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Review

The BirdLife Seabird Tracking Database: 20 years of collaboration for marine conservation

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ABSTRACT

The BirdLife Seabird Tracking Database (STDB) was established in 2004 to collate tracking data to address the incidental mortality of seabirds in fisheries and to contribute to identification of sites at sea relevant to establishment of Marine Protected Areas. After 20 years, the STDB has grown to hold ca. 39 million locations for 168 species from >450 breeding sites. The STDB has become a powerful tool to support marine conservation by facilitating the compilation of robust multi-species data to address broad-scale questions, made possible by continuous collaboration with the scientific community. The STDB has facilitated major marine conservation outcomes, including the designation of the first marine protected area to be identified solely using tracking data. Advocacy based on analyses demonstrating overlaps between seabirds and fisheries have led to the adoption of seabird-bycatch mitigation measures by Regional Fisheries Management Organizations. The STDB has also provided compelling evidence for migratory connectivity in the ocean, and been crucial in informing many policy instruments at scales from national (e.g. protection and management of important sites identified from tracking data), to regional (e.g. working with Regional Conventions), to global (e.g. the identification of Ecologically or Biologically Significant Marine Areas). This review presents an overview of 1) how the STDB started and gained traction, 2) its current status in terms of data coverage and gaps, 3) methodological developments, 4) conservation successes, 5) the opportunities and challenges experienced in managing this global database, and 6) research priorities and future directions for seabird tracking studies.

1. Introduction

The movement of wild animals has been tracked for millennia (Fraser et al., 2018). However, it is only in recent decades, with the advent of reliable technology to track individuals for long periods, that a golden era for studying animal movements has emerged (Hays et al., 2019; Kays et al., 2015). In the marine realm, fitting tracking devices to large fish, marine mammals, sea turtles and seabirds has been instrumental in providing unprecedented detail on species distributions, movement patterns, and the processes that drive their behaviour, as well as identifying overlap or interactions with threats (Bernard et al., 2021; Hussey et al., 2015; Pereira et al., 2023).

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Seabirds are one of the best-studied groups of marine megafauna, often regarded as sentinel species and ecological indicators for marine ecosystems (Dias et al., 2019; Hazen et al., 2019). However, they are also one of the most threatened groups of vertebrates in the world. Of the 365 seabird species, 30.4 % are listed as globally threatened and 10.7 % are listed as Near Threatened by the International Union for Conservation of Nature (IUCN), and 56 % of the species with a known population trend are in decline (BirdLife International, 2024; Dias et al., 2019). There are many threats to seabirds, but the main causes of population declines are invasive alien species, incidental mortality (bycatch) in fisheries, and climate change (Dias et al., 2019). Most seabirds (70 %), especially globally threatened species, face multiple threats throughout their life cycle (Dias et al., 2019).

Satellite tracking of seabirds was first achieved in the 1980s (Parmelee et al., 1985), but devices were larger at that time, so only albatrosses and large petrels could be tracked safely due to their size. By 2002, only about 20 species (5 % of seabird species) had been studied by approximately 30 scientists (BirdLife International, 2004). However, the continued miniaturization of devices and improvements in battery life and functionality have since expanded both the number of species and the life stages that can be tracked (Burger and Shaffer, 2008; Carneiro et al., 2020; Wakefield et al., 2009). By early 2019, over a thousand seabird tracking studies had been published in the scientific literature (Bernard et al., 2021). In particular, tracking data have proven invaluable in identifying frequently used marine areas and informing area-based conservation, including the design and implementation of marine protected areas (MPAs) and fishery regulation zones (Collins et al., 2021; Davies et al., 2021b; Trathan et al., 2018). Additionally, they have been instrumental in evaluating the effectiveness of these initiatives in protecting biodiversity (Handley et al., 2020).

BirdLife International (BirdLife) established the Seabird Tracking Database (www.seabirdtracking.org; STDB), previously known as 'Tracking Ocean Wanderers', in 2004. The aim was to create a platform for storing and standardising global data on seabird distributions obtained from tracking studies and analysing these data to address issues relating to the conservation and management of seabirds and their habitats. Initially, the main applications of such data were considered to be: a) investigating interactions between commercial fisheries and seabirds, particularly to address bycatch in longline fisheries, and b) contributing to newly-developing international initiatives seeking to identify, protect and manage critical habitats for seabirds at sea (marine Important Bird and Biodiversity Areas; IBAs). By 2014, the STDB had expanded to all seabirds to address many of the conservation issues, and by enhancing data sharing among users, the database had become one of the most influential marine conservation data collaborations in the world. This study presents an overview of 1) how the STDB started and gained traction, 2) its current status in terms of data coverage and gaps, 3) methodological developments, 4) conservation successes, 5) the opportunities and challenges experienced in managing this global database, and 6) research priorities and future directions for seabird tracking studies.

1.1. The development of the BirdLife Seabird Tracking Database

To create the STDB, BirdLife in 2002 invited all holders of seabird tracking data to collaborate in assembling a GIS database to review and analyse their data and to recommend how such a database might be operated and developed for users worldwide to address seabird conservation issues in the marine environment.

The resulting workshop (co-convened by John Croxall and Deon Nel, the Chair and Convenor, respectively, of BirdLife's Global Seabird Programme) was held at Gordon's Bay, South Africa in 2003. It was attended by almost all relevant data holders and reviewed and analysed ca. 90 % of extant tracking data for albatrosses and petrels (involving 16 species from 37 breeding sites). Based on the pioneering development and application of standardised and consistent analytical procedures for quantifying the spatial density-distributions of seabirds at sea, the workshop report (BirdLife International, 2004) demonstrated in detail the immense potential of such data and approaches for: a) quantifying the at-sea distribution of seabirds in relation to sex, age, life stage, season, year and breeding site; b) objectively identifying core areas/habitats in relation to criteria for establishing marine IBAs and candidate MPAs; c) quantifying overlap between seabird core ranges at sea and fishing effort, especially in relation to the risk of bycatch in longline fisheries, already known to be killing many thousands of albatrosses annually (Brothers, 1991; Croxall and Prince, 1990; Nel et al., 2002).

On this basis, workshop participants were unanimous that BirdLife should seek resources to maintain and develop the database for use in seabird research and conservation, subject to appropriate rules governing data access and use. A major additional achievement of the workshop was to develop the principles (and most of the details) of these rules, seeking to achieve a balance between protecting the interests of data holders and data owners and facilitating the use of these data to address key topics and issues in seabird research and marine conservation.

