et al. 2001a), the setting up of the monitoring scheme should subsequently include careful considerations about the goals. These goals amongst others include decisions on the target populations, variables, intended time span, required precision and the sources of bias and error (Ranlund et al. 2023). In the East Atlantic Flyway monitoring, the target populations (all waterbirds), variables (counts of birds) are clear. The time span has not been limited, but with a current frequency of simultaneous counts along the entire flyway of every three years (van Roomen et al. 2022). Thus, the main consideration concerns the desired accuracy, which will largely be determined by (inter)national nature legislation and policymakers. For managers this is essential information, as they will need to know when conservation action is required and thus when a population trend is actually meaningful (White 2019).

The accuracy of the monitoring scheme depends on the statistical power of the flyway count, i.e. the likelihood of distinguishing an actual trend from a trend detected by chance, and this depends on the quality of the data. In other words, accuracy can be improved by limiting potential bias and/or error (see 8.1), but the monitoring scheme can also be optimised in terms of spatial and temporal coverage (see 8.2).

In several countries, opportunistically collected count data, in addition to the January count are sometimes available. Such data are useful to understand seasonal changes in bird abundance, but because these counts are not internationally coordinated they are not available for international analyses.

6.2.2 Incomplete spatial and temporal coverage

Count data should be collected and analysed at a range of spatial and temporal scales, which allow the reliable detection of population changes (Greenwood et al. 1995), so it is essential to determine the minimal requirements of spatial and temporal scales to detect such change. Trends of flyway populations depend on actual variation in population sizes, but also to error in the estimates. Because not all important sites are always included in all simultaneous counts along the flyway, imputation of missing counts is needed and will inevitably result in some degree of uncertainty (Atkinson et al. 2006, Dakki et al. 2021).

Estimates of flyway population sizes and trends therein are primarily based on counts that take place in January. For some (European-wintering) species annual counts are available, whereas species whose only occur in Africa in January, only tri-annual data are available since recent. The frequency of counts can limit the reliability of population trends. A comparison of monthly or bi-annual surveys based on the same 28-year long dataset indicated that the direction of trends was similar, independent of the frequency of counts, but the uncertainty around the trends was generally lower in the monthly surveys, also leading to more trends being statistically significant in the monthly compared to the bi-annual counts. In other words, the temporal frequency of waterbird surveys influences the level of uncertainty around estimates of long-term trends, and thus the time period it takes before statistical significant increases or declines in trends can be detected (Henry and O'Connor 2019).

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Flyway population size estimates are, to some extent, based on expert judgement to account for incomplete coverage at the coast and especially inland (van Roomen et al. 2022). Inevitably, expert judgement is subjective and this complicates reproducibility of the estimated counts.

6.2.3 Reliability of waterbird counts

Counting or even estimating large flocks of waterbirds is difficult and even counts by experienced observers will likely contain substantial errors. Indeed, different observers that simultaneously counted the same flocks of waterbirds achieved considerably different results, especially for larger flocks (Rappoldt et al. 1985). Consequently, reported trends may to some degree be caused by error margins of the counts themselves. These error margins can be large and concern ca. one third of the absolute estimate of a flock size, on average (Rappoldt et al. 1985). This error is expected to be cancelled out when small flocks are counted, but in areas where the total numbers largely consist of a few large flocks, the error may be problematically large with a consistent underestimate of group sizes. This is exemplified by the estimation of number of geese; estimates by observers in the field were lower (62.5 - 71%) than those based on counts conducted from a low-flying plane, when flocks consisted of 2.000-4.000 or >4.000 individuals, respectively (Boyd 2000).

An additional challenge is that roosting waterbirds, especially shorebirds, often occur in mixed flocks which can easily result in species remaining undetected. Less conspicuous and less common species that roost among common species can easily be missed and will be more prone to be underestimated. Varying experience of the observers may also influence the results.

In some areas, such as the the Bijagós archipelago, it is impossible to count birds at high tide roosts because the birds roost in mangroves (Zwarts 1988, Salvig et al. 1994, Henriques et al. 2022) where they are visually obscured by the vegetation. In such areas, birds are counted during the upcoming tide in pre-defined quadrants of 14 hectares intertidal mudflats (Salvig et al. 1997). Due to the dynamics of birds during the upcoming tide, the small sites where counts take place within a vast intertidal area with inaccessible mudflats, might hamper reliable counts.

The estimated number of birds, in a flock or at a site, may vary due to imperfect observation conditions due to poor weather or habitat limiting the visibility of the birds to be counted, but estimates can also vary simply due to intrinsic differences in the abilities of observers to estimate numbers, which correlate with the experience of observers and depend on flock size and species (Erwin 1982, Rappoldt et al. 1985, Frederick et al. 2003).

Some sites may be too large for all high tide roosts to be visited during a single high tide, if the capacity of observers is limited. Movements of birds between roosts at different tides, may then result in double counts or underrepresentation of birds. Furthermore, when selecting which sites to include in a monitoring scheme, it could be that some sites essential to a number of populations are hitherto unknown. In addition, some species may not (always) be roosting during high tide but continue foraging away from the coast, leading to a variable degree of underestimation.

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6.2.4 Changes in population size may complicate trend estimates

Changes in population size may lead to changes in spatial distribution and behaviour of the individuals. This may affect the detectability of coastal waterbirds when species exhibit density-dependence in its ecological processes (Numminen et al. 2023). Density dependence, is the phenomenon where the size and growth rate of a population can be influenced by the population's own density or abundance within a given area. Insight in density-dependent processes are important to understand (local) population declines (e.g. Lok et al. 2011, 2013).

A form of density-dependence is the 'buffer effect', where certain factors or habitats can act as a buffer against environmental or anthropogenic stressors, helping to mitigate the impact of those stressors on a population (Brown 1969, Gunnarsson et al. 2005, Sullivan et al. 2015). The buffer effect can play a crucial role in influencing local population declines because populations distributed across a range of spatially heterogeneous environments are less likely to be uniformly affected by a single environmental factor. At low densities, birds are expected to occupy the better habitats, but at high densities when competition for the best sites intensifies, a larger proportion should occupy poorer habitat (e.g. Gill et al. 2001, Ntiamoa-Baidu et al. 2014). The buffer effect may complicate trend estimates based on a subset of all sites, due to variation in population trajectories across sites with different densities.

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6.3 Shortcomings in monitoring of vital rates

Except for a small number of species relative to the total number of species monitored along the flyway, demographic studies of waterbirds at the scale of (representative part of) a flyway are not common. This is understandable from a practical point of view. Estimating survival using colour-marking takes an effort of many years of ringing and observing marked bird at many sites (e.g. Reneerkens 2022) and measuring productivity (clutch survival, chick survival, fledging rate and juvenile percentages in non-breeding areas) also takes a lot of field work and may vary considerably between sites and years. More studies are being directed to monitoring of reproductive output than to monitoring of survival; For waterbirds that occur in the Wadden Sea, demographic data were available for 27 of 54 studied species (50%; van der Jeugd et al. 2014), with data on reproduction for 25 and on survival for 27 species. Importantly, there is large variation in the quality of data (e.g. methods used, confidence intervals around estimates) and the level of (spatiotemporal) detail between these studies. It is important to achieve sufficient spatial sampling coverage, as breeding success may be more variable between different sites than survival.

Existing monitoring of survival is less well spread across taxonomic groups than monitoring of productivity. The number of studies were largest on Geese, Great Cormorant and European Spoonbill, waders and gulls received intermediate coverage , while ducks and terns were least studied (van Roomen et al. 2011b). Demographic monitoring, where abundance data are analyzed together with vital rates includes both the classical two-step analysis of data on reproduction and survival followed by the use of matrix population models and the comparison of the predicted population trajectories with the available count data, and the ‘integrated population models’ (Schaub and Abadi 2011, Schaub and Kéry 2012), which integrate the demographic information contained in both population counts and data on vital rates in a comprehensive description of population development.

Integrated population models have not often been constructed for waterbird populations that use the East Atlantic Flyway (but e.g. see Lok et al. 2017 for an example of Spoonbills). Sandercock (2020) used a population matrix model based on demographic data from (Reneerkens et al. 2016, 2020) and concluded that the combination of non-breeding location-specific annual survival and annual variation in clutch survival predominantly determined population growth. Clearly, in most years, clutch survival, measured at a single site in Northeast Greenland, was too low to support a stable or growing population (Sandercock 2020). Given that the Sanderling population has grown for many years, this indicates that the locally estimated nest survival is not representative for the entire breeding range and calls for population-level estimates for annual reproductive output (see 9.1).

Carry-over effects may complicate the determination of the relationship between the environment and vital rates. Carry-over effects are changes in vital rates at one site and/or stage in an annual cycle that are caused by effects in earlier stages of the annual cycle and thus -in the case of migratory birds- often at another location (Harrison et al. 2011). An example of the latter is that the reproductive output of Spoonbills decreased with migration distance, especially in older individuals (Lok et al. 2017).

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6.4 Shortcomings in environmental monitoring

In the current monitoring scheme, organised by the Wadden Sea Flyway Initiative, the quality of habitat is assessed by observers who fill in questionnaires about the extent of possible threats to the wetlands where they count waterbirds (see 5.4). There are three potential shortcomings associated with this approach: (1) the answers to questionnaires are subjective and may thus be influenced about how certain threats are perceived by observers, rather than a measure how severe a possible threat is. Some threats are much more visible than others; e.g. disturbance of roosts is easier observed than the cumulative effects of climate change. (2) By being asked about possible threats, observers will implicitly feel that there will be threats, but this is not necessarily the case. (3) Actual threats to local waterbird populations may not necessarily result in declines in local or flyway populations. It has been argued that, food and predators determine to a large extent the quality of a site for birds (Piersma 2012a), both of which can be directly and indirectly influenced by human activities. However, food (benthos, vegetation or fish) and predation risk are not systematically monitored at most sites along the East Atlantic Flyway. Furthermore, although NDVI measures can be a good indicator of food availability to herbivorous waterbirds such as geese and ducks (Piersma 2020), most bird food is difficult or even impossible to assess by satellite remote sensing (Kersten et al. 2023) and the same applies to predation risk.

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7. POSSIBILITIES TO BETTER DEFINE FLYWAY POPULATIONS

7.1 Tracking

Following a large and representative sample of individual birds from each species and population, throughout their annual cycle will give an adequate indication of the used spatial range and thus of the (boundaries of) the population's flyway. Given the large distances travelled by birds, this can only be achieved by either colour-ringing and relying on a large network of observers (where spatial biases may likely occur due to uneven distribution of observers along the East Atlantic Flyway), or by tracking individual birds. Wildlife tracking (position telemetry) is one of the most mature areas of conservation technology, that has developed fast. Using tracking devices, the goal is to determine the absolute position (coordinates) of individual birds and their movement over time. Sometimes, also elevation, speed and acceleration are measured by tracking devices. Most tracking systems involve at least one emitter and one receiver, one of which is attached to the bird. Multiple different technologies are available to track individual birds, by logging their position or getting accurate GPS positions via satellites at variable time intervals (Klaassen and Reneerkens 2014). Tracking devices can coarsely be divided into two main groups, depending on whether an animal-mounted device (tag) receives an external signal that allows it to calculate its coordinates locally (e.g., by triangulation) or transmits a signal that can be used externally to calculate its position, by triangulation or by proximity to a point of known position (Lahoz-Monfort and Magrath 2021). Data gathered by tracking tags may be stored on the device for manual retrieval(so-called loggers, e.g. Lisovski et al. 2020), while other tags allow wireless data retrieval over relatively short distances (using VHF or UHF receivers), sometimes with very high spatiotemporal resolution (Bijleveld et al. 2022). Automated data downloading is possible, via satellite-based systems or the cellular network (Bridge et al. 2011). The optimal method depends on the species, research question and budget. Tracking devices continue to get smaller, cheaper and their battery life continues to improve and can thus be applied to a growing number of (smaller) bird species and with increasing functionalities. The financial costs of tracking devices will limit the sample sizes, but high-resolution information gathered by a limited amount of birds with tracking devices in combination with considerably larger number of birds tagged with cheap colour-ringing using citizen scientists, can result in important insights. Care needs to be taken that an unbalanced selection of individuals to be tagged will result in biased views, and tagging birds at representative locations in both wintering and breeding sites is recommended.

