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Synthesizing connectivity information from migratory marine species for area-based management

Connie Y. Kot [a,*], Sarah E. DeLand [a], Autumn-Lynn Harrison [b,c], Amalia Alberini [a], Hannah Blondin [a], Maggie Chory [a], Jesse Cleary [d], Corrie Curtice [a], Benjamin Donnelly [d], Ei Fujioka [d], Alejandro Herrero Palacio [a], Eleanor I. Heywood [a], Elizabeth Mason [a], Dina Nisthar [e], Guillermo Ortuño Crespo [a], Sarah Poulin [a], Meredith Whitten [a], Colyer Woolston [a], Daniel C. Dunn [a,e], Patrick N. Halpin [d]

[a] *Duke University, Nicholas School of the Environment, Marine Geospatial Ecology Lab, 135 Duke Marine Lab Road, Beaufort, NC 28516, USA*
[b] *Smithsonian's National Zoo and Conservation Biology Institute, Migratory Bird Center, 3001 Connecticut Avenue, NW, Washington, DC 20008, USA*
[c] *Duke University, Nicholas School of the Environment, 9 Circuit Road, Durham, NC 27708, USA*
[d] *Duke University, Nicholas School of the Environment, Marine Geospatial Ecology Lab, 9 Circuit Road, Durham, NC 27708, USA*
[e] *The University of Queensland, School of Earth & Environmental Sciences, Steele Building, St. Lucia 4067, Australia*

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ABSTRACT

Understanding the areas used by migratory marine animals and their movements is critical in supporting management decisions that target their conservation. This is especially important for long-lived species with large geographic extents and are more vulnerable to multiple threats. We conducted a literature review on data collected for 173 marine mammal, marine fish, sea turtle, and seabird species and determined that tracking animal movements with telemetry methods was the most effective tool for demonstrating ecological connectivity. From the references included for review, we found more references for sea turtles than other taxa, and more information was collected for all four taxa in the northern hemisphere. In addition, 30 % of references presented methods to process the raw telemetry tracks, only 11 % of references mentioned a repository for archiving data, and there was no significant trend in the number of references and current conservation level. For four case study species (Atlantic bluefin tuna, humpback whale, loggerhead sea turtle, and wandering albatross), we found more information published for adults and on the descriptions of sites focused on feeding and breeding activities, while sites used for migration and connectivity among areas used for migration were not well represented. Although connectivity data were published for most of the migratory marine species we reviewed, several knowledge gaps existed and there were limitations of the data presented within publications for direct applications to area-based management. We provided recommendations to address research gaps and guidance to improve the integration of connectivity data into area-based management decisions.

1. Introduction

Rapid increases in anthropogenic use of the open ocean and deep sea in areas beyond national jurisdiction (ABNJ), fueled by rising demands on marine resources, have occurred on a global scale (Merrie et al., 2014; Jouffray et al., 2020). Increased use of ABNJ has been met with growing concern over the fragmented sectoral and regional management structures therein (Ban et al., 2014) and lagging use of area-based management tools relative to terrestrial or coastal areas (Ortuño Crespo et al., 2020). International discussions regarding the need for more holistic and coordinated governance of marine biodiversity in ABNJ has culminated in negotiations over a new treaty for biodiversity beyond national jurisdictions (BBNJ; United Nations, 2018).

Marine biodiversity, including in ABNJ, transcends jurisdictional boundaries (Roberson et al., 2021). For example, the migration patterns and movements of many species cross numerous jurisdictions, with much of their life histories spent in the 47 % of the planet that lies in ABNJ (Harrison et al., 2018). The connectivity inferred by species

* Corresponding author at: Duke University, Nicholas School of the Environment, Marine Geospatial Ecology Lab, 135 Duke Marine Lab Road, Beaufort, NC 28516, USA.

E-mail address: connie.kot@duke.edu (C.Y. Kot).

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distributions and movements requires management and conservation measures to be coherent across jurisdictions. Thus, coordination between the governance of marine species in ABNJ and within national jurisdictions requires accessible information on connectivity to inform the development of sound ecological policies and management measures (Dunn et al., 2019). However, it is unknown how much scientific knowledge is currently accessible to efficiently contribute to these efforts and to inform management.

The study of marine animal movements has greatly improved in the last few decades. An increase in the number of methods and technologies used to collect data to investigate how areas are connected (e.g., telemetry tracking, capture-mark-recapture surveys, genetic analysis, stable isotope analysis), along with reduced processing and analysis time, have furthered our knowledge on marine animal ecology and the environment (Boulet and Norris, 2006; Hart and Hyrenbach, 2010; Calò et al., 2013). In particular, telemetry data from tracking animal movements can identify areas used by animals during different life history stages, as well as the migratory corridors they use to travel between these areas (Hazen et al., 2012). The identification of important areas and corridors could further be analyzed to help prioritize conservation, based on their relative contribution to maintaining populations, species, or ecosystems (Higuchi, 2012; Kot et al., 2022a; Tetley et al., 2022; Waliczky et al., 2019). Additionally, critical migratory corridors need to be taken into account when designing protective measures against threats that may occur throughout the geographic range of a species (Martin et al., 2007; Crowder and Norse, 2008; Albers et al., 2023). As a result, marine populations have benefited from management measures that have incorporated available spatial and temporal information on habitat use within a network of areas (Hays et al., 2019; Lennox et al., 2019; Visalli et al., 2020).

More frequently, managers and policy makers are reliant on published literature to provide the knowledge gleaned from the connectivity data or direct communication with researchers. However, the inclusion of these data into management measures has been taxonomically and geographically limited (Jeffers and Godley, 2016), and there are many barriers to the application of such data including constraints in time, budget, and capacity within management organizations and policy making bodies. Furthermore, the original objectives of studies that generate information on connectivity are highly variable, contributing to the challenge of accurately identifying, locating, and summarizing relevant connectivity data.