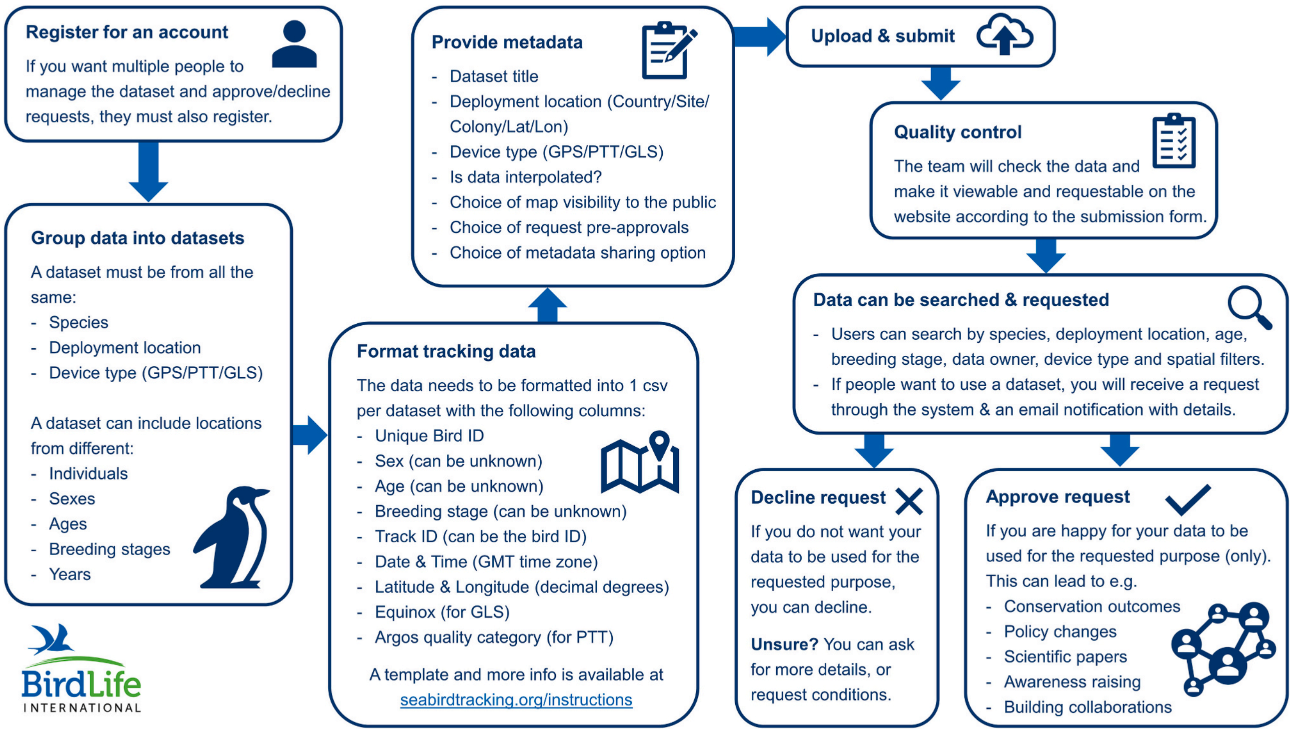
In 2010, the Global Procellariiform Tracking Database web portal was launched, allowing researchers to browse the database and submit data requests online. At the 8th International Penguin Conference (Bristol, UK), in 2013, a new project was launched with the aim of collating existing penguin tracking data into a centralised database to support MPA designation within the Scotia Sea (Southern Ocean), as well as the management framework for Antarctic krill fisheries overseen by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Strong support from the penguin research community led to the development of a relational tracking database for this species group. This relational database held 2085 tracks from nine species and 47 breeding sites, totalling over 1.2 million locations. In 2014, the Global Procellariiform Tracking Database was relaunched as the Seabird Tracking Database after a complete redesign to include the penguin data and to cover all seabird species. Some key improvements of the 2014 version included mapping and searching tools to visualise specific datasets of interest, options for data holders to upload and download datasets directly, and a data-request system to facilitate data exchange directly between users.

In 2023, a new version of the STDB was launched to keep up with online security requirements and to provide improved functionalities to facilitate collaboration and communication of the conservation and scientific outputs of the STDB. The website now features pages for news articles, case studies, resources, links to publications and summarised information by species group (aimed to ease data consultation by non-experts; e.g. conservation managers, decision-makers). Quality control ensures data quality standards and that all the required metadata are included, and the current system has an improved data submission workflow (Box 1).

2. Current status of the seabird tracking data

The STDB has grown into the largest collection of seabird tracking data in existence, holding ca. 39 million location records by March 2024, comprising over 54,000 tracks (Fig. 1). Most locations (ca. 33 million) and tracks are from GPS devices, reflecting both the miniaturization of these devices in the last decade and the increasing temporal resolution of many recent datasets (Fig. 1). The number of tracks in the STDB has increased strongly over time for GPS data and remained relatively stable for geolocator or global location system (GLS) data and platform terminal transmitter (PTT) data (Fig. 1). The median and mean (± SD) number of tracks per species is 84 and 321.3 ± 811.4, ranging from a single track for Henderson Petrel *Pterodroma atrata* and Grey-faced Petrel *Pterodroma gouldi* to 6716 for Scopoli's Shearwater *Calonectris diomedea*. There are over 1000 tracks for 10 other species in the STDB: Cory's Shearwater *Calonectris borealis* (6213 tracks), Northern Gannet *Morus bassanus* (3469), Black-browed Albatross *Thalassarche melanophris*

Box 1
The framework by which holders of seabird tracking data can upload and share their data using the Seabird Tracking Database at www.seabirdtracking.org.



(2596), Wandering Albatross *Diomedea exulans* (1969), Brown Booby *Sula leucogaster* (1555), Cape Verde Shearwater *Calonectris edwardsii* (1519), Audouin's Gull *Larus audouinii* (1330), European Shag *Gulosus aristotelis* (1324), Black-legged Kittiwake *Rissa tridactyla* (1130) and Red-billed Tropicbird *Phaethon aethereus* (1048).

Of the 365 extant seabird species, the STDB has data for 168 species (46 %) from 14 families, tracked from >450 breeding sites across 55 countries or jurisdictions. The proportion of species represented varies markedly across families. Diomedeidae (albatrosses, $n = 22$) and Phaethontidae (tropicbirds, $n = 3$) are the only two families with 100 % representation (Fig. 2). Gaps in taxonomic coverage remain for various groups, particularly for loons (divers), grebes, and phalaropes, with not a single species represented in the STDB (Fig. 2). Tracking data for at least 68 species are available in the peer-reviewed literature but have not been uploaded to the STDB, including 15 species of gulls, nine species of auks, and nine species of seaducks (Table S1).

Data for the two main phases of the annual cycle (breeding vs. non-breeding), when the distribution of birds can be very different, are available for most species (75.0 %) in the STDB, with data available only from the breeding season for 20.8 %, and only for the non-breeding season or unknown phase for 4.2 % of the species in the database (Table S1). Data for juveniles and immatures are only available for 18.5 % of the species in the database (Table S1). Additionally, the proportion of species with data in the STDB is currently higher for pelagic species (142 of 214 pelagic species; 66.4 %) than coastal species (26 of 151 coastal species; 17.2 %), according to the categorisation of Dias et al. (2019) (Table S1).