Much detailed, relevant information about e.g. the timing of migration in response to environmental factors can be gathered from tracking individual birds (e.g. Bom et al. 2024), while we can learn about (changing) species' flyway boundaries simultaneously (e.g. Madsen et al. 2023). Satellite transmitters have been very valuable in identifying (many) currently unknown staging sites of Great Knots *Calidris tenuirostris* that have no conservation status (Chan et al. 2019), and thus provide knowledge relevant for conservation. Using combined tracking data also help to identify flyway species connectivity, i.e. he ecological and geographical linkages between different locations along a bird's migratory route. Migratory connectivity describes the interactions and dependencies between different stages of birds' annual cycle (Webster et al. 2002, Hunter et al. 2011) and can have large consequences for flyway populations' vulnerability to threats (e.g. Iwamura et al. 2013). When connectivity is

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weak, individuals from one breeding population migrate to a variety of winter locations, and these might vary with respect to selective pressures. Intermixing on the breeding grounds will result in gene flow among winter populations, and local adaptation to the winter conditions could be hampered, and vice versa when connectivity is strong (Webster et al. 2002). At the same time, a strong dependency of a flyway population to a limited number of essential sites can significantly increase the flyway population's vulnerability to habitat loss at such key sites (Iwamura et al. 2013). Network analysis of movements and connectivity of migratory animals (Xu et al. 2022) may be used to identify sites along the East Atlantic Flyway that are monitored less frequently and/or that have high turnover of individuals, and as such may require extra conservation attention.

7.2 Genetic methods

Subspecies that cannot be reliably distinguished based on their appearance, but for which separate population sizes and trends are desired, can often be distinguished using molecular techniques. Several molecular (genetic) methods are employed to distinguish subspecies of birds (e.g. mitochondrial DNA sequencing, nuclear DNA microsatellites, single nucleotide polymorphisms, Restriction-site Associated DNA sequencing) each with its own advantages and disadvantages. Often, a combination of methods are used to obtain a more comprehensive understanding of genetic variation within and between subspecies of birds.

Recent studies show surprises in even some of the best studied waterbird species of which there was little doubt about the flyway boundaries and connectivity, such as Red Knot (Davidson and Piersma 1992, Piersma 2007). Using genetic markers, presumed tropically-wintering *canutus* Knots were found among *islandica* Knots in northwest Europe in January (Conklin et al. 2022), implying overlapping wintering range of both subspecies in western Europe which complicates the estimating of populations sizes and trends based on distinct wintering areas (van Roomen et al. 2015). Similarly, the distinction between *taymyrensis* and *lapponica* Bar-tailed Godwits based on their winter distributions is not as straightforward (Jesse Conklin *pers. comm*) and this may be the case for more waterbird species that use the East Atlantic Flyway, but which have hitherto not been screened with modern genetic techniques. Genetic sampling should be conducted in the breeding sites to be sure that the population we are dealing with is known.

7.3 Stable isotopes

Stable isotope analyses can provide valuable insights into bird migration by offering information about the bird's diet, geographic origin, and movement patterns. The stable isotope composition of certain elements in feathers, such as hydrogen (δ2H) and oxygen (δ18O), can reflect the geographic origin of a bird. These isotopes vary with latitude and altitude, providing a "geographic signature" that can help determine where a bird molted its feathers and, potentially, its breeding or wintering grounds (Hobson 1999). As such, stable isotope analysis can help identifying geographic boundaries and the (extent of mixture of) different sub-species in non-breeding areas, dependent on sufficiently distinct differentiation in stable isotope signatures in the areas used and embedded in tissue by the (sub)species of interest.

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Isotope analysis of waterbird tissue (e.g. red blood cells and plasma in collected blood samples) can also help identify stopover locations during migration and even estimate the length of stay at such stopover sites (Jouta et al. 2017) providing knowledge of connectivity, although in considerably much less detail and accuracy than when collected on the basis of individual tracking. Stable isotope analyses offers a non-invasive and retrospective method for studying bird migration, which if combined with more detailed tracking methods can be a relatively cheap way of obtaining reliable information about waterbird migration.

7.4 Colour-ring observations

A relatively cheap and easy method to learn about movements, site use, timing of migration and about the (boundaries) of species' flyways is the catching and individually marking of birds. Colour-ringing and subsequent observing of colour-ringed birds is also the basis of mark-recapture analyses to estimate (variation) in survival of waterbirds (see Box 3, 9.2) or to estimate (local) population sizes based on marked birds (see Box 1). Citizen scientists will report their observations if they receive the details of the whereabouts of the observed birds. The involvement of citizen scientists is a plus as they can be stimulated to report extra relevant information and will often be local advocates of birds and their habitats (see 8.3). A concern of using citizen scientists is that individuals will be reported on sites visited by these observers and this can give a biased view (Thorup et al. 2014). Based on colour-ring observations of Sanderlings by citizen scientists (Reneerkens et al. 2020) the flyway boundaries of Sanderlings from the Nearctic and Siberian populations were adjusted (van Roomen et al. 2022).

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8. POSSIBILITIES TO IMPROVE ABUNDANCE MONITORING

8.1 Possible solutions to improve direct counts

Clearly, it is important to untangle true population changes from variation in detectability (MacKenzie and Kendall 2002). Recent technological advances have the potential to considerably improve the monitoring of waterbirds across large spatial scales and to improve its reliability. In this chapter we discuss such technical innovations, their advantages and disadvantages and how such technologies are expected to develop in the future.

8.1.1 Counting breeding or non-breeding birds

Most bird species that use the East Atlantic Flyway breed in low densities in the vast (sub)Arctic in areas that are not easily visited, and are thus easiest monitored in the non-breeding area. However, for some species the breeding range is considerably more restricted, potentially allowing more reliable and logistically easier monitoring of these species during the breeding season, instead. This especially concerns colonial breeding birds such as terns, gulls, cormorants, spoonbills and pelicans. A comparison of long- and short-term trend estimates of 42 waterbird species indicated that trend estimates based on monitoring breeding or non-breeding counts can be considerably different, and 15 paired comparisons even showed contrasting trends (van Turnhout et al. 2022). This was most likely is due to sampling different subsets of individual birds in either breeding or the non-breeding counts, but also the trend assessment of breeding populations could be further improved (van Turnhout et al. 2022). A benefit of monitoring breeding populations is that is often also possible to simultaneously measure annual reproductivity.

Counts of birds at colonies can be largely influenced by annual variation in the proportion of breeding birds. As such, breeding propensity in some colonial birds can challenge the interpretation of temporal changes in population size (Talis et al. 2022) and should ideally be corrected for.

8.1.2 Counts with drones

The use of unmanned aerial vehicles (UAV's) –commonly called drones– to count birds is a recent but rapidly developing technology. Aerial surveys with drones are particularly useful for rapid coverage of large areas, counting birds that are difficult to see from the ground (e.g. waterbirds roosting in mangroves) and accessing remote habitats that are difficult to approach by human observers without causing disturbance (Kingsford and Porter 2009). Although it is possible to estimate the number of birds based on live views from a drone, it is common practice to analyse aerial images taken by cameras on board of drones using artificial intelligence (Kellenberger et al. 2021; Box 5). The latter approach results in more accurate and consistent estimates (Erwin 1982, Boyd 2000, Frederick et al. 2003, Buckland et al. 2012, Hodgson et al. 2018). The use of high-resolution cameras allows drones to fly at increasingly high altitudes to be able to identify birds which reduces the disturbance to the birds by the drone and the consequent difficulties to get reliable counts (Goodship et al. 2015). Digital cameras show a continuously improving performance and resolution (Bakó et al. 2014), image-analysis software becomes ever more sophisticated and computer processing speeds increases as well.

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Thus far, this technique it has mainly been used to count the number of breeding pairs of single species in colonies. For example, drones have been successfully used to count the number of nests in colonies of breeding Common Terns (Chabot et al. 2015), Lesser Black-backed Gulls (Rush et al. 2018) and African royal terns, Caspian terns, slender-billed gulls and grey-headed gulls (Kellenberger et al. 2021) with large precision and minimal levels of disturbance. Monitoring breeding colonies of a single bird species is currently easier than mixed flocks of non-breeding waterbirds, because species do not need to be identified and birds in breeding colonies tend to be more concentrated. Waterbirds in breeding colonies (terns, gulls, pelicans, spoonbills etc) are often large and have a plumage contrasting with the surrounding, making automated detection considerably easier and often requires basic image analysis software only (Chabot and Francis 2016).

Data processers and camera resolution have become faster and bigger, making it increasingly easy to reliably identify individual species on images, also of mixed flocks (Castenschiold et al. 2022, e.g. Wilson et al. 2022). The success and accuracy of the identification obviously depend on several factors, including the resolution, angle, lighting, and colour contrast of the images, as well as the expertise and experience of the observer or the automated software used for the identification (Chabot and Francis 2016). Identifying different species in mixed aggregations is possible (Francis et al. 2020), also of shorebirds on drone images (Wilson et al. 2022), but it requires high-quality images, sophisticated image analysis techniques, and expert knowledge and experience. The minimal requirements of the images, camera, and flight altitude depend on the specific conditions and objectives of the study, and should be optimized for each case (Castenschiold et al. 2022).

A wide variety of bird species are currently being monitored using drones, with a clear focus on waterbirds (Chabot and Francis 2016). Drones offer an aerial perspective on bird flocks, which from a ground view can be difficult to approach without causing disturbance. Indeed, the relative advantages of aerial counting for wildlife monitoring is long established, including reduced detection error, increased precision reduced observer effects and retrospective analysis of data (Lyons et al. 2019).

Drones can provide more accurate counts of non-breeding waterbirds (Hodgson et al. 2018, Dundas et al. 2021, Fig. 6), especially when the birds are scattered across large areas or difficult-to-access habitats, such as mudflats, wetlands, or estuaries. Drones can fly at different heights and angles, capture high-resolution images or videos, and create detailed maps or 3D models, which can be used to estimate bird densities and identify species. Counts from remotely sensed imagery can be semi-automated with a high degree of accuracy. Indeed, the accuracy of counts made by a drone was shown to be between 43% and 96% more accurate than the traditional ground-based data collection method (Hodgson et al. 2018). The increased accuracy and increased precision of monitoring data by the use of drones allows a greater statistical power to detect fine-scale population fluctuations (Hodgson et al. 2018).