Here, we conducted a review to summarize the published information within the literature on area-use and connectivity, gathered by tracking the movements of highly migratory marine species. We also examined the ways tracking datasets were processed and analyzed and how authors made data from these publications available to a wider audience. We selected four case study species, based on the number of references that could be included in the literature review and their broad geographic distribution, and presented results as the first steps in assessing the state of knowledge for identifying important areas (sites) and connections among sites (routes) within the known spatial extent of the species. Through this literature review, we identified two key knowledge shortfalls that limit effective marine conservation management: 1) the gaps in connectivity research for marine migratory species, ocean regions, sex, age classes, and animal behaviors, and 2) the gap between the connectivity data that are published in the literature and how accessible these are for uptake in marine policy and management decision making. Finally, we described current knowledge gaps and provided recommendations to improve the link between connectivity data and area-based management decisions.

2. Materials and methods

2.1. Literature search and initial review

We used Clarivate's Web of Science and Elsevier's Scopus citation databases to search for literature on ecological connectivity data collected by the movements of 173 marine species within 4 taxa (Appendices A and B). The search was conducted in February to June 2017 for references published beginning in 1990 on 61 marine fish, 42 marine mammal, 7 sea turtle, and 63 seabird species. The list of species was identified by Dunn et al. (2019) as migratory megavertebrates, based on input from multiple expert sources. The scientific name of each species was used within search strings, customized by taxa, to gather and identify references to describe sites or routes. Sources for marine connectivity data were determined as having geospatial information on sites and routes; sites were defined as areas used by animals that were described in the literature (usually associated with a specific animal behavior activity) and routes were defined as connections among sites.

Four reviewers compiled references to be included for review following methods by Moher et al. (2009), after identifying, screening, and selecting references with eligible telemetry data by using information from the title, abstract, or full text. After the four reviewers agreed upon a standardized method to extract information from the references we should include for review, these references were divided among a team of nine additional reviewers that were trained to collect details from the full text. Information was recorded within organized spreadsheets for each reviewed reference, including the: 1) publication year, 2) study's ocean region where data were collected, 3) type of results presented, whether it was "raw" telemetry data (i.e., trackline, points) or "processed" telemetry data (i.e., methods used for processing or modeling tracks), and 4) the repository if data were archived (Appendix B). In addition, we noted the journals that were most frequently found with relevant telemetry data and included in our review to compare the current data sharing policies of the top journals.

For all 173 species, we analyzed the relationship between the number of references initially found, the number of included references for review, publication year, and the current International Union for Conservation of Nature (IUCN) Red List conservation category (i.e., "Critically Endangered," "Endangered," "Vulnerable", "Near Threatened," "Least Concern," "Data Deficient") using R (R Core Team, 2022). We fit the number of references by publication year to a linear model using R ($\alpha = 0.05$; R Core Team, 2022). The IUCN Red List category for each species was collected using the "rredlist" package (Gearty and Chamberlain, 2022; IUCN, 2022). When five Mobulidae species names used in the literature search string were not found in the IUCN Red List database (IUCN, 2022), we noted the conservation category of each species based on the recent taxonomic revisions by White et al. (2018). We used the Kruskal-Wallis rank sum test (Kruskal and Wallis, 1952), followed by a post-hoc Dunn's test of multiple comparisons (Dunn, 1964) with Benjamini-Hochberg p-value correction (Benjamini and Hochberg, 1995) when there was a significant difference among categories ($\alpha = 0.05$; Dinno, 2022).

2.2. Case study species review

From the 173 marine species used for the literature search and initial review, we selected one species per taxa as a representative for an in-depth literature review to better understand the available information on large-scale movement patterns: Atlantic bluefin tuna *Thunnus thynnus*, humpback whale *Megaptera novaeangliae*, loggerhead sea turtle *Caretta caretta*, and wandering albatross *Diomedea exulans*. These case study species were selected because they had the greatest number of references within each taxa that could be included for review (after identifying, screening, and noting eligible references with relevant telemetry data), with the exception of humpback whale (Table 1). More references that could be included for review for three top marine mammals were beluga whale *Delphinapterus leucas* ($n = 33$), grey seal *Halichoerus grypus* ($n = 43$), and polar bear *Ursus maritimus* ($n = 56$). However, the known geographic distribution for beluga whale (Lowry et al., 2017; O'Corry-Crowe, 2018), grey seal (Bowen, 2016; Hall and Thompson, 2018), and polar bear (Wiig et al., 2015; Stirling, 2018) were

Table 1
The number of references included in the literature review, the number of animals reported within these references, by sex and age class (number of references within information in parenthesis), for each case study species. Each reference was reviewed independently for unique individuals, with the potential for individuals reported within more than one reference.

Common name	References	Male	Female	Unknown	Juvenile	Adult	Unknown
Atlantic Bluefin Tuna	22	0	3 (1)	2920 (22)	47 (5)	490 (12)	2363 (11)
Humpback Whale	29	191 (16)	245 (19)	333 (25)	6 (3)	419 (16)	276 (14)
Loggerhead Sea Turtle	115	396 (24)	2718 (61)	1909 (49)	1341 (31)	2860 (83)	663 (22)
Wandering Albatross	57	881 (40)	798 (41)	2275 (33)	117 (4)	3036 (47)	53 (1)

relatively restricted compared to the humpback whale. Therefore, humpback whale was selected as the most appropriate over other marine mammal species because of its relatively broad geographic distribution (Clapham, 2018; Cooke, 2018), compared to the other marine mammal species found with a higher number of references (Appendix B).

In addition to the methods we used to collect information for all other species, we conducted a second search for references published from 2017 to 2022 to examine the relationship between the initial number of references on case study species and publication year for a longer period (1990–2022) and to estimate effort needed for updating our dataset (Appendix B). We used the same methods to search for references published between 1990 and early 2017 (Appendix B).