The number of datasets uploaded to the STDB and the number of contributors have increased constantly, and most contributors are from institutions in the UK, USA, Australia, New Zealand and France (Fig. 3). Most STDB datasets were collected in breeding sites in the North Atlantic (40.8 %), followed by the Antarctic (15.3 %), South Atlantic (15.1 %), South Pacific (12.7 %), Indian (6.7 %), Arctic (5.4 %) and North Pacific (4.0 %) oceans (Fig. 4). The spatial distribution of the ca. 39 million tracked locations and species are broadly similar, with the proportions in each ocean as follows: North Atlantic (53.9 %), South Atlantic (22.0 %), South Pacific (7.4 %), Indian (7.0 %), Antarctic (6.7 %), North Pacific (2.2 %) and Arctic (0.8 %) oceans (Fig. 4). The number of tracked species per region does not correlate spatially with seabird species richness, with the greatest proportion of species tracked in the Atlantic and the lowest proportion in the Pacific. For example, New Zealand is a hotspot for seabird tracking, but the region still has many species for which no tracking data exist (Fig. 4). Despite substantial tracking of seabird species in the North Pacific (e.g. Block et al., 2011; Kirk et al., 2008; Lamb et al., 2019; Lok et al., 2012; Petersen and Douglas, 2004; Petersen, 2009; Petersen et al., 2006), few of these data have been contributed to the STDB. This at least partially explains the mismatch in some regions between tracking data in the STDB and species richness from BirdLife range maps (Fig. 4). Gaps are also clear in some coastal areas, reflecting the lower coverage of coastal species (Fig. 4).

Of the species in the STDB, 35.1 % are globally threatened, of which 76.3 % are affected by ongoing marine threats (Table S1). As 30.4 % of all seabird species are globally threatened, the STDB holds a slightly greater proportion of tracking data from threatened species, likely due to tracking effort being directed at species of conservation concern. Of the 59 globally threatened species with tracking data available in the STDB, 48 have data for both breeding and non-breeding seasons, eight species have data only for the breeding season, and three species have

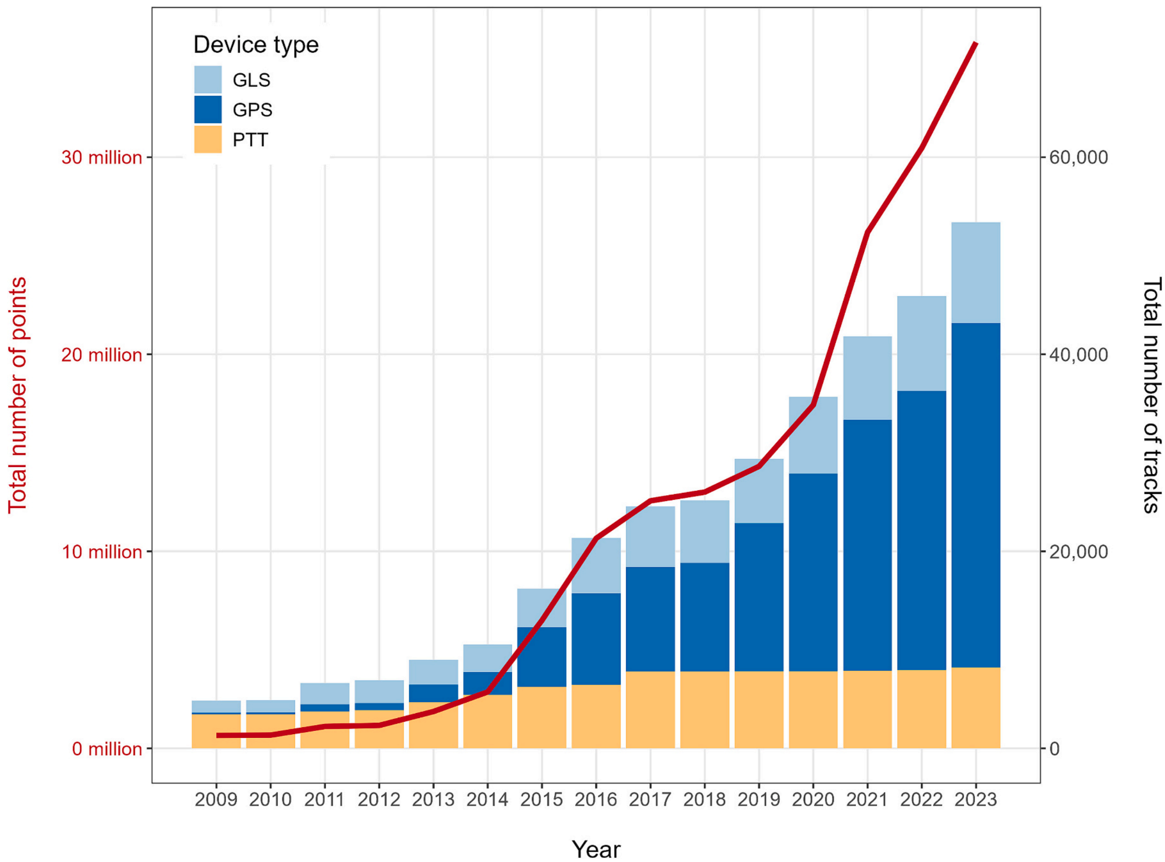


Fig. 1. Trends in the amount of tracking data held in the BirdLife Seabird Tracking Database (STDB) over time. Bar chart shows number of tracks per device: GLS = global location sensor; GPS = global positioning system; PTT = platform terminal transmitter. Red line shows cumulative number of data points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

data only for the non-breeding season or unknown season (Table S1). Nine of these 11 species with a single season of data are affected by ongoing marine threats (Ainley's Storm-petrel *Hydrobates cheimomnestes*, Buller's Shearwater *Ardenna bulleri*, Cape Gannet *Morus capensis*, Erect-crested Penguin *Eudyptes sclateri*, Hutton's Shearwater *Puffinus huttoni*, Snares Penguin *Eudyptes robustus*, Southern Royal Albatross *Diomedea epomophora*, Townsend's Storm-petrel *Hydrobates socorroensis*, Waved Albatross *Phoebastria irrorata*), including fishing activities (bycatch and overfishing, $n = 7$), climate change and severe weather ($n = 4$), and pollution ($n = 3$). No additional data for the season lacking data in the STDB for the species listed above were found in the peer-reviewed literature (and for Monteiro's Storm-petrel *Hydrobates monteiroi* and Henderson Petrel, which are currently not known to be affected by ongoing marine threats).

Tracking data from another 18 threatened species impacted by ongoing marine threats are available in the peer-reviewed literature but not included in the STDB, including cormorants (Flightless Cormorant *Nannopterum harrisi*, Cape Cormorant *Phalacrocorax capensis*, Bank Cormorant *Phalacrocorax neglectus*, Socotra Cormorant *Phalacrocorax nigrogularis*), penguins (Galapagos Penguin *Spheniscus mendiculus*, Yellow-eyed Penguin *Megadyptes antipodes*), shearwaters (Pink-footed Shearwater *Ardenna creatopus*, Newell's Shearwater *Puffinus newelli*), sea ducks (Long-tailed Duck *Clangula hyemalis*, Steller's Eider *Polysticta stelleri*), gulls (Red-legged Kittiwake *Rissa brevirostris*, Saunders's Gull *Saundersilarus saundersi*), auks (Marbled Murrelet *Brachyramphus marmoratus*, Japanese Murrelet *Synthliboramphus wumizusume*), and one species of petrel (Hawaiian Petrel *Pterodroma sandwichensis*), tern (Aleutian Tern *Onychoprion aleuticus*), frigatebird (Christmas Island Frigatebird *Fregata andrewsi*), and booby (Abbott's Booby *Papasula abbotti*) (Table S1).