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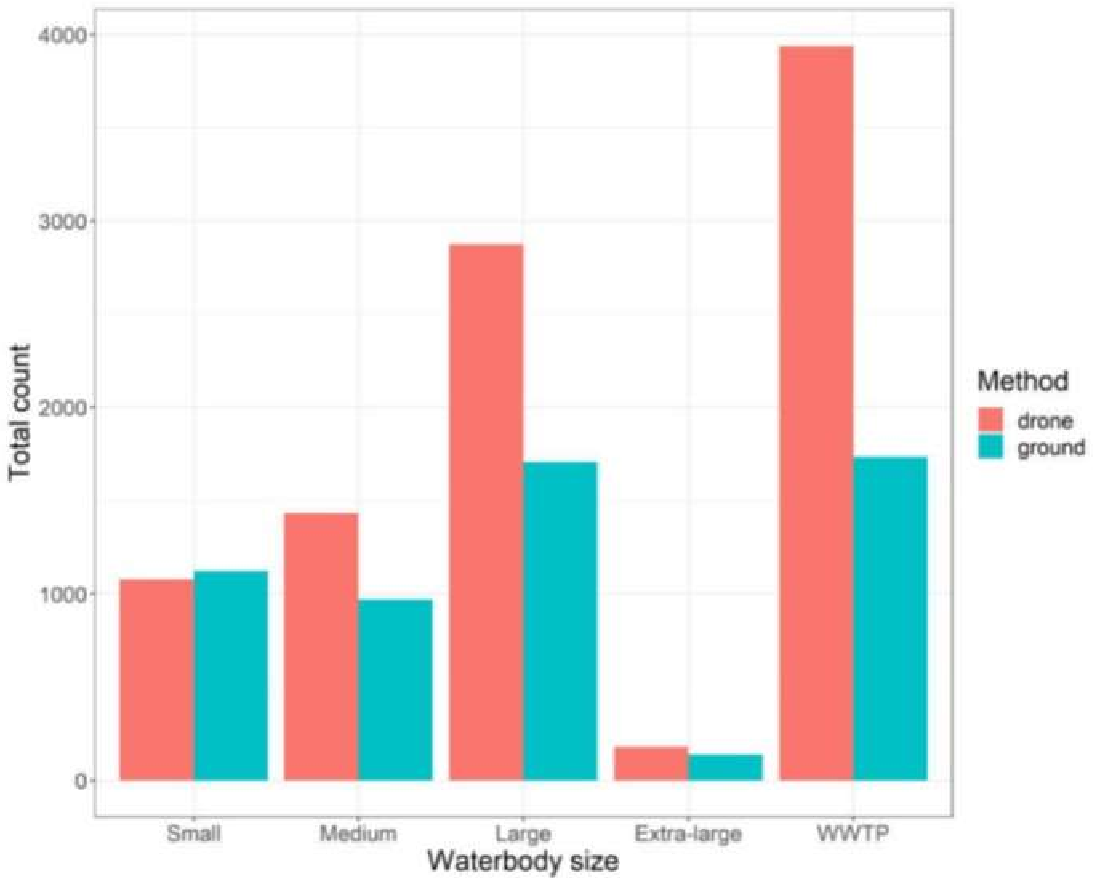

Figure 7. Comparison of total counts of waterfowl using two survey methods (drone and ground) across waterbody of different sizes indicates that especially for larger waterbodies with an overall large number of birds, fewer individual birds were missed by drones compared with ground observers. From (Dundas et al. 2021).

Drone surveys are generally faster and less expensive than traditional surveys, which involve ground-based or aerial observations, and require large teams, equipment, and logistics. Drone surveys can cover more ground in less time, and may reduce the risk of disturbing birds or their habitats (at least in breeding colonies). Also, drones can be reused multiple times, and their data can be easily stored, analysed, and shared with other researchers or conservationists.

Still, despite the potential advantages, the technique cannot be used yet as an alternative for the current methodology based on observers that count waterbirds. Drones can face technical limitations, such as battery life, range, connectivity, or weather conditions, which can affect their flight time, data quality, or safety. Also, drones may require specialized training, skills, or permits, which can limit their accessibility or affordability.

Furthermore, drones may raise ethical concerns related to privacy, surveillance, or disturbance of animals. Drones may disturb and consequently (temporarily) displace birds or their habitats, if they fly too low (Castenschiold et al. 2022), or if they emit noise or visual disturbances (Jarrett et al. 2020) and flight speed and the frequency of fly-overs may affect the level of disturbance too (Dundas et al. 2021). Different bird species respond differently to an approaching drone. Especially the larger shorebirds seem very sensitive to an approaching

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drone and mixed-species flocks react according to the most sensitive species in the flock (Jarrett et al. 2020, Castenschiold et al. 2022, Wilson et al. 2022). This has led to the conclusion that with the current technology, extensive surveys of shorebirds, which are a very large part of the current monitoring along the East Atlantic Flyway, are not practical and not ethical (Wilson et al. 2022). Recent tests with high-flying drones equipped with a high-definition camera and aided by machine learning, could reliably identify and count shorebird species during high tide without disturbance (Nehls pers. comm). The still troublesome large proportion of “unidentified small waders” were almost certainly all Dunlins. Drone technology and resolution of images are still developing fast, together with machine learning techniques, so in the foreseeable future, reliable monitoring of waterbirds using drones will likely become possible, although the financial costs, required licences and training could still slow down the (full) implementation of such drones in the waterbird monitoring along the entire east Atlantic Flyway (Rasmussen et al. 2023).

For some areas, where birds cannot be counted during high tide, because they roost in mangroves, it could be of interest to count birds with drones during low tide. Currently, drones have only been tested on areas with high densities of birds, such as in breeding colonies (e.g. Chabot et al. 2015, Brisson-Curadeau et al. 2017) and at high tide roosts of shorebirds (Castenschiold et al. 2022, Wilson et al. 2022). Its effectiveness in terms of area that can be covered within a short time frame (e.g. a tidal cycle), identification of species and individuals in more heterogenous landscapes and also in terms of disturbances urgently needs to be tested and evaluated in different ecological contexts and using a variety of drone types.

Human operators are still required to visit field sites, which can limit their application in inaccessible locations. Another current challenge with the use of drones for bird monitoring is that drones can generate large amounts of data, which can be challenging to process, interpret, or analyse, especially if they involve complex algorithms, machine learning, or remote sensing techniques (but see below). The use of drones requires data validation or verification, which involves ground-truthing or independent surveys, to ensure the accuracy and reliability of their counts or estimates.

Advances in drone technology, such as increased flight time and improved imaging capabilities, have made it easier and more cost-effective to monitor bird populations. The sophisticated analysis capabilities of modern object-based image analysis software provide ways to detect birds in more challenging situations based on a variety of attributes including colour, size, shape, texture, and spatial context. Some techniques developed to detect mammals may also be applicable to birds, although the prevalent use of aerial thermal-infrared images for detecting large mammals is of limited applicability to birds because of the low pixel resolution of thermal cameras and the smaller size of birds (Chabot and Francis 2016). However, the increasingly high resolution of true-colour cameras and availability of small drones that can fly at low altitude now make it feasible to detect even small shorebirds in aerial images. Continued advances in camera and drone technology, in combination with increasingly efficient methods to process and analyse images (e.g. using crowd sourcing and machine learning, see below), now make it possible for investigators involved in monitoring bird populations to save time and resources by increasing their use of automated bird detection and counts in aerial images. Still, the use of drones for bird monitoring is still relatively new, and the method is still improving with improving technology. Research to

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determine the best practices for using drones to count non-breeding waterbirds in the field while the technology rapidly develops continues to be necessary.

8.1.3 Counts from planes

For many waterbird populations such as ducks, swans and seabirds, aerial surveys are the only way to collect data over large areas at a relatively low cost (Kingsford and Porter 2009). Once drones do not require line of sight with the operator and/or can be launched hand-held will have sufficiently long flight times and altitudes to yield spatial coverage at the scale of a wetland, they can also replace the current (expensive) counts from planes. High-altitude imagery from planes allows large areas to be captured in single images. The costs of flying manned or unmanned planes will always be larger than those of drones, but the advantage of covering considerably larger areas can be considerable. For example, with ca. 30 photos, flocks of around 10,000 geese could be captured (Boyd 2000). Because similar areas would require many thousands of drone images and to the extra complexity from increased spatial resolution, the use of drones to monitor waterbirds continues to be limited to monitoring relatively small aggregations (i.e. <5–10,000 individuals) and is thus also limited in the area that can be covered. The potential yield in terms of data that can be collected needs to be considered together with operational and logistical aspects in the choice of type of flying vehicle. This includes constraints imposed by the kind of platform and sensor and operational and environmental constraints (Certain and Bretagnolle 2008, Anderson and Gaston 2013).

8.1.4 Counts using satellite imagery

Advances in the spatial and spectral resolutions of sensors now available to ecologists are making the direct remote sensing of certain aspects of biodiversity increasingly feasible. Examples are the identification of individual trees (Vibha et al. 2009, Ke and Quackenbush 2011, Li et al. 2017). The presence or even abundance of individual animals can now also be directly or indirectly be determined or estimated (Hollings et al. 2018). Indirectly, the presence of seabirds in colonies could be detected using spectral signatures of vegetation that are correlated with altered soil below nests (Williams and Dowdeswell 1996). Similarly, the size of penguin colonies have been estimated using remotely sensed guano (Lynch et al. 2012, LaRue et al. 2014, Fretwell et al. 2015). Emperor Penguins in inaccessible areas were directly estimated making use of regressions between actual counted birds and the number of pixels classified as ‘‘penguin’’ in the satellite images of the accessible colonies (Barber-Meyer et al. 2007).

The recent development of new technologies, the greater resolution of and the availability to remotely sensed data have led to an improved direct detection of individual organisms such as large waterbirds, mammals and other large animals (e.g. Groom et al. 2011, Fretwell et al. 2012, LaRue et al. 2014, Laliberte and Ripple 2015). Many current studies using remotely sensed images to detect animals from remotely sensed imagery appear promising, but are not yet applicable in all circumstances. Successful studies demonstrating high accuracy using automated and semi-automated techniques were conducted on small spatial scales relative to the geographical range of the species of interest and/or in homogenous environments, such as sea ice (Hollings et al. 2018). This implies that reliably counting small waterbirds along the entire non-breeding range of the East Atlantic Flyway is currently yet not possible. Current major limitations of direct remote sensing of individual

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organisms are the relatively low accuracy of automated detection techniques across large spatial ranges, false detections, the cost of high-resolution data, difficulties associated with movements of birds in relation to the temporal resolution of the satellite imagery and a decreased accuracy of population counts (Terletzky and Ramsey 2016).

The accessibility of large amounts of remotely sensed data can also come with the risk that users with limited training in remote sensing – this may apply to the majority of ecologists– will not sufficiently considering important aspects such as atmospheric effect, saturation phenomenon, and sensor factors (Huang et al. 2021).

With continued developments in image processing, remotely sensed data can complement and/or improve current waterbird monitoring based on field observations. Eventually, it may potentially even reduce the need for data gathered by field observers. According to Hollings et al. (2018), future developments in the analysis of remotely sensed data for population surveys will improve detection capabilities, including the advancement of algorithms, the crossover of software and technology from other disciplines, and improved availability, accessibility, cost and resolution of data.

8.2 Statistical improvements and alternative ways to determine waterbird numbers

For an optimal design of a monitoring scheme, it is essential that the goals are clear beforehand and hypotheses should be stated (Yoccoz et al. 2001b). If additional goals are added during the ongoing monitoring, the scheme needs to be adjusted. The current goals of the waterbird monitoring along the East Atlantic Flyway are to estimate the size of flyway populations and to detect trends herein. Additional goals are to gain insight into the proximate causes that explain changes in waterbird numbers or in their distribution. Null hypotheses would be that there are no such changes, but they could also be defined by specific conservation needs according to AEWA, e.g. that specific wetlands along the flyway that are designated as Ramsar-sites will keep that status following the criteria.

In optimally-designed monitoring schemes, prior power analyses should be the basis for decisions on the desired spatiotemporal cover of the counts, such that significant trends can be detected within a desired time frame, making the monitoring scheme more robust and cost-effective. There are four techniques that can help determining the best design of the monitoring scheme:

(1) power analyses
(2) experiments with different sampling designs (in space and/or in time)
(3) simulations
(4) (non-random) resampling of existing data.