For references published between 1990 and early 2017 on the case study species, we conducted an in-depth literature review by recording the number of tracked individuals present at each site and completing each route, by species, sex, and age class (Appendix B). We collected detailed information on the main animal behavior activity, or purpose for animals using each site, and each connecting route between two unique sites as described by the authors (Appendix B). We did not correct for datasets used in multiple publications, with the potential for sites, routes, or individuals reported in more than one reference. A unique site or route described with the presence of tracked animals was defined by using the combination of the reference, species, and described location (for sites) or the combination of the starting site location and ending site location (for routes). Each site (start and end points for routes) could have more than one detailed activity type (e.g., spawning, nesting, wintering, staging, nursery), as this was recorded based on the information authors provided within the reviewed literature. To facilitate comparisons of sites and routes across taxa, we then categorized the 12 detailed activity types that were described in the literature into four broader activities: “breeding,” “feeding,” “migrating,” or “unknown” (Appendix C).

For references published between 1990 and early 2017, we also recorded the device type used to track individuals, as reported within case study references included in our literature review. Finally, when processed telemetry data were presented within a reference, the methods used to process the data were categorized as either: 1) track processing only (e.g., state-space model, speed-distance-angle filter, light-based geolocation algorithm), or 2) track processing and modeling of area or behavior.

3. Results

3.1. All migratory species

For the 173 species, our literature search identified an average of 7 references published between 1990 and early 2017 and included for review, determined from an average of 80 references initially found per species from the literature search; 15 species did not have any references, and an additional 52 species did not have any references included for review (Appendices A and B). Our literature search did not identify any references for 2 seabird and 13 marine fish species that were listed under different conservation categories (Appendix B). We did not include any references for an additional 52 species of marine fish, marine mammals, and seabirds, after screening the collection of references initially identified by the literature search (Appendix B).

In total, 981 references were included in the literature review, with some containing area-use and connectivity information for multiple species. There was a significant increase in the number of included references from 1990 to 2016 for all species combined (linear model, $r^2 = 0.72$, $p < 0.001$; Fig. 1). References were included in the literature review for 106 species: all 7 sea turtle species, 32 marine fish species, 27 marine mammal species, and 40 seabird species. Compared to other taxa, the number of included references was the greatest for sea turtles ($n = 298$), despite having the fewest number of species within this taxa (Fig. 2). The remaining marine taxa had fewer included references per taxa ($n = 276$ for marine mammals; $n = 211$ for marine fish; $n = 196$ for seabirds).

Within the included references, data were mostly collected from the northern hemisphere, with the greatest number in the North Atlantic Ocean, while the Antarctic Ocean had the fewest number of references (Fig. 3). Additionally, the proportion of references found for each region was unevenly distributed among the four taxa; only marine mammal data were available in the Arctic Ocean and the majority of data available in the Antarctic Ocean were from seabirds (Fig. 3). For regions in the southern hemisphere, there was a greater number of included references for seabirds compared to other taxa; included references did not have data for sea turtle and marine fish in the polar regions.

Home range analyses, movement models, or location optimization methods were presented as ways to process telemetry data for 296 (30 %) of the included references. Methods for processing data were described for 70 of the 106 species found to have at least one included reference for review. Of the references that presented processed telemetry data, 66 % applied area estimation models in addition to processing the raw tracking data, while the remaining references described methods only to process the raw tracking data. The most frequently used method for modeling area or behavior were kernel density estimates (KDEs) or kernel utilization distributions (KUDs; 108 references), minimum convex polygons (MCPs; 38 references), and switching state-space models (SSSMs; 25 references); the most frequently mentioned methods used for processing the raw data were the Kalman filter or state-space model (62 references).

Only 110 (11 %) of all included references, published between 1995 and 2017, contained information on where data were archived, while all other references did not mention if data were archived or if a repository was used. About 8 % of all telemetry references archived data on the seaturtle.org Satellite Tracking and Analysis Tool (STAT; http://www.seaturtle.org/STAT); about 2 % of publications archived their data on other repositories (e.g., Dryad [https://datadryad.org], Ocean Biodiversity Information System [OBIS; https://obis.org], Movebank [https://www.movebank.org], BirdLife International's Seabird Tracking Database [http://www.seabirdtracking.org]). The remaining 1 % of references reported data were either published in the supplementary materials of the original publication or stated that data were available upon request from the authors.

The five most frequently mentioned data repositories were not active until after 1999: the OBIS repository started around 1999 (Grassle and Stocks, 1999; Grassle, 2000), the STAT repository contained data starting in 2002 (Coyne and Godley, 2005), the Seabird Tracking Database started around 2004 (BirdLife International, 2004), and both