As far as we are aware and according to our search criteria (see Material and methods), there are no tracking data published or in the STDB until September 2023 for 14 threatened species affected by ongoing marine threats. These species are mostly distributed in the Pacific (Ashy Storm-petrel *Hydrobates homochroa*, Chatham Islands Shag *Leucocarbo onslowi*, Chinese Crested Tern *Thalasseus bernsteini*, Craveri's Murrelet *Synthliboramphus craveri*, Fairy Tern *Sternula nereis* [also in the Indian Ocean], Fiji Petrel *Pseudobulweria macgillivrayi*, Guadalupe Murrelet *Synthliboramphus hypoleucus*, Lava Gull *Larus fuliginosus*, Rough-faced Shag *Leucocarbo carunculatus*, Scripps's Murrelet *Synthliboramphus scrippsi*, Stewart Island Shag *Leucocarbo chalconotus*), with three elsewhere (Horned Grebe *Podiceps auritus*, Velvet Scoter *Melanitta fusca*, and White-headed Steamerduck *Tachyeres leucocephalus*). Each of these species faces on average more than one marine threat (median = 2, range = 1–4 threats), including bycatch (10 species), pollution (8 species), climate change and severe weather (7 species), human intrusions and disturbance (2 species), energy production and mining (2 species), and light pollution (2 species).

3. Research to address seabird conservation: from local to global

Tracking data plays an increasingly important role in conservation by providing information on distribution and connectivity, which are critical for informing government policy and management actions (Davies et al., 2021a; Hays et al., 2019). However, scaling up from individual-level movement data to infer population-level spatial patterns is challenging, particularly for wide-ranging pelagic species, which often show high individual variability in space use (Carneiro et al., 2017; Phillips et al., 2017). To address this in practical conservation terms, the

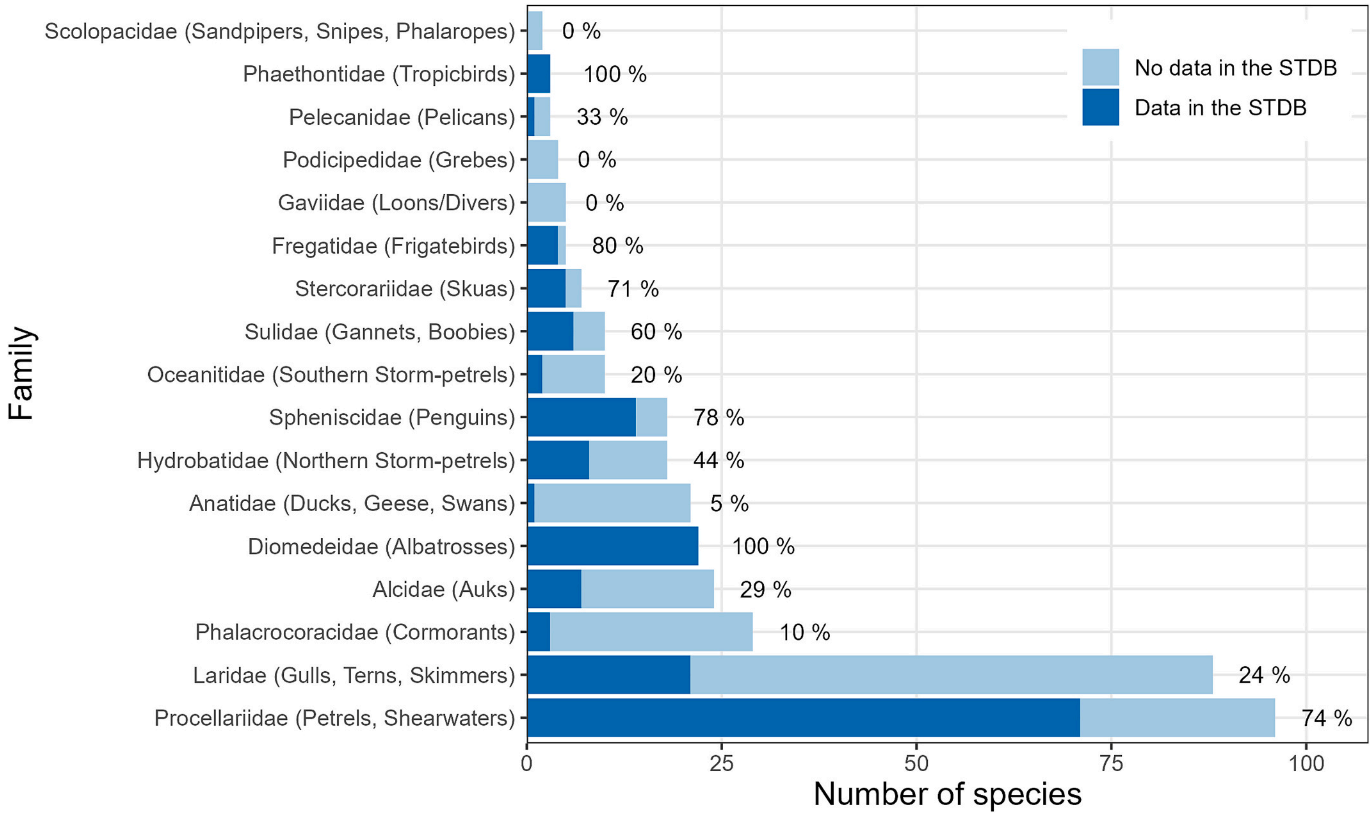


Fig. 2. Total number of seabird species per family, and the number for which tracking data were available in the BirdLife Seabird Tracking Database (STDB) in March 2024. The percentage indicates the coverage of species per family with data in the STDB. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

STDB enabled collaborations which facilitated analyses at several spatial scales, depending on the geographic and temporal scope of the threat (Beal et al., 2021b; Carneiro et al., 2020; Clark et al., 2023; Davies et al., 2021b; Lascelles et al., 2016). Management options to address the threats to seabirds across scales can range from local scale actions, including the protection of breeding colonies, marine areas around colonies, and areas further offshore where substantial seabird concentrations occur, to large-scale or global actions that regulate detrimental human activities.