Power analyses require knowledge of the sampling error and of the extent of spatial or temporal autocorrelation (per species) which is often not available and thus makes their use in practice complex. Experiments with different monitoring regimes would be very insightful but it will be logistically and financially challenging to simultaneously conduct different methods to count waterbirds along the entire flyway. Simulations and re-sampling techniques are less complex, but knowledge of the system parameters are needed in the former, while data need to be representative in the latter. Re-sampling from existing data enables “experiments” with existing data to understand the consequences of different monitoring designs, such as the optimal length and frequency of monitoring (White and Bahlai 2021). Re-sampling and

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simulations can be used to test the effects of leaving some sites out of the analyses on calculated trends for several species with different distributions or behaviours, such that the relevance of including specific sites within the monitoring scheme can be revealed. Another possibility is to measure what frequency of counts or the duration of a scheme that is required to find significant population trends (White et al. 2022).

Long-term waterbird monitoring typically will have to deal with missing counts because it requires a lot of human resources due to its large span in both time and space. Missing values in datasets however can lead to biased or inaccurate results if not accounted for correctly. A common way to correct for incomplete counts is imputation, which are methods to estimate and replace missing values within datasets based on the observed data (Underhill and Prŷs-Jones 1994). Imputation is also applied in the current monitoring of waterbirds along the East Atlantic Flyway (Atkinson et al. 2006, van Roomen et al. 2011a). There are several methods of imputation e.g. TRIM (van Swaay et al. 2008), iterative imputation method based on a random forest (Stekhoven and Bühlmann 2012), multiple imputation (Onkelinx et al. 2017) or a method based on penalized Poisson models (Low-Rank Interaction, LORI) (Dakki et al. 2021). Imputation is a crucial step in the data preprocessing phase, and the choice of method depends on the characteristics of the data, the extent of missing data and the goals of the analysis. It is advisable to critically compare imputation methods (Onkelinx et al. 2017, Dakki et al. 2021) and adopt the method which is best suited for the available dataset on waterbirds along the East Atlantic Flyway.

8.2.1 Mark-recapture models for mixtures of marked and unmarked birds

There are several statistical techniques that can improve the estimation of bird numbers based on the counts of marked or unmarked birds. Which technique is most suitable depends on the situation: (1) is the population to be estimated closed (e.g. an entire flyway, where immigration or emigration is presumed to be minimal) or open and whether a population is stationary (e.g. as presumed to be the case during the January counts) or migratory and turn-over of birds within the local population has to be taken into account (as is the case on staging sites during the migration periods), (2) which sampling protocol is possible, e.g. distance sampling, counts of unmarked birds or whether marked birds can be encountered, (3) whether surveys are based on counts only, or whether resightings or recaptures of marked birds can be included, (4) the kind of uncertainty that needs to be taken into account, such as error in estimation of flock sizes, the potential for double counts and the imperfect detection of marked birds, and (4) whether we want to estimate absolute bird abundance to estimate population sizes, or whether estimation of relative bird abundance to estimate population trends are sufficient.

"Distance sampling" is a method to estimate bird numbers based on their recorded distances to a transect or observation point can improve estimation, as it takes into account that the probability of detecting a single bird, or a flock of birds, decreases with the distance from the observer. The encounter probability depending on the distance to the transect – the detection function – is then used to translate counted numbers into total estimates (Buckland et al. 2004). While distance sampling probably is not very useful when counting waterbirds at large high tide roosts by foot, they can considerably improve estimates when counting breeding waterfowl and non-breeding shorebirds by use of transects from planes (Kingsford and Porter 2009, Morrison et al. 2012).

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8.2.2 Estimating local population sizes

In many avian research projects, birds are individually marked with metal rings (Brown and Oschadleus 2009). The recovery of a dead bird or the re-trapping of a live bird with a metal ring, provides information about longevity or movement. The recovery rate of metal-ringed birds is very low and it is therefore that researchers have often added plastic rings, in colour combinations or with unique inscriptions, that enable visual re-encountering ('resighting') of birds. The combination of the current sheer number of bird watchers – especially in Western countries – and the relative ease to mark large numbers of birds, makes colour-ringing a powerful way to track a large proportion of bird populations throughout their annual cycle (Greenwood 2007). There are many scientific goals that can be targeted with colour-ringing schemes, such as studies of movement, phenology, survival and abundance (Reneerkens 2022).

Individually recognisable birds allows researchers to estimate the total number of birds that use winter sites or staging sites, while accounting for turn-over (Frederiksen et al. 2001, Atkinson et al. 2007, Loonstra et al. 2016), see Box 1. The total number of birds estimated can be up to three times higher when turnover is taken into account (e.g. Loonstra et al. 2016), and this can make the difference on whether a site does or does not attain the required international importance to be protected as a Ramsar site (Atkinson et al. 2007).

Box 1 Estimating bird numbers using individually-recognisable birds

The method used to estimate bird numbers based on observations of individually recognisable birds is straightforward: typically, bird abundance at sites has been designated by using the (maxima of) individual counts. At sites, especially at staging sites during migration, birds enter and leave the site (Schaub *et al.* 2001). Consequently, counts will typically underestimate the local population size (or: volume of birds). When individual staging duration is considered, however, numbers using a site can be estimated (Bishop et al. 2000, Frederiksen et al. 2001, Ydenberg et al. 2004, Lee et al. 2007). Using observations of individually recognisable birds within a local population can give insight into the extent of turnover based on individual arrival date, local survival of individually marked birds (i.e. the probability that a bird present in one time interval is still present on the next interval, taking resighting probability into account) and counts. Based on these data, the total number of birds using a site can be estimated (Frederiksen et al. 2001, Schaub et al. 2001). Variation in individual staging duration, resulting in turnover of birds at sites, can also be estimated based on individual birds tagged with radiotelemetry (e.g. Lee et al. 2007, Verkuil et al. 2010). An advantage of this approach, compared with colour-marked birds, is that the detection of birds can be automated which may allow larger detection probabilities of radio-tagged birds. Indeed, estimates of staging duration have been shown to be sensitive to low probabilities to observe colour-marked birds, leading to underestimates of staging durations (Calvert et al. 2009, Verkuil et al. 2010). To avoid low resighting probabilities, large sample sizes of colour-marked birds are needed (Sandercock 2003) in which case an automated approach could be favoured. Estimates of staging duration based on either (many) colour-marked birds or (a small number of) radio-tagged were consistent with each other (Lee et

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al. 2007), but more studies comparing both approaches in different situations would be valuable.

8.2.3 Estimating flyway population sizes using marked birds

Individually marked birds have been used to estimate flyway population sizes. Repeated observations of individually-marked birds can be used to estimate annual survival (accounting for resighting probability and/or emigration Sandercock 2006). These can subsequently be used to estimate the actual number of marked birds alive. If birds that are marked on a single staging site randomly distribute themselves among non-marked birds within the entire flyway population, densities of marked birds on sites away from the ringing locations can be used to estimate total flyway population sizes by multiplying the estimated number of marked birds alive by the measured ratio of unmarked to marked birds (Spaans et al. 2011). Following this approach for three shorebirds populations, Red Knot (*islandica* and *canutus* subspecies) and the *taymyrensis* population of Bar-tailed Godwit, it was shown that this could be an effective alternative method for on-the-ground counts along the entire flyway, with estimates not deviating much from the estimates based on these counts (Spaans et al. 2011).

This method can and has been used to estimate the number of birds at sites, accounting for turnover. The extent of turn-over during counts in January needs to be addressed, but will likely be significantly less than during the migration periods at staging sites. It can be an effective method to accurately estimate the size of flyway populations, although it is difficult to compare its precision with the estimates based on counts because the true population sizes are unknown (there is no golden standard). An advantage of the method is that not all areas need to be visited, making it cost-effective. The method relies (or: can rely) on a citizen scientists which is beneficial for the engagement (see 8.3).

Sophisticated mark–resighting methods can be applied to local populations, but are generally too labour-intensive to implement in large-scale surveys and on all species of interest. A major assumption for this method to work need to be met regarding random mixing and equal resighting probability, which else need to be statistically accounted for (e.g. Rakhimberdiev et al. 2022) and will increase confidence intervals.

8.2.4 Abundance estimates from unmarked individual waterbirds

The number of birds at a site can also be estimated based on data from populations with unmarked individuals (Buckland et al. 2015). The choice of the most appropriate design and analysis of unmarked populations depends on the ecological questions to be answered and on the probability of detection of the unmarked animals in the population (Kéry and Schmidt 2008, McClintock and Thomas 2020).

An often-used model is the N mixture model, which is a hierarchical extension of a generalized linear mixed model (GLMM) that estimates abundance while accounting for detection error (Royle 2004, Kéry et al. 2005, Schaub and Kéry 2012, Dennis et al. 2015). An advantage of N-mixture models is the possibility to include covariates relevant to abundance (Joseph et al. 2009). Replication of counts in both time and space, and an adequate specification of the random-effects distribution of abundance are essential aspects of mixture models (Kéry et al. 2005). An important assumption for the use of N-mixture models is that populations are closed (i.e. no immigration or emigration takes place). Nevertheless, if the individual heterogeneity is low and the counting frequency is high, transient populations of

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shorebirds at staging sites can also be reliably estimated using N-mixture models (Kwon et al. 2018).

8.2.5 Species distribution models

Species distribution models are used to predict the spatial distribution of species based on environmental variables. These models aim to identify suitable habitats for a species and understand the factors influencing its distribution across geographic areas. Species distribution models are based on information about the locations where a species has been recorded and environmental variables that are assumed to influence the distribution of the species (e.g. temperature, altitude, vegetation cover, mudflat availability etc), derived from remote sensing data or climate models. The model is then trained to learn the relationship between species' occurrence and the environmental conditions at those locations, validated and used to predict the potential distribution of the species across a larger geographic area. The model can then be used to understand which environmental variables are most influential in determining the species distribution and provide insights into the ecological requirements of the species (Austin 2002). Generated distribution maps can e.g. identify suitable habitats for conservation planning or assess the impact of climate change on species distributions . Importantly, species distribution models are based on assumptions and correlations and careful consideration of the data quality, model assumptions, and potential limitations is essential when interpreting the results. For example, a species distribution model predicted a fast loss of suitable breeding habitat for Arctic-breeding shorebirds (Wauchope et al. 2017), but this is solely based on current relationships between temperature and occurrence of shorebird species, while it cannot take species' adaptation to temperature changes and the many other aspects of habitat suitability (e.g. food and predators) into account. Species distribution models do not directly provide information about the abundance or density of a species in a particular location, but abundance-based species distribution models are being developed. The performance of abundance-based species distribution models is, however, often still limited, especially when it concerns predictions of species abundance outside of the environmental conditions used in model training (Waldock et al. 2022). Based on observations by citizen scientists (see 7.9), statistical models and machine learning techniques developed by Cornell University, are used to produce weekly relative abundance estimates and estimates of population size of shorebirds in the western hemisphere (Fink et al. 2020, 2023).

8.3 Improving skills of observers and monitoring protocols

Monitoring waterbirds along the vast biogeographical range of a flyway involves significant time, manpower and funding. Crowdsourcing (Papadopoulou and Giaoutzi 2014) and citizen science (Bonney et al. 2009, Dickinson et al. 2010, Johnston et al. 2021) have been shown to be effective in overcoming such logistical and financial issues, also in monitoring waterbird populations along the East Atlantic Flyway (Barnard et al. 2017, Reneerkens 2022). Crowd sourcing and citizen science are essentially two distinct methods of collecting and utilizing information from a large group of people tapping into the collective intelligence and effort of a group. Crowd sourcing is an approach to solving problems whose solutions require innovation, where citizen science is a way to involve (large numbers of) volunteers from the public without prior experience to complete clearly outlined tasks.