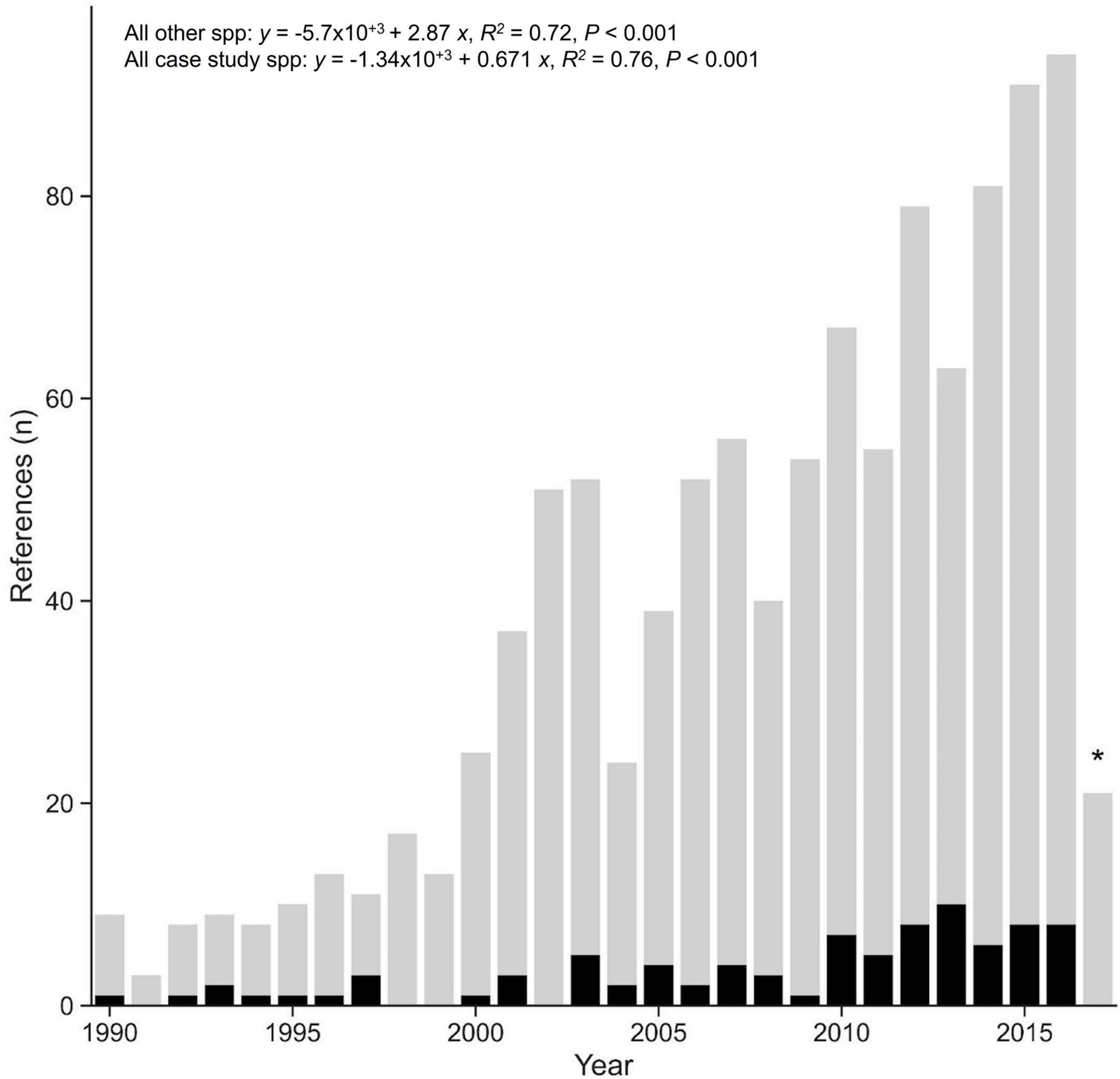

Fig. 1. The total number of references included for review, by year for all case study species (black), and all other species (grey). References published between 1990 and 2017 were reviewed. Data were fitted with a linear model for 1990–2016 (α = 0.05). *literature search was conducted in early 2017.

the Dryad (Carrier et al., 2007) and Movebank (Kranstauber et al., 2011; Kays et al., 2022) data repositories were available starting around 2008. However, data archiving within these five repositories were only noted within 85 included references, published between 2006 and 2017.

References included in our review, for all species, were published in 216 different sources. Of those sources, the journal most frequently found with area-use or connectivity information was Marine Ecology Progress Series ($n = 107$ references), followed by Marine Biology ($n = 74$), PLOS ONE ($n = 48$), Endangered Species Research ($n = 41$), and Biological Conservation ($n = 33$). Each of the top five journals included relevant data for all four taxa, which represented 31 % of the references. The Marine Mammal Science journal also was a highly ranked source of information, containing data for marine mammals only ($n = 32$ references), followed by the Journal of Experimental Marine Biology and Ecology with data on all four taxa ($n = 31$ references).

The top five species with the most references initially found (green sea turtle *Chelonia mydas*, humpback whale, loggerhead sea turtle, European eel *Anguilla anguilla*, and killer whale *Orcinus orca*) were all listed as different conservation categories under the IUCN Red List (Appendix B). There was no significant difference among the initial number of references found by the literature search and the IUCN Red List category of all species (Kruskal-Wallis test, $\chi^2 = 9.78$, $p = 0.08$). However, there was a significant difference among the number of included references and the IUCN Red List category of all species (Kruskal-Wallis test, $\chi^2 = 17.06$, $p < 0.004$). The number of included references for species categorized as "Vulnerable" was significantly higher than species categorized as "Least Concern" (Dunn's test, Z-test $= -3.65$, $p = 0.002$); within each category, the average number of included references per species