To fulfil the urgent need for a consistent, comparable and repeatable approach to identify at-sea sites of global conservation importance for seabirds, several national and international workshops were held between 2004 and 2010. These workshops were pioneered by a collaborative effort between BirdLife Partners in Spain (Sociedad Española de Ornitología, SEO) and Portugal (Sociedade Portuguesa para o Estudo das Aves, SPEA) seeking to identify marine IBAs within Iberian waters (Arcos et al., 2009; Lascelles et al., 2012; Ramírez et al., 2008) in recognition that the European Union's Birds and Habitats Directives applied to the Exclusive Economic Zones of Member States (Donald et al., 2019). Global standards for collecting, analysing and interpreting data from a range of sources were developed to identify marine IBAs using the pre-established criteria, and published as a toolkit (BirdLife International, 2010). A workflow to delineate marine IBA boundaries from a variety of tracking devices was subsequently described in Lascelles et al. (2016). The method has since been revisited and tested across other taxonomic groups (Beal et al., 2021b). An R package (track2KBA; Beal et al., 2021b) and an open-access online toolkit (Marine Megafauna Conservation Toolkit; https://www.seabirdtracking.org/case-studies/conservation-toolkit/) were later developed to update these methods and make them more accessible. Recent work has shown that this method is robust in identifying the key areas used by seabirds from the same colony in multiple years, even if based on data collected in a single year, provided there is a sufficient sample of individual birds (Beal et al., 2023).

Another method for the identification of marine IBAs that was facilitated by the availability of tracking data is the foraging radius approach (Osieck, 2004). This method was first advocated by BirdLife in 2009 (BirdLife International, 2010) and then by Grecian et al. (2012) and Thaxter et al. (2012). It involves the delineation of a seaward extension boundary around a colony of breeding seabirds. This method is generally used when tracking data is not available for the colony of interest, and is particularly useful for species that remain relatively close to the colony (Oppel et al., 2018). Tracking data for the same species at a different location facilitates the identification of the most appropriate buffer distance from a colony. This method has since been refined using, for example, additional environmental covariates (Soanes et al., 2016a), or radius-based density-decay functions (Critchley et al., 2018; Handley et al., 2021, 2023). Distance to the breeding colony often emerges as the most important predictor of seabird distribution even in complex habitat models, highlighting its predictive power (Wakefield et al., 2017). Furthermore, areas in the vicinity of the colonies tend to be used intensively as rafting areas even by wide-ranging species such as albatrosses and petrels for activities such as plumage maintenance or for a social function (Kowalska O'Neil et al., 2023).

At larger scales, the STDB has been used to identify areas of overlap between seabirds and marine threats. Collaboration enabled through the STDB helped improve on previous approaches to estimating seabird densities at sea by integrating tracking data with demographic and phenological information to estimate density distributions of all major life-history stages (Carneiro et al., 2020). This framework was demonstrated with 22 seabird species of global conservation concern, using overlap with fisheries to show how neglecting particular life-history stages can lead to incomplete maps of risk. R scripts and a Shiny app are available to facilitate future applications (https://github.com/anac

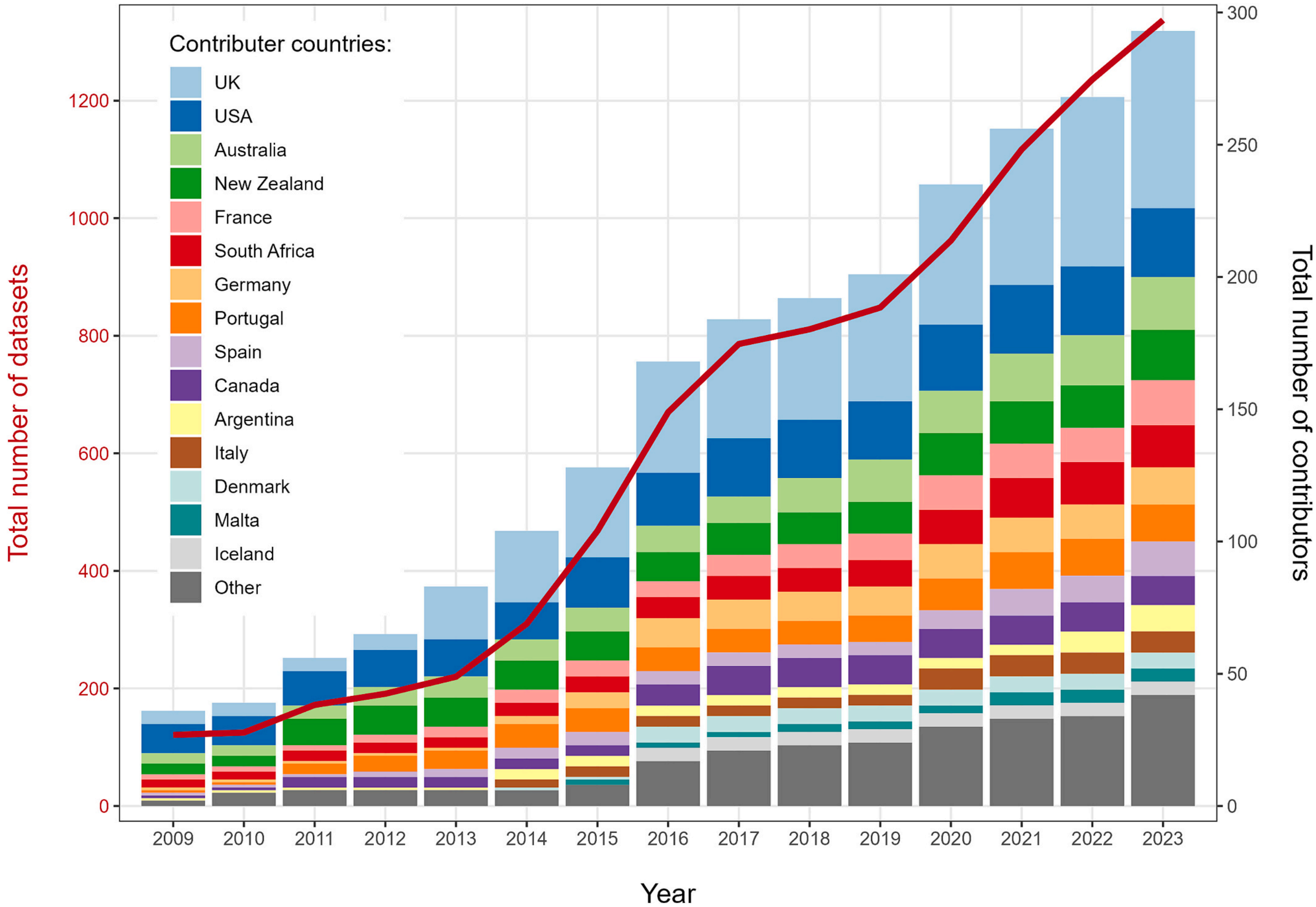


Fig. 3. Trends in the number of datasets held in the BirdLife Seabird Tracking Database (STDB) over time (red line) and the number of contributors by country (bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

arneiro/DensityMaps). This framework has since been adapted for populations lacking phenological data, using distance from the colony to categorise months into breeding or non-breeding seasons, and applied to map risk to marine plastic pollution (Clark et al., 2023).