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Crowd-sourced science requires prior investment in the training of new volunteers (Bonney et al. 2009, Silvertown et al. 2013). Once trained, citizen scientists can help produce valuable data at no financial cost (Silvertown et al. 2013). For example, when animals will be remotely sensed this may result in large amounts of photographic material from which individual birds need to be counted and/or identified. Crowd-sourcing can make the laborious task of counting animals on photographs or other tasks considerably easier (LaRue et al. 2020), but must first be validated against expert counts to measure sources of error (Swanson et al. 2016). Because crowd sourcing based on judgements by many untrained volunteers, it is essential that the accuracy and reliability of data is safeguarded. With appropriate protocols, training, and oversight, volunteers can collect data of quality equal to those collected by experts (Bonney et al. 2014). If done properly, a crowd sourcing initiative can successfully make a large and expensive task manageable and even generate useful ideas that can be implemented in monitoring schemes (Can et al. 2017).

To a large extent, the monitoring of waterbirds in Europe and Africa already relies on citizen science, as it largely relies on unpaid volunteers (van Roomen et al. 2011b) who are likely motivated by the value of documenting population sizes and trends (Bell et al. 2008). Setting up a large and reliable network of citizen scientists costs continued efforts to engage and train people. It could be useful to involve sociologists to think of effective ways to get more African counters sustainably involved. There is a delicate balance between the amount of useful data to be collected by volunteers on one hand and the quality of the data and the motivation of the volunteers on the other hand. Specific tasks in the field may ask for specific interests and skills by individual observers. For example, observers that are very skilled in bird identification and counting may be less interested in scanning flocks of birds to search and identify colour-ringed birds or to age birds of a particular species.

8.3.1 Technical aids to train and involve more observers

Especially in Europe there is a rich tradition in monitoring birds, including waterbirds, with institutes that coordinate the monitoring (e.g. BTO in the United Kingdom, Sovon in the Netherlands and the LPO in France). Monitoring schemes rely to a very large extent on volunteers who like to observe and counts birds, and are thus part of essentially large networks of citizen science. This implies that in Europe there are large networks of experienced professional and volunteer bird watchers which are key to knowledge-based (water)bird conservation (Bell et al. 2008, Schmeller et al. 2009, 2012). The simultaneous counts of waterbirds in the international Wadden Sea are conducted by volunteers in Denmark, Germany and the Netherlands. These bird watchers also use their experience during the tri-annual counts of waterbirds along the East-Atlantic Flyway.

There is a large and consistent geographical difference in experience with waterbird monitoring. In general, there is much less of a tradition and thus experience for bird watching and counting in Africa. This creates a disbalance in the sense that while African wetlands contain very large numbers of waterbirds (e.g. Salvig et al. 1994, Oudman et al. 2020), they are primarily being counted by (a significant involvement of) European birdwatchers. Few monitoring schemes exist in Africa (Barnard et al. 2017) (but see Ntiamoa-Baidu et al. 2000, 2014, Henry and O'Connor 2019) while stimulating public interest and volunteer assistance in data collection and monitoring programmes is essential for the conservation of nature in general (Bonney et al. 2014) and coastal habitats in particular (Boere and Rubec 2002).

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By accurately filtering and further processing abundance data entered by citizens through apps for mobile phones (e.g., eBird Johnston et al. 2021), the relative site of species along the entire flyway could be described. Such apps could also be developed to train counters in species recognition and help streamline counts following strict protocols. There are reliable apps on the market that help with species recognition of organisms using artificial intelligence (Box 5) (e.g. ObsIdentify, Ebird mobile, Merlin BirdID app), but access to mobile phones and to a network may be limited at some locations. Ideally, information reported via such apps should be linked to national databases which are part of the international waterbird census so that managers can use the information. Existing apps ask users to record and submit photographs of observed birds (or other organisms) to compare with photos in a global database. Artificial intelligence is then used to tell which species observers (most likely) have reported. A side-by-side comparison of similar species often allows users to ensure that birds were correctly identified, while the submitted photos can be used to verify the observations by professionals. The typically large distance to birds and the mixing of different species during high tide counts, currently will complicate the making of useful photos by cameras on phones, while professional cameras and lenses are not available for most observers. Audio recordings can be very efficient in detecting presence of bird species, but is less often used to estimate abundance (but see Borker et al. 2014, Pérez-Granados and Traba 2021, Baroni et al. 2023). For non-breeding waterbirds, occurring in large densities at selected roosts, or distributing themselves (mostly silently) over large areas of mudflat, passive acoustic surveys are likely not a useful method to monitor abundance. Passive acoustic monitoring can however likely successfully be used to monitor shorebirds at breeding sites, although the detection rates of recorders relative to those of actual field observers should always be evaluated (Vold et al. 2017).

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9. POSSIBILITIES TO IMPROVE VITAL RATE MONITORING

Changes in waterbird population size are due to changes in survival, reproduction and emi- or immigration. Flyways are considered to be closed (i.e. no emi- or immigration takes place) and will thus essentially be regulated though (environmental factors impacting) survival and reproduction (vital rates), which can in migratory species vary in space and time. Knowledge about how the environment affects demographic rates and how this is translated into a change of population growth is therefore essential for understanding of how populations are regulated, which is a final goal of monitoring and the information needed for conservationists and policy makers. Identifying spatiotemporal components of variation in vital rates can importantly hint at the causes of population declines if at the time and/or location of a limiting vital rate an environmental factor can be associated to the low vital rate(s), although this may be complicated by carry-over effects (see 6.3) .

9.1 Monitoring reproduction

Reproduction can be measured at multiple levels, ranging from nest survival to population-level reproductive success (Box 2). Variation in breeding output can be monitored by assessment of age ratios, or simple counts of juvenile birds, on autumn migration stopovers or in wintering areas in wader species, gulls and some duck species. Age ratios or the number of juvenile birds can be based on field observations or based on catches (Robinson et al. 2005, Rogers 2006). In the field, observers scan a flock of birds with a telescope and count the number of adult and juvenile birds one-by-one for the entire flock, or of a subsample of the flock (Lemke et al. 2012). When waterbirds are caught for scientific purposes by use of mistnets or canon-nets, a varying number of waterbirds can be caught and the number or fraction of juveniles within the catch can be reliably determined based on plumage characteristics of the birds in the hand (Clark et al. 2004). Some shorebird ringing groups have been and are actively catching shorebirds for long periods already at fixed locations. The value of this source of information to estimate recruitment deserves more exploration, including the testing of assumptions and addressing issues of study design, sample size, and scales of inference into account (Mccaffery et al. 2006). Notably, shorebirds are very difficult to age in the field in mid-winter and this would take extra monitoring effort in August-September.

Ageing shorebirds in the hand can also take place in January. Currently, shorebirds can only be classified as juvenile (i.e. less than one year old) or adult (older than one year). Knowledge of the actual age distribution within populations would be an important step forward, because survival and reproduction are usually age-dependent and the age structure of a population is an important indicator of its viability. It has recently been shown that markers of DNA methylation are reliable markers of age, also in wild animals, and this offers potential to study age (structure) of caught waterbirds. Given the relationship between age and reproduction, this can become especially powerful in combination with ongoing colour-ringing schemes, such that (changes in) age-dependent survival can be used in population matrix models to explain population trends.

In contrast to shorebirds, in many goose species recruitment data are collected annually, based on field observations of family groups, on a wide geographic scale and provide a useful

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measure of the reproductive output of populations (e.g. Ebbinge et al. 2002, Nolet et al. 2013b).

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Box 2. Estimating reproduction

Free-ranging populations remain stable if during a lifetime each pair of animals replaces themselves with two young that will start reproducing themselves, provided that the life span and age of first reproduction is similar for each generation. Clearly, we will not understand what causes population change if we do not measure both survival (Box 3) and reproduction simultaneously. Estimating individual lifetime reproductive success of wild animals is complicated: most individuals cannot be followed from birth to death, nor can their offspring. Fortunately, there are useful alternative metrics available that can be used in population models. Reproduction consists of several components:

(I) the probability to occupy a territory and find a partner;
(II) the number of eggs laid;
(III) the probability of eggs to hatch;
(IV) the probability of chicks to survive from hatching to fledging and
(V) survival until first reproduction.

The boundary between what is considered part of reproduction and of survival is sometimes a bit vague and may vary between sources. While (V) above is often included in 'fecundity' in population models, it is usually described as (juvenile or fist year) 'survival' and estimated in the same way as adult survival. How it is treated may depend on how and when in the annual cycle reproductive output is quantified, e.g. as the number of fledged young or from an age ratio among birds reaching a wintering ground. The distinction between reproduction and survival does not really matter as long as all components of the life cycle are covered in population models, without overlap. The latter can be an issue when reproduction is quantified as the number of young fledged, but first-year survival is estimated from data of young ringed at an earlier stage in the pre-fledging period.
Ideally, we would have reliable estimates of all the probabilities associated with reproduction, but that is usually not possible. Many studies focus on daily clutch survival or daily chick survival, albeit both components have complications too, because most clutches cannot be followed from the day they have been laid until either failure or hatching (Weiser 2021). Similarly, most chicks cannot be followed from hatch until death or fledging. There are however useful field methods and statistical methods to get reliable estimates of both clutch and chick survival (e.g. Dinsmore et al. 2002, Ruthrauff and McCaffery 2005). These metrics can be useful indicators of which ecological factors have a local impact on reproductive success.

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To identify whether annual reproductive success at the population level is limiting, the number of juvenile birds that recruit into the non-breeding population can be estimated. This measure of productivity includes components of mortality prior to fledging and from the first southward migration. However, the critical recruitment parameter from a demographic point of view is that of birds recruiting into the breeding population(Clark et al. 2004). In geese, families migrate and stay together until spring, and family sizes and the proportion of juveniles in the population can easily be determined using field observations (Nolet et al. 2013). In shorebirds, the number of recruits into the non-breeding population can be determined by counting the number of juveniles and adults during field observations or in catches (e.g. Blomqvist et al. 2002, Lemke et al. 2012).

9.2 Monitoring survival

In long-lived species, such as most waterbirds, population growth rates are especially sensitive to variation in annual survival. Survival in waterbirds is usually estimated using individually marked birds (Box 3). Observations of the marked birds can then be used in mark-recapture models, which vary in their assumptions and applicability (Sandercock 2003). Essentially, mark-recapture models account for the fact that not all marked individuals are recaptured (i.e. re-sighted) during each time period and as such reliably can distinguish (local or apparent) survival from the resighting probability (i.e. the probability that a marked individual is alive, but not observed). The models include parameters for the probability of an individual being marked, the probability of being recaptured given marking, and the probability of being recaptured given not marked. These parameters help adjust the raw counts of marked individuals to estimate population parameters more accurately.

Box 3. Estimating survival

Survival is a demographic parameter that has been shown to have one of the greatest potential impacts on population growth (Crone 2001). Conservation actions will often have the best potential to effectively influence rates of population change when they influence survival rates(Sandercock 2006). However, the timing and cause of mortality of individual free-living animals is often unknown and survival rates of populations can only be estimated from long-term data. Another complication is that in most bird populations, the age classes with often different survival rates to which individuals belong cannot be distinguished based on their appearance.

The most common method to estimate survival rates is the analysis of live observations of individually marked birds within a population, which can be analysed using mark-recapture analyses (Sandercock 2003). Observations can be either physical (re) captures, resightings of colour-marked birds or a combination of both. The concept is rather straightforward; when you individually mark a sample of birds, you monitor how many and which of them are present in the future and thus have survived. The more individuals return to the site of marking, the more have survived. However, the probability of re-encountering a bird not only depends on its survival until the next period, but also on its site fidelity. Individuals that permanently emigrate to other sites are still alive but will not be re-encountered. Furthermore, individuals

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that are site faithful should be available to be detected by observers. Even if they are present, there still is a probability that they will not be detected. Mark-recapture analyses are able to disentangle the probability of 'true survival' - the variable of interest to ecologists and conservationists - from site fidelity, site propensity and detection probability (Sandercock 2006). Usually, models include sex, time, and age-class but ecological variables, such a predator densities or weather, can also be included as covariates.