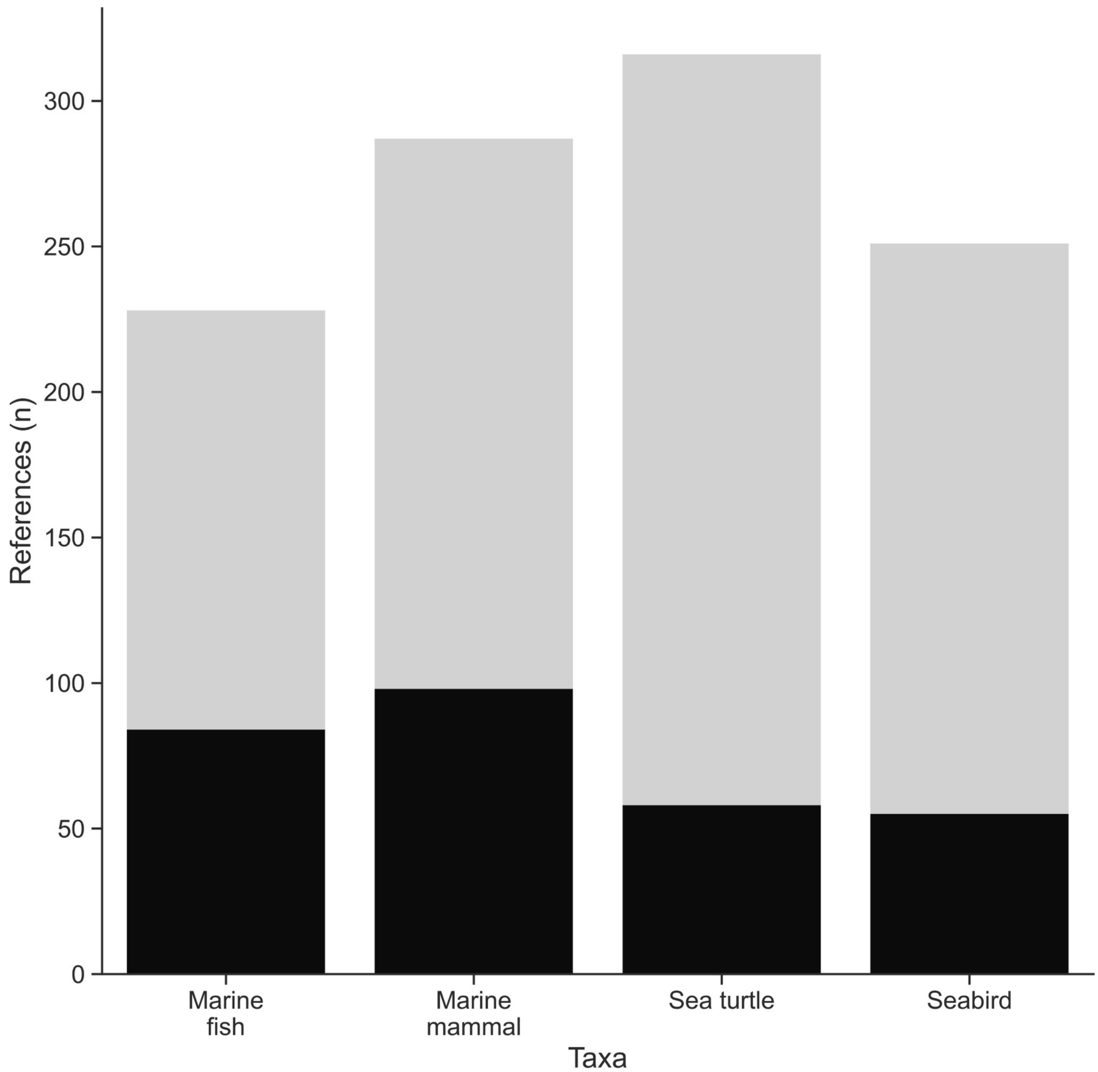

Fig. 2. The total number of references included for review that presented processed telemetry data (black) and raw telemetry data (grey) for 173 marine fish, marine mammal, sea turtle, and seabird species.

was 12 ($n = 37$ species) and 4 ($n = 39$ species), respectively. For the case study species, the IUCN Red List categorized both Atlantic bluefin tuna and humpback whale as "Least Concern," while loggerhead sea turtle and wandering albatross were both categorized as "Vulnerable." More references were found with area-use or connectivity information for loggerhead sea turtle and wandering albatross compared to Atlantic bluefin tuna and humpback whale (Table 1). However, no significant difference was found when comparing other IUCN Red List categories (Dunn's test, $p > 0.84$).

3.2. *Case study migratory species*

A large number of references published between 1990 and 2017 was initially found from the literature search for each case study species: 812 for humpback whale, 783 for loggerhead sea turtle, 385 for Atlantic bluefin tuna, and 333 for wandering albatross (Appendix B). For each case study species, the initial collection of references increased significantly by year, between 1990 and 2016 (linear model, $r^2 > 0.55$, $p < 0.001$; Fig. 4) and between 1990 and 2022 with the inclusion of 1114 references from an updated literature search (linear model, $r^2 > 0.10$, $p < 0.01$; Appendix B). There was a slightly significant increase in the number of potential references for humpback whales published per year, between 2016 and 2022 (linear model, $r^2 = 0.60$, $p = 0.04$). However, the linear model showed no significant trend over the years for the number of references initially found, published between 2016 and 2022, for Atlantic bluefin tuna ($r^2 = 0.03$, $p = 0.73$), loggerhead sea turtle ($r^2 = 0.08$, $p = 0.55$), and wandering albatross ($r^2 = 0.39$, $p = 0.13$). Between 2017 and 2022, there was no significant change in the number of initial references found for each of the four case study species (linear model, $p > 0.09$; Appendix B).

The in-depth literature review for the four selected case study species contained information gathered from 223 included references published between 1990 and 2017 (Appendices B and C). Following the same trend found for the number of included references for all species, there was a significant increase in included references per year, between 1990 and 2016, for all case study species combined (linear model, $r^2 = 0.76$, $p < 0.001$; Fig. 1) and broken down by species (linear model, $r^2 > 0.1$, $p < 0.03$), except for wandering albatross (Fig. 4). No significant change was found for the number of included references on wandering albatross over time (linear model, $r^2 = 0.03$, $p = 0.35$; Fig. 4). For references published between 1990 and 2017, included references for review ranged from 4 to 17 % of references initially identified for each of the case study species, with an average of about 56 included references per species (Appendix A). For references published in 2016, the greatest rate of included references was on wandering albatross (38 %), followed by loggerhead sea turtles (15 %), Atlantic bluefin tuna (13 %), and