A global analysis of almost all tracking data available for albatrosses and large petrel species revealed the importance of each national jurisdiction and the high seas, and quantified the connectivity between national breeding populations of these seabirds and the waters they visited (Beal et al., 2021a). The connections can be explored through an interactive Shiny app (https://birdlifeseabirds.shinyapps.io/seabird-connections/). The STDB has also facilitated the identification of marine flyways (Morten et al., *in review*). Flyways are major routes followed repeatedly and consistently by birds migrating between their breeding and non-breeding areas (Boere and Stroud, 2006; Kranstauber et al., 2015; Shamoun-Baranes et al., 2017). Flyways can forge international collaboration and promote conservation efforts by linking sites used by birds during different parts of their lifecycles. Until recently, tracking data have been used to identify the main migratory routes followed by individual seabird species (e.g. Egevang et al., 2010; Oppel et al., 2008; Shaffer et al., 2006; Stenhouse et al., 2012), but comprehensive, multi-species migratory routes were yet to be identified. A novel method made possible by the wealth of seabird tracking data involved extracting the portion of the track corresponding to the migration period by clustering individuals based on the shape of the migratory route (irrespective of species or timing of migration), and estimating line densities for each cluster, with higher densities representing flyways.

4. A tool for scientific collaboration

The success of the STDB for marine conservation would not be possible without the contribution of hundreds of researchers. Most of the data currently held in the STBD were initially collected for scientific projects targeting specific populations and breeding colonies, often to address ecological or behavioural questions (Clark et al., 2021; Lane et al., 2019). The compilation and standardization of the data into a single database, alongside the development of the methodological frameworks outlined above, facilitated the compilation of multi-species and multi-colony datasets from hundreds of researchers, thus enabling new questions to be asked, including at ocean basin or global scales.

The STDB has played a key role in boosting scientific collaborations between seabird researchers. Data-sharing initiatives that were promoted via the data request tool, or otherwise facilitated by the STDB have resulted in at least 92 scientific papers in the peer-reviewed literature (Table S2). Many of these studies have a clear conservation focus, such as addressing seabird bycatch, understanding the consequences of the expansion of offshore wind farms or contributing to marine spatial planning (Kot et al., 2023; Krüger et al., 2018; Lemos et al., 2023; Trevail et al., 2023). The STDB has also facilitated more fundamental research into ecology (e.g. Nourani et al., 2023), multi-species comparisons (e.g. Lambert and Fort, 2022; Oppel et al., 2018), testing of specific hypotheses (e.g. Ashmole's halo; Weber et al., 2021; the impacts of marine heatwaves; Welch et al., 2023), or global reviews of specific topics (e.g. the effect of wind on the movement of seabirds; e.g. Thorne et al., 2023).

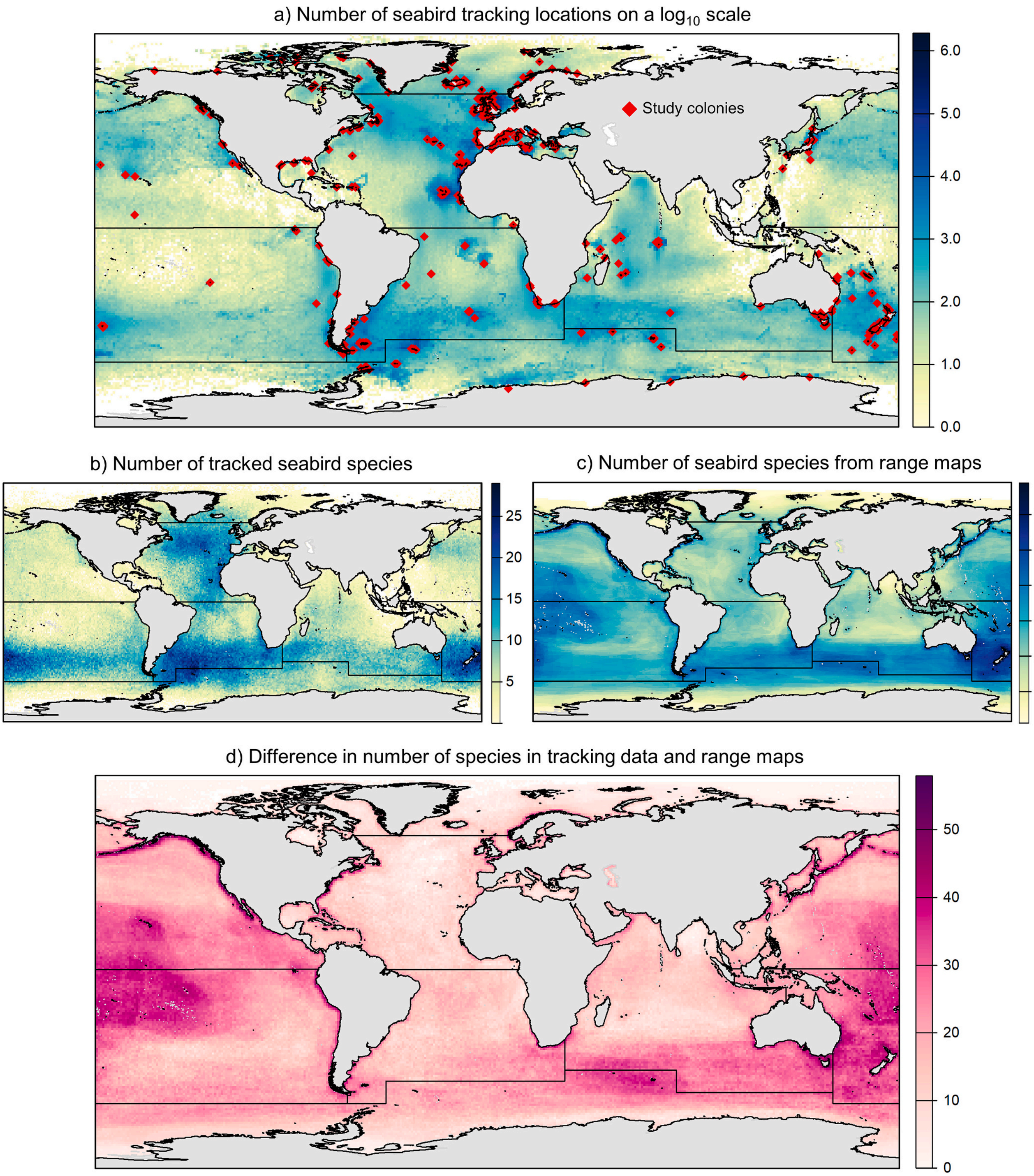


Fig. 4. Spatial variation in tracking intensity across ocean basins in 1 × 1° grid cell. (a) The number of seabird tracking locations from all species in the BirdLife Seabird Tracking Database (STDB). (b) The number of seabird species in the STDB with at least one location in each grid cell. (c) The number of all extant seabird species obtained from BirdLife range maps. (d) The difference between maps (c) and (b), (i.e., gaps in terms of the number of species covered). Note that gaps may occur because of genuine gaps in tracking effort or because existing tracking data have not been uploaded to the STDB.

5. Conservation outcomes of the seabird tracking database

5.1. Area-based conservation

The compilation and analysis of seabird tracking data have led to substantial conservation gains through identifying marine sites that meet the criteria for an IBA, contributing a marine element to the largest global network of sites of significance for biodiversity (Donald et al., 2019). This marine site network has been used in a range of decision-making processes to promote marine conservation (Waliczky et al., 2019).