A necessity to study (changes in) demographic variables within populations over the vast area of a flyway, is to make use of a network of citizen scientists. International colour-ringing projects with individually recognizable birds can be used to estimate various demographic variables. Along the East Atlantic Flyway, there are numerous such projects (http://www.cr-birding.org/), but only few of those are used to measure demographic variables that can inform nature conservationists and policy makers.

9.3 Integrated population models

The (combined) use of vital rates and abundance in integrative population models will explain observed population trends better and can predict future trends based on assumptions of (changes in) vital rates (Schaub and Abadi 2011, Schaub and Kéry 2012).Integrated population models combine count data, such as those collected in the waterbird monitoring along the east Atlantic Flyway, with demographic data into a classical or Bayesian statistical analysis. This has large advantages as it allows the estimation of more demographic variables, results in more precise estimates of parameters enhancing the statistical power compared to separate analyses and adequately includes all sources of uncertainty (Abadi et al. 2010, Schaub and Abadi 2011, Schaub and Kéry 2012). Integrated populations models are based on the link of changes in population size and the demographic rates via a demographic model (usually a Leslie matrix model) and the likelihoods of all existing datasets. Once the monitoring of vital rates (see 9.1 and 9.2) becomes an integrated part of the current flyway monitoring scheme for a selected number of well-chosen waterbird species, integrated population modelling will be very insightful in explaining population trends.

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10. POSSIBILITIES TO IMPROVE ENVIRONMENTAL MONITORING

10.1 Determining habitat quality

Many migratory bird populations are worldwide in decline (Wilcove and Wikelski 2008), but due to the large distances over which these birds occur throughout an annual cycle, it is difficult to find out for each population what the causes of the declining populations are (Reneerkens 2022). The loss and degradation of habitat are among the largest threats to wildlife, including waterbirds (Sutherland et al. 2012, Murray et al. 2015, Piersma et al. 2016, Conklin et al. 2016, Studds et al. 2017). Clearly, the conservation of suitable habitat is of fundamental importance. To conserve habitat important for migratory birds, knowledge of what constitutes suitable habitat is needed.

All waterbirds along the East Atlantic Flyway rely on wetlands, and in many cases intertidal flats or other estuarine habitat. However, not all wetlands are equally suitable for all waterbirds. The quality of habitat encompasses a variety of environmental parameters. Within each wetland, each individual within a population has its own multiple requirements to manage energy, water, danger and the social environment (Piersma 2012b). Measuring all the relevant ecological factors that determine habitat suitability is daunting and will in practise turn out to be near-impossible (Johnson 2005).

Ecologists have used a variety of direct and indirect indicators of waterbird habitat quality; measures of habitat attributes and measures of the birds using that habitat (Mott et al. 2023). Studies of the effect of habitat characteristics or bird condition to indicate habitat quality usually assumed that the used indicator of habitat quality affected demographic rate, instead of empirically determined such a relation (Mott et al. 2023).

Instead of studying indicators of habitat quality that are presumed to affect demographic rates, a more direct approach -for some key species- could be to estimate such demographic rates (survival, reproduction or age of first reproduction) preferably in combination with small-scale tracking of birds to determine habitat use (Bijleveld et al. 2022). For example, it is possible to estimate which sites along the flyway relatively contribute the most to population growth (e.g. Sandercock 2020). Essential in this approach is that (local) survival is estimated, which is a demographic variable that often contributes most to population growth rates (Crone 2001, Cleasby et al. 2017). Survival can be estimated using mark-resighting models based on observations of individually marked waterbirds (Sandercock 2003, Reneerkens 2022, Box 1).

Knowing which site(s) are contributing relatively much to the flyway population of a waterbird species, may indicate which sites are suitable, or of highest importance, for waterbird populations. However, it will not explain what makes the habitat suitable at those sites (Piersma 2012b). A combination of ecological research of the many possible habitat characteristics, waterbird behaviour and condition, population structure, demographic rates and how they relate to each other and how they eventually explain changes in bird numbers will be the best possible indication of which habitat is of highest quality to specific bird populations. In practise this will take intensive long-term ecological studies. Although an indirect method (Fig. 8), arguably the easiest way to measure habitat quality along an entire flyway is remote sensing using satellite imagery.

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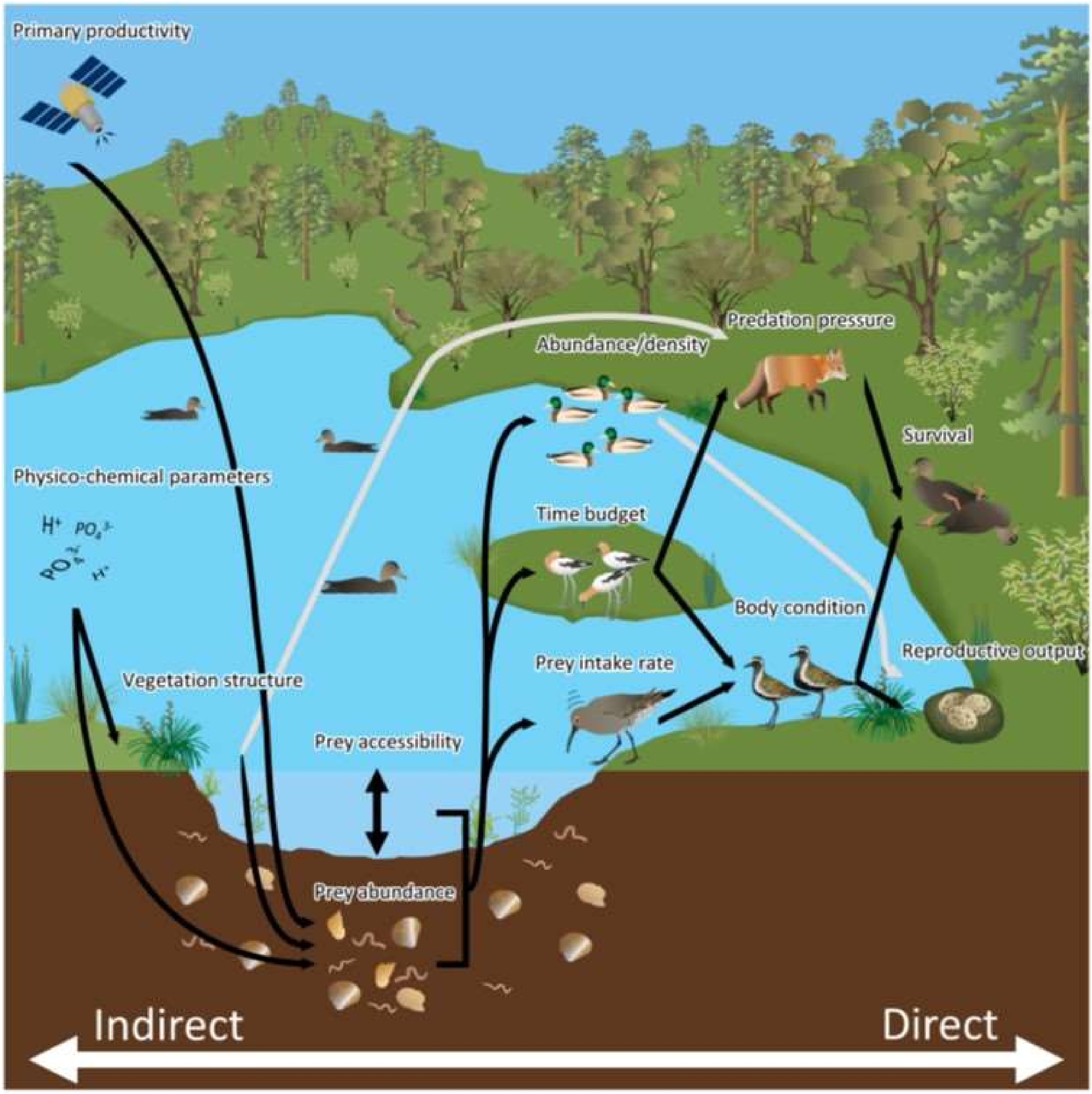

Figure 8. An illustration of the many variables used to assess waterbird habitat quality. The horizontal axis indicated how directly or indirectly a selected habitat quality indicator is related to demographic variables. The combined demographic variables ultimately determine the relative contribution of habitat quality to population growth habitat quality. Arrows point in the direction of the presumed relationship from causal factor to outcome. Arrows originating from a line linking two proxy measures together indicate that the outcome results from the interaction between the two linked factors. Gray arrows depict relationships where the link likely manifests itself via another pathway in the ecological web. For example, greater waterbird abundance/density does not necessarily increase the reproductive output of an individual. Rather, more individuals are probably drawn to sites with high prey abundance and accessibility, where prey intake rates and thus waterbird body condition and then reproductive output can be maximized. From (Mott et al. 2023).

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10.2 Satellite remote sensing of habitat quality

Satellite remote sensing (Box 4) has become an essential tool for environmental monitoring. Technological developments in platforms and sensors, increased data storage and transfer possibilities, and the increasing demand for remotely sensed data have led to rapid expansion applications of satellite remote sensing. It is increasingly used in ecology. Global, daily, systematic, high-resolution images obtained from satellites provide a good data source from which (changes in) habitat suitability can be assessed (Turner et al. 2003, Kersten et al. 2023). Freely available web-based platforms such as Google Earth Engine (Mutanga and Kumar 2019, Amani et al. 2020) implemented in packages for different coding languages such as R (Aybar et al. 2020), make computationally demanding analyses of satellite remote sensing imagery accessible. For species that are restricted to discrete habitats, such as seagrass beds (Hossain et al. 2015) or intertidal flats (Murray et al. 2022), the extent of habitat which can clearly be identified using remote sensing.

Habitat availability, however does not say much about habitat quality. A first essential step, is determining which remotely sensed variables are meaningful indicators of habitat quality (see 10.1). For example, while it has become increasingly easier to monitor marine and coastal plastic litter using remote sensing techniques (Salgado-Hernanz et al. 2021, Veettil et al. 2022) and while coastal waterbirds ingest plastics (Flemming et al. 2022, Daudt et al. 2023), it is unlikely to find significant effects of the occurrence of plastic litter on bird numbers. Other examples of environmental parameters which are monitored using satellite remote sensing are the Normalized Difference Vegetation Index (NDVI) as a measure of the development of plant biomass (Pettorelli et al. 2011, Shariatinajafabadi et al. 2014), snow cover, which is an important indicator of phenology in Arctic regions (e.g. Rakhimberdiev et al. 2018).

Using satellite imagery, a long-term analysis of the global surface of intertidal flats showed a significant decline in the amount of intertidal area (Murray et al. 2019, 2022). An analysis combining monthly count data with remotely sensed environmental data (land surface temperatures, precipitation, and chlorophyll-a) showed that non-breeding abundance was correlated with the climate conditions in the Arctic breeding grounds (Murray et al. 2017).The extent of mudflats, which can be assessed using satellite imagery (Murray et al. 2012, 2014, 2019, St-Louis et al. 2014), will likely be a more relevant factor affecting the number of coastal birds (Studds et al. 2017).

Remote sensing of Arctic habitat can be a solution to the difficulties to conduct bird monitoring in the Arctic. It is now common practice to study snow cover and/or the timing of the greening of the vegetation (Pettorelli et al. 2011, Estilow et al. 2015, Schmidt et al. 2019) in the Arctic regions, which are closely correlated with the average phenology of arthropod prey (Høye and Forchhammer 2008), although this depends on the spatial scale at which it is measured. Thus, remote sensing may give some indication of how sites have changed and possible correlations with bird numbers or reproductive output can hint at potential threats of e.g. Arctic climate change for Arctic-breeding waterbird populations.