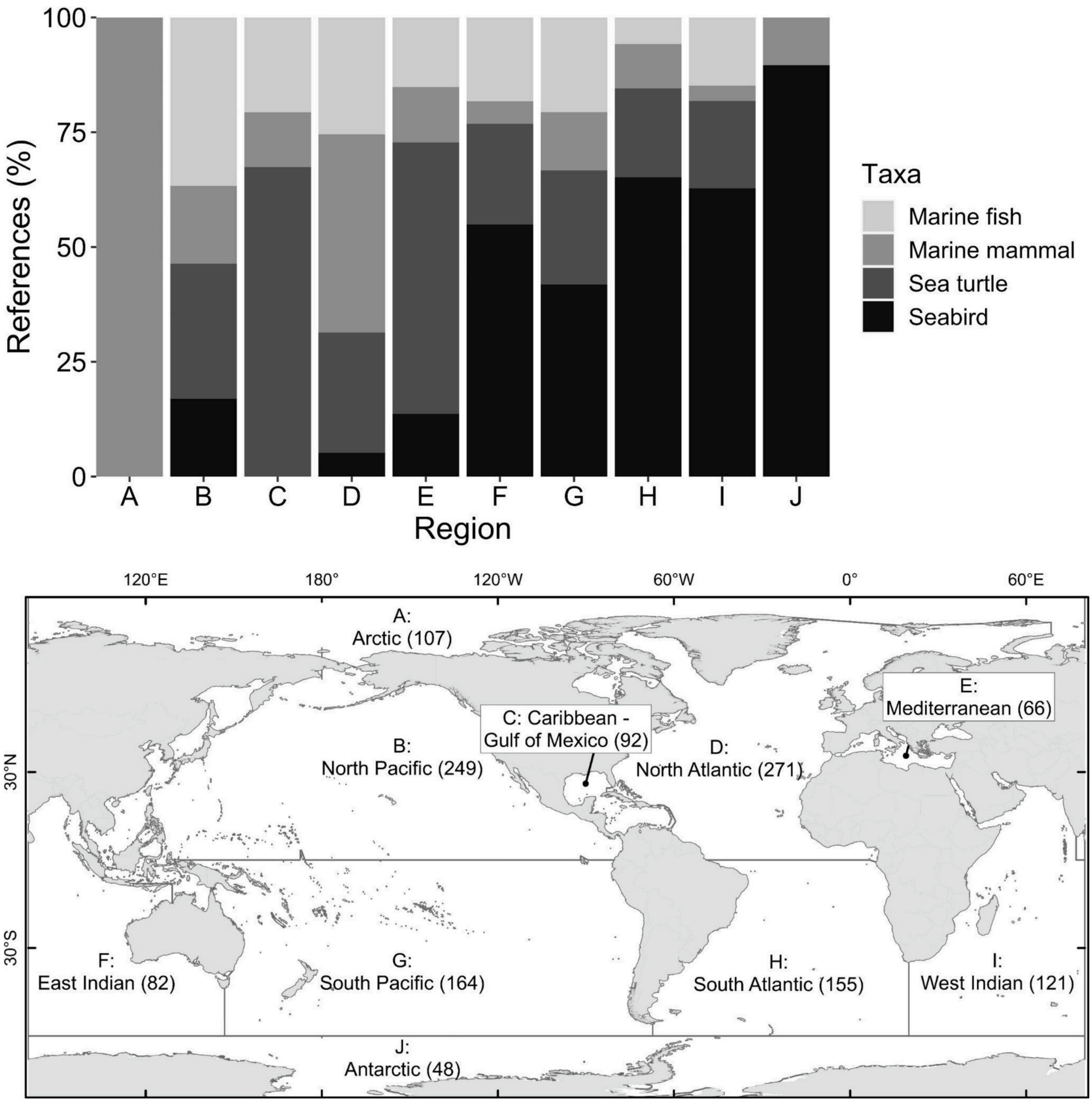

Fig. 3. The percent of all included references found for each taxa (top panel) and the total number of references (in parenthesis) within ocean regions (bottom panel) within the a) Arctic, b) North Pacific, c) Caribbean-Gulf of Mexico, d) North Atlantic, e) Mediterranean, f) East Indian, g) South Pacific, h) South Atlantic, i) West Indian, and j) Antarctic regions. Unique references may be attributed to more than one region. Country data source: Global Administrative Areas Database (2018).

humpback whale (3 %). Because the number of initial references did not change between 2016 and 2022, we used the 2016 rates and estimated a potential collection of about 118 references, published between 2017 and 2022, that could be included with area-use or connectivity information for an updated literature review on the four case study species.

All case study species had at least one included reference collected from oceanic regions that overlapped with their known geographic distribution, except for the humpback whale (Fig. 5). Humpback whale data were available for all regions within their distribution except for the Caribbean Sea, Gulf of Mexico, Mediterranean Sea, and East Indian Ocean. Most of the marine telemetry references for Atlantic bluefin tuna collected data from the North Atlantic Ocean ($n = 17$), while the greatest number of references with data on loggerhead sea turtle was from the Mediterranean Sea ($n = 31$). For wandering albatross, the greatest number of included references contained data from the West Indian Ocean ($n = 35$); the greatest number of included references was reported in the South Pacific Ocean for humpback whale ($n = 9$). For regions that contained data for a case study species, all categories of activities (i.e., breeding, feeding, migrating, or unknown) were reported by at least one reference for the case study species. The exceptions were for Atlantic bluefin tuna in the Caribbean Sea and Gulf of Mexico (no references reported breeding or migrating activity), humpback whales in the Antarctic Ocean (no references reported breeding or unknown activity), and loggerhead sea turtles in the East Indian and South Pacific Oceans (no references reported migrating activity).