Within Europe, IBAs are recognised as a scientific reference list for the designation of Special Protected Areas (SPAs) under the European Union Birds Directive, which form part of the European Natura 2000 network. More than 63 % of marine IBAs are now covered by SPAs in Europe, with >95 % of the area of marine IBAs covered by SPAs in Estonia, Malta, Romania and Spain – countries that all have well-developed marine IBA networks (Mitchell et al., 2022). The analysis of tracking data for three species of seabirds (Scopoli's Shearwater, Yelkouan Shearwater *Puffinus yelkouan*, and European Storm-petrel *Hydrobates pelagicus*) led to the identification of eight marine IBAs for breeding seabirds in Malta, and subsequently, the first marine SPA for Malta (Mitchell et al., 2022).

The STDB has also directly contributed to the creation of marine protected areas. A large compilation of tracking data (>2000 tracks for 21 seabird species, shared by 79 contributors) led to the identification of a site now known as the North Atlantic Current and Evlanov Seabasin marine protected area (NACES MPA; Davies et al., 2021b). This analysis directly contributed to a regional process to address a gap for seabirds within the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) high seas MPA network (Davies et al., 2021a).

5.2. Marine spatial planning

Seabird tracking data have also supported spatial prioritisation analyses for marine spatial planning processes. In the Falkland Islands/Islas Malvinas, tracking data for 33 seabird species (and three pinnipeds) were used to identify core areas and combined in composite maps of intensity of use and species diversity that were used in a marine spatial planning process to identify areas: 1) for protection (e.g. areas with high biodiversity indices); 2) where particular activities needed to be managed (e.g. shipping, oil extraction), and 3) that required more detailed assessments if new developments are proposed (e.g. Environmental Impact Assessments; Augé et al., 2018). Similar approaches were used to support marine spatial planning in Malta, and French and UK Overseas Territories (Dias et al., 2017; Heerah et al., 2019; Requena et al., 2020; Soanes et al., 2016b).

5.3. Mitigating threats to seabirds

Regional analyses of seabird tracking data have been used repeatedly to demonstrate to Regional Fisheries Management Organizations (RFMOs) and national fisheries bodies that foraging areas of threatened species or populations are within their area of competence, even if the breeding colonies are outside these areas. This has been integral in addressing bycatch of seabirds, particularly in areas beyond national jurisdiction, because RFMOs were made aware of their potential contribution to seabird declines. Many of the tracking syntheses based on the STDB were presented as papers submitted to working groups. A few have been published in peer-reviewed scientific journals, often within the wider framework of an Ecological Risk Assessment (ERA) (Reid et al., 2023; Tuck et al., 2011; Waugh et al., 2012). These aim to identify the species or populations that are most at risk, and collate data on at-sea distributions to quantify overlap with fishing effort, often as part of a productivity-susceptibility analysis (Small et al., 2013; Tuck et al., 2011). Analyses showing high seabird bycatch risk at certain latitudes or seasons, combined with advocacy, have led to regulations requiring a minimum level of bycatch mitigation measures by vessels in all five tuna RFMOs in areas of high seabird abundance, including south of 25°S in the Atlantic and Indian Oceans, and south of 30°S in the Pacific Ocean (ICCAT, 2011; IOTC, 2012; WCPFC, 2018). The use of tracking data also applies to other mechanisms for evaluating impacts of fisheries such as the Marine Stewardship Council framework for Endangered, Threatened or Protected (ETP) species, which incorporates spatial overlap into the susceptibility attribute (Good et al., 2024). Maps of at-sea distributions during the breeding and non-breeding seasons based on data in the STDB are also incorporated into the Species Assessments (https://www.acap.aq/resources/acap-species) of the Agreement on the Conservation of Albatrosses and Petrels (ACAP), which provide key information relevant for conservation and are used in various fora to advocate for improved management of threats to the 31 listed species (Phillips et al., 2016). Fisheries overlap is also included in the process by which ACAP identifies priority fisheries that represent the potentially greatest threats to the listed species.

5.4. International policy processes

The STDB and the network of marine IBAs have also contributed to regional workshops of the Convention on Biological Diversity (CBD) to identify Ecologically or Biologically Significant Marine Areas (EBSAs). EBSAs are intended to contribute to the protection and sustainable use of marine biodiversity by describing areas of particular significance that are valued by stakeholders (Johnson et al., 2018). IBA data were fed into regional workshops from 2012 to 2019, which resulted in the inclusion of over 600 marine IBAs within the 338 EBSA boundaries. Some EBSA descriptions are entirely based on the underlying seabird data, such as the seabird foraging zone in the Southern Labrador Sea and the Central Indian Ocean Basin (CBD, 2021). The recognition of IBAs and seabird tracking data within the EBSA process has raised the profile of using seabird data for area-based decision-making at a global level. Seabird tracking data and the marine flyways have also demonstrated the collective responsibility of nations and highlighted the need for collaborative conservation action to the Convention on Migratory Species (CMS), which has led to the creation of a Seabird Working Group under this Agreement.

6. Challenges and recommendations

A key challenge for the STDB is the potential overlap with other databases, given the efforts required to contribute data to more than one repository. Other global databases, such as Movebank (Kays et al., 2022), accept data submission of tracking data for all animal taxa, and have therefore more flexible data submission protocols. Movebank also has an environmental data system that annotates tracking data with environmental parameters from global remote sensing and weather reanalysis products (Dodge et al., 2013). There are also multi-taxa databases with regional audiences or focuses, such as ZoaTrack in Australia (Dwyer et al., 2015), the Biologging intelligent Platform (BiP) in Japan (Sato et al., 2024), and SEATRACK (Strøm et al., 2021), which contains standardised GLS data for several seabird species in the North Atlantic. For conservation, a crucial advantage of the STDB is its standardised data format with predefined categories regularly used in seabird-specific analysis, such as individual and track identification, age, sex, breeding stage, and deployment location. This standardization enables datasets to be easily combined for analysis, and facilitates links to other data sources such as population size of focal colonies. Code-based toolkits are available to process raw tracking data files into the standardised format required for uploading data to the STDB (Langley et al., 2024; Marine Megafauna Conservation Toolkit). The STDB metadata categories provide information and context for translating data into derived products that facilitate seabird conservation, and were informed by ecological knowledge to account for possible sources of data biases or pseudo-replication. In addition, the STDB has a sophisticated nested filter and spatial search system (Box 1), allowing users to easily find tracking data that match their needs – a feature that is not available in other data repositories. The STDB can also be used as a free online data repository to comply with many journal or funding requirements of public data availability instead of using generic data-sharing platforms that have no format specifications and are not as easily discoverable.

Interoperability between databases is a long-term goal; however, such interoperability presents challenges in terms of data flows and data protection. A major challenge is to avoid duplication and redundancy of separate databases and the interoperability and complementarity of datasets contained in different repositories that can serve a similar purpose for different spatial or taxonomic groups. A global registry for animal tracking devices could facilitate interoperable databases minimizing duplication (Rutz, 2022). Until interoperability is achieved, we highly recommend that data owners upload their seabird tracking data to the STDB even if they are already included in other repositories to facilitate scientific analyses that inform seabird conservation and broader environmental policy.