However, caution is warranted that (1) correlations are not causations and, (2) remotely-sensed indicators, such as NDVI and snow melt, are only indirect measures which may poorly correlate with the factor of interest (e.g. food availability, Zhemchuzhnikov et al. 2021). Relying on a few parameters that can be inferred from satellite imagery, as indicator of habitat quality affecting vital rates or -more important- population sizes, is challenging. For example, despite a well-documented link between changing snow melt patterns on lemming abundance and

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cyclicity (Kausrud et al. 2008, Korpela et al. 2014), which has been shown to affect the survival of Arctic bird nests (Nolet et al. 2013, McKinnon et al. 2014), there is no direct link between snow melt and population-level reproductive output. In other words, while we can reliably measure snow melt using satellite imagery at large spatial scales and at high spatial and temporal resolution, we would ideally measure nest survival or reproductive output across the breeding range of (Arctic-breeding) waterbird species, which is impossible using remote sensing.

Many aspects of Arctic ecosystems that directly or indirectly have an impact on Arctic waterbird abundance, reproduction and/or survival, such as predator abundance, predation pressure or food abundance cannot be measured with satellites. This is an important caveat, because these variables often play key roles in local and/or population level annual reproductive output (e.g. Bulla et al. 2019). Validation of satellite-derived estimates of the environment with on-the-ground ecological monitoring across all trophic layers will remain essential. However, long-term ecological monitoring in the Arctic is very rare (Schmidt et al. 2017, Mallory et al. 2018), and the limited spatial coverage of monitoring sites might bias the perception of ongoing Arctic change (Post et al. 2018, Schmidt et al. 2023, López-Blanco et al. 2024). Without strong links between remotely assessed environmental variables and (the chain of effects on) eventual demographic variables or number of territories, forecasting how the changing Arctic environment will impact the distribution or (changes in the) population size of birds (Wauchope et al. 2017) should be treated with caution.

Box 4. Remote sensing

Remote sensing are techniques that detect electromagnetic energy reflected or emitted from the Earth surface from above, using unmanned aircrafts (drones), (un)manned planes or satellites. Within the full range between small drones and satellite imagery, many different aspects of waterbird monitoring can be addressed and each technique comes with its own operational, logistical, financial and scientific possibilities and limitations (Kersten et al. 2023; see 11.1).

The electromagnetic spectrum detected by remote sensing techniques can be categorized into optical and microwave wavelengths. Because optical and microwave radiation occupy separate regions of the electromagnetic spectrum and necessitate different detection technologies. There are two types of sensors that are used to detect and measure the electromagnetic radiation: passive and active sensors. Passive sensors measure radiation that reaches a detector without transmitting a pulse of radiation. In contrast, active sensors emit a pulse and subsequently measure the energy returned or bounced back to a detector. Both passive and active sensors quantify the intensity of a signal within a specified wavelength interval, referred to as a "band", within the electromagnetic spectrum. Remote sensing data typically come in the form of a matrix comprised of pixels. The pixel size corresponds to the spatial resolution of the sensor, which determines the smallest detectable object (Turner et al. 2003).

Passive sensors are often used for land-cover and land-use monitoring, measuring visible, near- and middle-infrared, and thermal-infrared radiation. Data related to energy reflected or emitted from the Earth's surface is statistically or visually analysed to identify objects. Passive remote

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sensing depends on natural energy (sunrays) reflected by the object of interest. Therefore, it can be applied only with sufficient sunlight, otherwise there will be nothing to reflect.
In contrast, active sensors are used to measure e.g. vegetation structure and ground surface elevations. Light detection and ranging ("lidar") systems operate in the visible to near-infrared wavelengths, while radio detection and ranging ("radar") emits radiation in longer microwave wavelengths. Both the strength and timing of the signal returned to the sensor provide information about the physical characteristics of remotely sensed objects. Active remote sensing fully functions at any time of the day as it does not need sunlight, making active remote sensing relatively independent of atmospheric scatterings. Because multispectral (i.e. passive) and radar (i.e. active) collect complementary data about the Earth's surface, a combined use of both types of satellite imagery have great benefits (Schulte to Bühne and Pettorelli 2018).

The ability of a sensor to detect spectral differences is determined by the width of the bands of the electromagnetic spectrum it can detect, which constitutes its spectral resolution. Every object (for example an animal, or a vegetated area) has a spectral signature based on how it reflects and emits electromagnetic radiation. More spectral bands of narrower width enable researchers to identify more unique features in the spectral signature of an object that distinguish it from other objects.

Temporal resolution refers to the duration between successive passes over an object being remotely sensed. For example, Landsat satellites pass over the same point on Earth's surface every 16 days, resulting in a temporal resolution of 16-days. There is often a trade-off between spectral and temporal resolution. Systems that remotely sense larger areas may pass over the same point every day but usually at the cost of a lower spatial resolution to achieve this. As a result, they are only able to only detect larger objects. For example, Fretwell *et al*. (2014) identified whales using satellite with a spatial resolution of 50 cm in an area (satellite image) of 113 km^2. For studies of larger areas, satellite images of a lower spatial resolution would have been needed, which would result in a lower detectability of the animals. When the areas of interest have a large probability of being covered by clouds which cannot be penetrated by optical sensors, a high temporal resolution becomes especially important (Turner et al. 2003, Hollings et al. 2018).

Turner et al. (Turner et al. 2003) distinguish two types of remote sensing of biodiversity: (1) the indirect remote sensing of biodiversity via environmental variables that serve as indicators of habitat suitability and (2) the direct remote sensing of individual organisms, species assemblages or ecological communities. Both types of remote sensing are important tools to improve the monitoring of waterbirds along the East Atlantic Flyway (Kersten et al. 2023), although estimating bird abundance through remote sensing is -even at a local scale- often still challenging.

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Box 5. Artificial intelligence

Artificial Intelligence (AI) is the ability of a machine or computer program to perform tasks that typically require human intelligence. AI can be used to build intelligent systems that can perceive, reason, learn, and adapt to new situations. Machine Learning (ML) is a subset of AI that focuses on the development of algorithms that enable machines to learn from and make predictions or decisions based on data. ML algorithms use statistical techniques to identify patterns in data and learn from them, without being explicitly programmed to do so. Deep Learning (DL) is a subset of machine learning that uses neural networks to learn from and make predictions or decisions based on data. DL algorithms can automatically learn to recognize patterns in data and make predictions or decisions based on them. Artificial intelligence has revolutionised the way we use computer power to automatically detect specific features in data and to perform tasks such as classification, clustering or prediction (Olden, Lawler, & Poff, 2008). Deep learning has been used successfully in ecological studies to identify species, classify animal behaviour and estimate biodiversity in large datasets such as camera-trap images, audio recordings and videos (Christin et al. 2019). Using deep learning, individual animals can be detected, identified and classified in such automatic monitoring data. As such, deep learning tools can be scaled up to aid population monitoring (Norouzzadeh et al. 2018, Guirado et al. 2019) and population distribution or abundance can be calculated using these datasets, following traditional methods. Thus far, this has been used for relatively large animals and/or small spatial scales and a current bottleneck for the application of deep learning in monitoring waterbirds along the East Atlantic Flyway is not the technique, but the spatial resolution of remote sensing data across the entire flyway.

For the analysis of large datasets –which are becoming more and more common also in ecology– deep learning might be a solution. It takes considerable programming and mathematical skills to master deep learning techniques, but these challenges can likely be easily overcome. It is recommended to consider the need for deep learning: how large are the datasets, how long will it likely take to analyse them, and how much computer power is expected to be needed and based on that make a trade-of. Collaboration between ecologists and computer scientists will show to be beneficial (Carey et al. 2019). Sharing of data and code will become even more common practice, which will speed up the development and use of deep learning, eventually making deep learning a useful tool for ecologists and nature conservationists (Christin et al. 2019).

At the smaller scale of a single wetland or roost, the use of drones can create large amounts of data that will likely be of sufficiently high resolution to identify species and individuals. Even at such a relatively small scale, this will create large amounts of imagery and manually scanning through these photos is a very large, if not near-impossible task. Machine learning algorithms are being increasingly used to process large volumes of wildlife imagery data from unmanned aerial vehicles (UAVs); however, suitable algorithms to monitor multiple species are required to enhance efficiency. This is certainly the case if surveys occur frequently. Machine learning has already greatly improved the efficiency of identification of intertidal habitat types from satellite imagery at the scales of mudflats, wetlands and even the world (Murray et al. 2019, Henriques et al. 2022, Madhuanand et al. 2023).

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11. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The success of the monitoring of coastal waterbirds along the East Atlantic Flyway depends on clear objectives, consistent methodology, a minimization of sources of error and a long-term continuation (Yoccoz et al. 2001a, White 2019). With the innovative techniques explored in this publication, the monitoring can especially be improved by reducing error, but also by giving context to observed trends in population trends.

Technology, novel methods and statistical techniques are advancing rapidly and biological monitoring schemes can largely profit from these developments at multiple levels. Technology will not be able to replace the current on-the-ground counting of birds, and even if monitoring would be considerably more automated, the on-the-ground presence will remain essential to install equipment, control devices and especially for ground-truthing and interpretation purposes. Additionally, on-the-ground observers, who assess bird numbers, experience the nature and the changes in habitat. Information from these observers is essential to signal the possible conservation issues first. Affinity with wetlands and their birds often results in people becoming local ambassadors and/or engaged biologists that are essential for nature conservation (Greenwood 2007, Sterling et al. 2017). Importantly, local monitoring programs in some African regions struggle to find finances for the essential equipment (fuel for transport, telescopes) and with capacity building of observers and manpower for data management. Maintaining investment in these regions and people will be as important as investing into new technology.

Nevertheless, expanding the current toolbox of monitoring methods aided by the rapid developments, accessibility and lower financial costs of new technology will improve the accuracy of counts. To ensure consistency of the methodology in this monitoring scheme aimed for the long-term, new methods will initially have to be added to the current methodology, instead of replacing current methodology. Changing the procedures and analytical methods involved in long-term monitoring will likely improve the quality of data, but will complicate comparisons of past and present results (Beard et al. 1999). Therefore, we highly recommend to use old and new methods simultaneously for some period to enable evaluation and validation of both methods and the extent to which they affect the outcomes. Ideally, this should result in possibilities to correct older data for changes in methodology.

11.1 Comparing possible innovations

Of course, each innovative method addresses different shortcomings of the current monitoring at varying geographical scales. They differ in how urgent the implementation is, in their impact and relevance and the speed with which they can be implemented. Every method comes with different (financial and logistical) costs and can be implemented within different time periods e.g. because they are in various stages of being developed, tested and applied.

In Table 1, we have scored these different aspects relative to each other. Some methods (e.g. drones, colour-marking and tracking birds) may serve more than one purpose (e.g. to count/estimate bird numbers and/or to study their habitat or estimate their survival and connectivity between areas). In such cases the same method occurs multiple times in the table. The speed of implementation (i.e. how feasible a short-term implementation is), financial and logistical costs (the latter e.g. being the need for skills of specialists or special permits),

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their impact on the current monitoring and the urgency of implementation is scored using four different categories: 0 = negligible, + small, ++ moderate or +++ large ($ signs are used when indicating costs). The table should be interpreted with care and can only be seen as a coarse indication.