Within the sexes and age classes reported for the case study species,

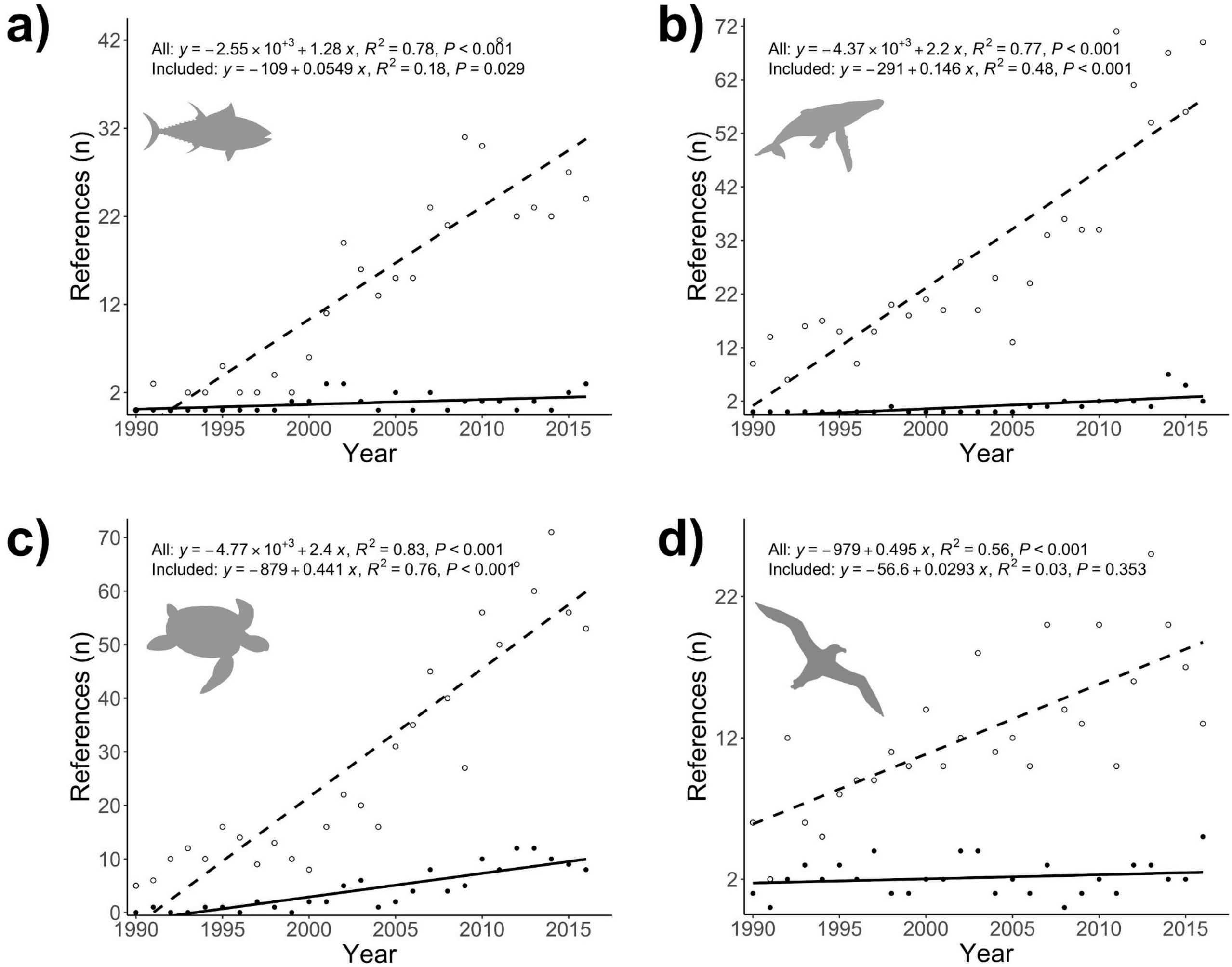

Fig. 4. The number of initial references (hollow circles, dashed line) and included references for review (solid circles, solid line), per year, from 1990 to 2016 for a) Atlantic bluefin tuna, b) humpback whale, c) loggerhead sea turtle, and d) wandering albatross. Data were fitted with a linear model (α = 0.05).

there were large differences in what information was reported for each species (Table 1). The Atlantic bluefin tuna had the least amount of information for the sex and age class of tracked individuals, with >99 % of individuals reported as an unknown sex and about 81 % of individuals reported with an unknown age class. No male Atlantic bluefin tunas were tracked using telemetry methods in our literature review, while only the movements of three females were reported within the references. Of the known age classes for Atlantic bluefin tuna, more adults were tracked compared to juveniles. Reported sexes for humpback whales were more evenly distributed between males and females, though 43 % of the tracked individuals were reported as unknown sex (Table 1). For the age classes of humpback whales, 60 % of tracked individuals were reported as adults, with 39 % of unknown age class and only 1 % reported as juveniles. Almost an equal percentage of male and female wandering albatrosses were tracked (22 % and 20 %, respectively), while the remaining 58 % of tracked individuals were of unknown sex. The vast majority (95 %) of tracked wandering albatrosses were adults, with only about 4 % of individuals reported as juveniles (Table 1). Loggerhead sea turtle was the only case study species with more females tracked (54 %), with 38 % reported as unknown sex and only 8 % reported as male. The majority (59 %) of tracked loggerhead sea turtles were adults, while juveniles made up 28 % of tracked loggerhead sea turtles in our review (Table 1).

For all species except wandering albatross, the most information published on sites was focused on feeding behavior. Most (44 %) information published on sites for wandering albatross did not record animal behavior activity, followed by feeding activity and then breeding behavior at sites (34 % and 22 %, respectively). Migration was the least common activity reported at sites, making up 9 % of reported behaviors at sites within only 17 % of the included references for all case study species. Sites reported feeding and breeding behavior for all case study species within 67 % and 60 % of included references, respectively, indicating that many references contained information on both types of sites.

Most (66 %) of the included references with telemetry data for the case study species presented information on routes in addition to sites, describing movements for a total of 812 routes across case study species. The most information was found for loggerhead sea turtles (62 % of all routes; 61 % of all references with routes), compared to all other case study species (Table 2). The type of route that was most commonly described, across all case study species, was the movement between breeding and feeding sites ($n = 269$ routes), collected from 65 references (44 % of the references with route information). The least number of routes described were between sites identified with migratory activities, specifically between sites identified as having migratory and unknown activities (16 routes; 10 references) or between two sites identified with migratory activities (17 routes; 9 references).

When considering direction, 220 routes from breeding sites to feeding sites were identified from 60 included references for case study species. “Breeding to feeding” routes made up the greatest percentage of all types of routes with direction for loggerhead sea turtle and wandering albatross (Fig. 6). For Atlantic bluefin tuna, most (57 %) of the