As tracking studies proliferate, it becomes challenging to increase awareness of the STDB with new researchers and keep data owners engaged in uploading datasets. BirdLife has earned the trust and engagement of data owners through consistent communication, transparent data policies, and robust data protection measures, ensuring that contributing data to the STDB is both secure and beneficial. However, earning and maintaining this trust requires continuous effort. By demonstrating tangible benefits, such as fostering collaborations that lead to novel research, highlighting the conservation and policy impacts of data sharing, and putting the data owners at the forefront of the outputs, ongoing engagement from data owners can be further encouraged. There is also a need for increased data storage capacity and more advanced search and filter capabilities to ensure datasets remain discoverable as the volume of tracking data expands. We recommend that users provide an alternative email address to reduce the risk that data owners do not receive requests when the primary email expires, and that datasets are submitted with multiple data owners, when applicable. Data owners are also encouraged to periodically update their contact details and the accessibility options of older datasets over time, such as making them generically available for conservation purposes.

Additionally, the implementation of the European Union's General Data Protection Regulation (GDPR) in May 2018 required new data policies (Gourd, 2021) and the threat of cybercrime has increased, especially since the COVID-19 pandemic (Buil-Gil et al., 2021). These factors led to the complete redevelopment of the STDB in 2022–2023 to ensure a secure and lasting service. Maintaining a database without long-term funding is challenging (Urbano et al., 2021), but conservation research based on long-term data collection is essential given it can provide insights that short-term project funding cannot (Birkhead, 2014).

7. Main priorities and future perspectives

The STDB has provided invaluable insights into the movements and behaviours of seabirds, identified critical habitats, and informed policy and management actions that benefit seabirds. Collaboration and data sharing remain fundamental to the success of the STDB. Looking ahead, several key areas will be crucial for maintaining and enhancing its impact. A primary goal is to continue expanding the database to include data from more species and life history stages, especially for threatened species and those affected by marine threats that can be mitigated with available solutions. Additionally, increasing efforts to cover less represented regions (e.g. Pacific archipelagos and coasts) will ensure a more comprehensive global perspective on seabird movements and habitat use, which will be crucial to protect important areas for biodiversity.

Global analysis of tracking data facilitated by the STDB will continue to provide important information on distribution and connectivity, which is critical for informing government policy and management actions. The adoption of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) presents an opportunity for translating the knowledge gained from tracking data into area-based conservation. This includes the design and implementation of marine protected areas and other conservation measures for important habitats in the high seas. The ever-increasing spatial and temporal resolutions of seabird and threat data also means that analyses based on the STDB will continue to be useful for monitoring sites to ensure that agreed measures are fully implemented and effective, and to identify regions and time of year (and fishing fleets, in the case of bycatch) towards which engagement, monitoring and management efforts should be directed. The combination of tracking data with other sensors (e.g. loggers which detect vessel radar and cameras) will pave the way to fill critical knowledge gaps for global conservation by, for example, revealing the fundamental drivers of seabird-fisheries interactions, identifying illegal, unregulated and unreported fishing vessels, which will be crucial in setting management priorities (Carneiro et al., 2022; Weimerskirch et al., 2020).

The integration of tracking data in conservation policy processes can be enhanced by strengthening collaboration between the STDB and other tools that facilitate data sharing, processing and analysis (e.g. Movebank), are targeted at bridging the science-to-policy gap (e.g. the Migratory Connectivity in the Ocean initiative; Kot et al., 2023), or help monitor human activities (e.g. Global Fishing Watch; Kroodsma et al., 2018). For that end, improving the interoperability between databases is a priority.

Finally, the STDB can help address emerging threats to seabirds and marine biodiversity, in particular the expansion of offshore windfarms (Croll et al., 2022), increasing incidence and spread of avian diseases (Boulinier, 2023), and overexploitation of mesopelagic resources (Herbert-Read et al., 2022). With a concerted collaborative effort, the STDB and the broader seabird research and conservation community can be at the forefront of solving major challenges in marine conservation.

8. Materials and methods

8.1. *Data considerations and analyses of the current status of the BirdLife Seabird Tracking Database*

We followed the taxonomy used by BirdLife International (BirdLife International, 2024) and considered seabirds to be those species for which a large proportion of the population rely on the marine environment for at least part of the year (Croxall et al., 2012). We classified each seabird species into pelagic and coastal based on Croxall et al. (2012) and Dias et al. (2019): pelagic seabirds are those that primarily use marine deep water (typically >200 m in depth), or neritic, continental shelf water; and coastal seabirds are those that primarily use inshore waters (typically <8 km from the shoreline). Timing and source of each threat were identified based on Dias et al. (2019). We only considered threats that were classified as ongoing and from marine sources.

8.2. *Literature search of publications with seabird tracking data*

We updated the database available from Bernard et al. (2021) to include peer-reviewed manuscripts published between May 2019 and September 2023. Following the same methodology, for each extant seabird species, we searched the Web of Science using as search terms: "Latin name or English name" and "GLS or GPS or PTT or VHF or ARGOS or biologging or track*". To calibrate the analysis with Bernard et al. (2021) and ensure data accuracy, we included an overlap period from January 2019 to mid-May 2019. For each publication, we extracted information on the species, study site, year of deployment, number of individuals (or tracks), device type, season (breeding, non-breeding, or both) and age (adult, juvenile, or immature). Only studies in which tracking locations were illustrated in figures were retained in the database. In addition, for all threatened species, we verified if the data were deposited in the STDB. We filtered the database to include only studies using GPS, PTT and GLS devices.

8.3. Literature search of publications facilitated by the BirdLife Seabird Tracking Database

In order to identify the peer-reviewed publications that were facilitated through collaborations using the STDB, we used three different methods. First, we searched within all fields the search terms "seabirdtracking.org or Tracking Ocean Wanderers or Seabird Tracking Database" using both Scopus and Web of Science databases. We also contacted all STDB users requesting information on papers published/co-authored that originated from requests (or searchers) made using the database (either as a requester or data owner). Finally, we checked all individual data requests sent via the STDB to see if the author of the request had papers available in Google Scholar that matched the title and abstract content of the data request.

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CRediT authorship contribution statement

Ana P.B. Carneiro: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Maria P. Dias:** Writing – review & editing, Writing – original draft, Conceptualization. **Bethany L. Clark:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Elizabeth J. Pearmain:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Jonathan Handley:** Writing – review & editing, Conceptualization. **Amy R. Hodgson:** Writing – review & editing, Formal analysis, Data curation. **John P. Croxall:** Writing – review & editing, Writing – original draft. **Richard A. Phillips:** Writing – review & editing, Writing – original draft. **Steffen Oppel:** Writing – review & editing, Writing – original draft. **Joanne M. Morten:** Writing – review & editing. **Ben Lascelles:** Writing – review & editing. **Cleo Cunningham:** Writing – review & editing. **Frances E. Taylor:** Writing – review & editing. **Mark G.R. Miller:** Writing – review & editing. **Philip R. Taylor:** Writing – review & editing. **Alice Bernard:** Writing – review & editing, Data curation. **David Grémillet:** Writing – review & editing. **Tammy E. Davies:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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