There are important qualifications to be made for each method. E.g. drone types differ considerably in their functionalities, costs and (practical) limitations (Rasmussen et al. 2023). Analyses of satellite imagery have different financial costs depending on the use of open data products or commercial data products (Kersten et al. 2023). Implementation speed and logistical costs largely depend on the availability of samples and data and on existing experience (e.g. whether methods need to be learned and tested). For example, studying flyway boundaries using genetic studies are considerably faster implemented if DNA samples do not need to be collected at remote locations first. Similarly, setting up a colour-ring scheme costs a lot of time and investment, especially if an online portal for reporting and collecting such data needs to be implemented (Reneerkens 2022). Also, financial costs may vary considerably between species depending on their geographical distribution (travel costs to remote areas) and size (e.g. affecting the application of different types of tracking devices).

Importantly, some methods can serve multiple goals (e.g. colour-ringing and tracking can be used to assess flyway boundaries, turnover, survival, and habitat use) and the combined use of some methods can strengthen each other. The added impact of a combination of methods may be stronger than the sum of effects of each separate method. Many innovative techniques or methods can be used in parallel, preferably through collaboration between institutes or groups thus additionally fostering a community. As an example, catching waterbirds with the aim of equipping some individuals with a tracking device can easily be combined with colour-ringing birds with the longer-term aim of demographic monitoring, age determination based on plumage, taking blood samples for genetics and/or DNA methylation markers, while the eventual tracks of birds may be investigated in relation to the visited habitats, that can be investigated by satellite imagery and on-the-ground mapping of food resources.

11.2 Recommendations

All three aspects of the current monitoring i.e. monitoring waterbird abundance (including a better understanding of flyway boundaries), monitoring vital rates and environmental monitoring, can be improved with added (novel) techniques and methods, which differ in their costs and benefits. Below we make a few recommendations.

11.2.1 Recommendations for abundance monitoring

The scheme and network of collaborators are well established (van Roomen et al. 2022). Consistent continuation of the monitoring following this scheme will result in the required estimates of population sizes and trends.

Importantly though, the robustness of abundance data can likely be improved by relatively simple adjustments in sampling design (frequency and spatial coverage) and by careful consideration of statistical aspects (e.g. zero-inflation, detection bias and imputation method). Power analyses, simulations of different sampling design and/or the re-sampling of current data can indicate the relative importance of inclusion of certain sites into the monitoring scheme and/or identify which frequency of counts is better. Such analyses are highly

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recommended because they give clear insights into strengths and weaknesses of the current scheme. Such analyses are relatively easy to perform, and at low costs by using the already available data (e.g. Godeau et al. 2024). The implementation of the suggestions by such analyses (e.g. for an adjusted monitoring design or analysis) can have a large positive impact on the reliability of the monitoring results.

Some new techniques will initially take training and/or pilot studies to avoid current drawbacks of a technique. Evaluation of new methods will be essential to learn whether they are correctly performed and actually measure what we expect them to measure. For example, the use of drones to count colonial-breeding waterbirds is well-established and will result in a more effective monitoring while limiting the disturbance of the breeding birds. However, monitoring non-breeding waterbirds (the core of the current monitoring) using drones still comes with considerable challenges related to disturbance of birds, coverage and species recognition. The technology is, however, developing fast and with large, high-flying drones equipped with high-definition cameras and machine learning techniques, such current limitations might be overcome in the future.

11.2.2 Recommendations for flyway boundaries

For most species there is a relatively good understanding of the species-specific flyway boundaries within the flyway, but there are some species where two-three populations which are difficult to distinguish in the field based on their appearance. The use of genetic methods, tracking and/or individual colour-marking, or even better a combination of these methods, will provide the knowledge to reliably identify the flyway boundaries of these species. This will make population trends, and the interpretation thereof, considerably more reliable.

11.2.3 Recommendations for vital rate monitoring

Clearly, it will be a true challenge to estimate spatiotemporal variability in survival and reproduction for each waterbird species whose abundance is currently monitored. Whether and which vital rates can be estimated depends on the species. Different species have different requirements of their environment, and are differently affected by environmental factors, for example because of different geographical distributions and/or niches within wetlands (e.g. Henriques et al. 2022), or because the relative importance of survival or reproduction on population trajectories differs between species. Thus, for a proper long-term embedding of monitoring vital rates, important choices need to be made regarding the species to be included. Feasibility, urgency and representability are aspects that will need to be considered when making such choices.

Monitoring vital rates through the implementation of colour-marking schemes help in multiple ways (vital rate monitoring, knowledge of site use, calculating passage population sizes accounting for turnover, defining boundaries of (sub)species' flyways etc). Colour-marking schemes are also relatively cheap because the manpower partly comes from citizen scientists who observe and report colour-ringed birds, but they also require considerable investments to catch, measure and ring birds. By ensuring the long-term maintenance of already existing colour-ringing schemes of a few pivotal species (e.g. Avocet, Brent Goose, Barnacle goose, Bar-tailed Godwit, Common Tern, Lesser Black-backed Gull, Oystercatcher, Sanderling, Sandwich Tern, Eurasian Spoonbill, Red Knot, Whimbrel) and include the

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analyses of annual survival of these species into the reporting of the monitoring of waterbirds along the East Atlantic Flyway, a large step can be made into including explaining trends, which is a first step towards mitigating negative trends. The choice of species should represent species that have different life histories (long- or relatively short-lived, migratory or resident) and which use different habitat types and have different food requirements and as such can represent a larger number of species that use the same niche (and are thus expected to be similarly affected by changes in their environment). Investment in the continuation of existing programmes will ensure that can be counted on a longer time series, sufficiently large sample sizes and existing knowledge on the ecology and demographic modelling.

Given the large number of coastal waterbirds that breed in the Arctic and given the fast ecological changes in the area, it will be advisable to invest in long-term ecological monitoring of reproduction of Arctic-breeding birds in relation to their (changes in) food and predators. There is an urgent need to monitor the annual population-level reproductive success of many coastal waterbird species, which can be estimated by field observations and/or within catches of birds. Estimates of survival and reproduction in combination with the abundance monitoring can be incorporated in integrated population analyses and such (updated) analyses would clearly pinpoint where and when population growth is limited.

11.2.4 Recommendations for environmental monitoring

The collection of data that indicate where, when and which environmental factors influence (changes) in bird numbers is poorly developed in the current monitoring. Through questionnaires a qualitative overview of possible pressures and causes is collected, but these are subjective and do not allow quantitative analyses of relations between the environmental factor and e.g. vital rates or changes in waterbird abundance. More detailed ecological studies of environmental variables which are linked to vital rates are conducted in relatively short-term research projects and often on local scales. Such studies require labour-intensive measurements of e.g. food availability, predator abundance and bird behaviour (e.g. Reneerkens et al. 2016, Oudman et al. 2018). It will be difficult to implement such detailed studies as part of a long-term monitoring scheme that spans the entire flyway. Systematic quantitative measurements of habitat availability and human pressures through satellite remote sensing could be an interesting innovation to pursue, allowing a more quantitative and unbiased measurement of potential environmental pressures that can be linked to (local and flyway-wide) changes in waterbird abundance. Satellite imagery is stored on web clouds and available for analyses whenever needed, although historical data are not always available. Also, the spatial and temporal resolution and frequency of satellite imagery have changed with time (Kersten et al. 2023). Still, satellite images can be analysed in retrospect and it is thus not required to perform analyses at the same frequency as the international waterbird counts. The main challenge will likely be the choice of environmental stressors to study. The need for specific analyses of habitat quality may arise from observed population trends and/or annual survival of key species.

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Table 1. Implementation speed, monetary costs, impact, and urgency of the possible innovations discussed in this report. Each innovation addresses different topics and can be applied at different spatial scales. The number between brackets after each name of the innovation refers to the section in this report where the innovation is described. Characteristics are scored using four different categories: 0 = negligible, + small, ++ moderate or +++ large ($ signs are used when indicating monetary costs). Note that more +'s for implementation speed indicates that the innovation can rather quickly be applied. Innovations that need pilot studies first will have a low implementation speed. The innovations are ordered, within the overarching themes (Flyway boundaries -grey, Abundance - green, Vital rates -red, and Environment – blue), based on urgency, impact and subsequently according to costs and implementation speed. Innovations that are useful at a local scale can be implemented at many sites, upgrading it to a regional or flyway-scale, but with consequences for the implementation speed, costs and impact.

Recommended innovation	Topic	Overarching theme	Spatial scale	Implementation speed	Monetary cost	Impact	Urgency
Individual bird tracking (7.1)	Tracking different subspecies, boundaries	Flyway boundaries	Flyway	++ **	Logistical $$ Financial $$	+++	++
Population genetics (7.2)	Distinguishing and assigning subspecies	Flyway boundaries	Flyway	++ / +++ *	Logistical $ Financial $$	++	++
Individual colour-ring scheme (7.4)	Observations along flyway	Flyway boundaries	National - Flyway	+ / +++ *	Logistical $$ Financial $	++	+
Stable isotopes (7.3)	Flyway boundaries	Flyway boundaries	Flyway	++ / +++ *	Logistical $$ Financial $$	0	0
Power analyses, simulations, re-sampling methods (8.2)	Reliability flyway counts	Abundance	Flyway	+++	Logistical $ Financial $	+++	+++
Phone app, count protocol (8.3.1)	Reliability counts	Abundance	Flyway	++	Logistical $ Financial $$	+++	+++
Mark-recapture models (colour-marked birds) (8.2.1-3)	Estimating bird numbers	Abundance	Local - Flyway	+ / +++ *,**	Logistical $ - $$ Financial $ - $$	++	++
Drones for counting (8.1.2)	Reliability counts	Abundance	Local	++	Logistical $$ Financial $$	++	++
Counts using satellite imagery (8.1.4)	Reliability counts	Abundance	Local – Flyway	+	Logistical $$$ Financial $$$	+++	+
Mark-recapture models (unmarked individuals) (8.2.4)	Estimating bird numbers	Abundance	Local - Flyway	+++	Logistical $ Financial $$	++	+
Counts from planes (8.1.3)	Reliability counts	Abundance	Regional	++	Logistical $ Financial $$$	+	+
Species distribution models (8.2.5)	Geographical distribution in changing world	Abundance	Flyway	++	Logistical $ Financial $	+	0

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Integrated population models (9.3)	Understanding causes of population trends	Vital rates	Local – Flyway	+ / +++ *	Logistical $ Financial $	+++	+++
Mark-recapture analyses (colour-ringing projects) (9.2)	Estimating (variation in) survival	Vital rates	Local - Flyway	+ / +++ *	Logistical $ - $$ * Financial $ - $$	+++	+++
Estimating population-level reproductive output (9.1)	Understanding causes of population trends	Vital rates	Local - Flyway	+ / +++ **	Logistical $$$ Financial $	+++	+++
DNA methylation markers (9.1)	Ageing individual birds	Vital rates	Local - Flyway	++ *	Logistical $ Financial $$$	++	++
Estimating nest and chick survival (9.1)	Understanding causes of population trends	Vital rates	Local	++ / +++ **	Logistical $ Financial $	+	++
Phone app (8.3.1)	Reporting colour-ringed bird and/or juvenile percentages	Vital rates	Flyway	++	Logistical $ Financial $$	+	+
Individual bird tracking (10.1)	Nest success	Vital rates	Flyway	++	Logistical $ Financial $$	+	0
Satellite remote sensing of habitat quality (10.2)	Describing (changes in) habitat	Environment	Local - Flyway	+++	Logistical $ Financial $$	+++	+++
Individual bird tracking (10.1)	Habitat use, connectivity	Environment	Local - Flyway	++	Logistical $ Financial $$	++	+++
Phone app (8.3.1)	Standardised local reporting of environmental variables	Environment	Flyway	++	Logistical $ Financial $$	+	+
Drones for quantifying habitat quality	Improving knowledge of local habitat	Environment	Local	+++	Logistical $ Financial $$	+	+

* Depends on the availability of existing data or samples. Where these are available a fast implementation can be achieved as indicated by the second assessment. ** Depending on species and method.

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