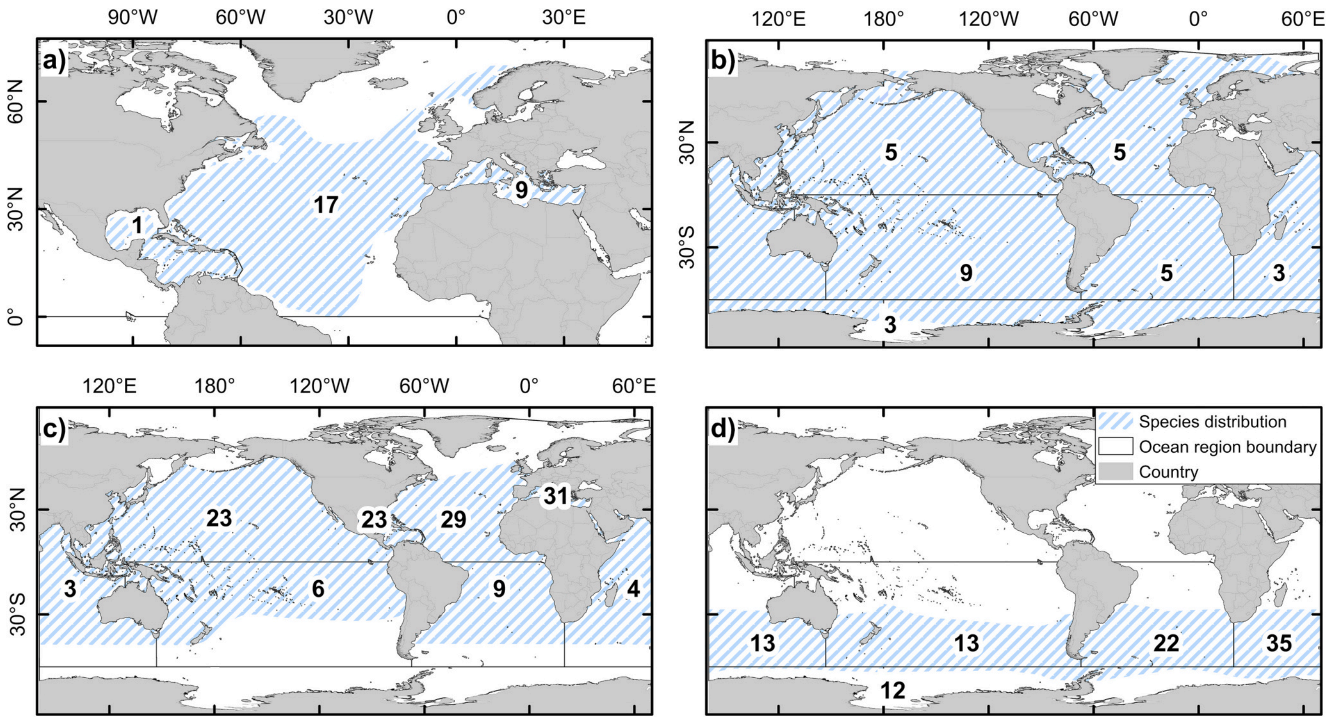

Fig. 5. The number of included references for review within each ocean region for a) Atlantic bluefin tuna, b) humpback whale, c) loggerhead sea turtle, and d) wandering albatross. Unique references may be attributed to more than one region; see Fig. 3 for ocean region details. Data layer sources: Country (Global Administrative Areas Database, 2018), Atlantic bluefin tuna species distribution (Food and Agriculture Organization, 2020), humpback whale species distribution (IUCN SSC Red List Technical Working Group, 2022), loggerhead sea turtle species distribution (Wallace et al., 2010), wandering albatross species distribution (BirdLife International and Handbook of the Birds of the World, 2020).

Table 2
The number of sites per activity and total number of routes described in the references included in the literature review (number of references in parenthesis), and the percent of included references with processed data, for each case study species. All references reported at least one site and more than one activity could be reported for each site. Each reference was reviewed independently for unique sites and routes, with the potential for sites or routes reported within more than one reference.

Common name	All	Breeding	Feeding	Migrating	Unknown	Routes	Processed (%)
Atlantic Bluefin Tuna	100 (22)	41 (15)	41 (14)	13 (4)	33 (11)	107 (14)	36
Humpback Whale	92 (29)	25 (14)	48 (19)	11 (6)	17 (7)	111 (21)	41
Loggerhead Sea Turtle	544 (115)	145 (80)	206 (79)	54 (21)	164 (53)	504 (90)	30
Wandering Albatross	264 (57)	59 (31)	89 (40)	11 (7)	115 (27)	90 (23)	18

routes from the available information started at feeding sites whereas most (54 %) of the routes from the available information for humpback whales started at breeding sites (Fig. 6). Across all four case study species, the least number of routes were described for migratory sites to breeding sites (6 routes; 4 references) and migratory sites to sites with unknown activities (6 routes; 5 references). In general, the number of routes starting at migratory sites was relatively low for all species.

For all case study species except for Atlantic bluefin tuna, Argos satellite telemetry tags were the most common device used to track animal movements (Appendix B). Loggerhead sea turtle and wandering albatross were tracked with all of the tagging methods identified for case study species, with more references found for Argos tags than other device types ($n = 103$ and 45 references, respectively). Additionally, more references were found on Argos satellite telemetry tags or using radio or acoustic tags for tagged loggerhead sea turtle compared to other case study species. Compared to other case study species, wandering albatross were more often tracked with global positioning system (GPS) tags ($n = 15$) or global location sensing (GLS) tags ($n = 8$). Atlantic bluefin tuna had more references on satellite archival tags ($n = 18$) than other device types, and the most references on satellite archival tags compared to the other three case study species (Appendix B).

References presenting processed telemetry data, as part of the analyses and results, made up about 29 % ($n = 64$) of all included references for case study species (Table 2). About 80 % of references with processed data mentioned methods for modeling area or behavior following track processing of the telemetry data. Specifically, the development of KDEs and SSSMs were presented within 58 % of all references with processed data. The remaining 20 % of references mentioned methods only for processing tracking data, without modeling area or behavior, most frequently applying a light-based geolocation algorithm or state-space modeling. At the species level, all eight Atlantic bluefin tuna references with processed data used methods to process tracking data, while no behavioral modeling methods were presented within any references. Humpback whale tracks were processed using behavioral modeling for 99 % of the references that mentioned data processing. About two-thirds of the behavioral modeling references used SSSM methods to process humpback whale telemetry tracks. Only two (20 %) of the wandering albatross references used methods to process tracking data, while the remaining eight (80 %) references estimated core areas from the tracks (e.g., KUDs). Similarly, six (15 %) of the loggerhead sea turtle references presenting methods to process data used state-space modeling for telemetry tracks. The majority (85 %) of loggerhead sea turtle references processed the telemetry data with behavioral modeling methods, mainly using KDEs or MCPs.

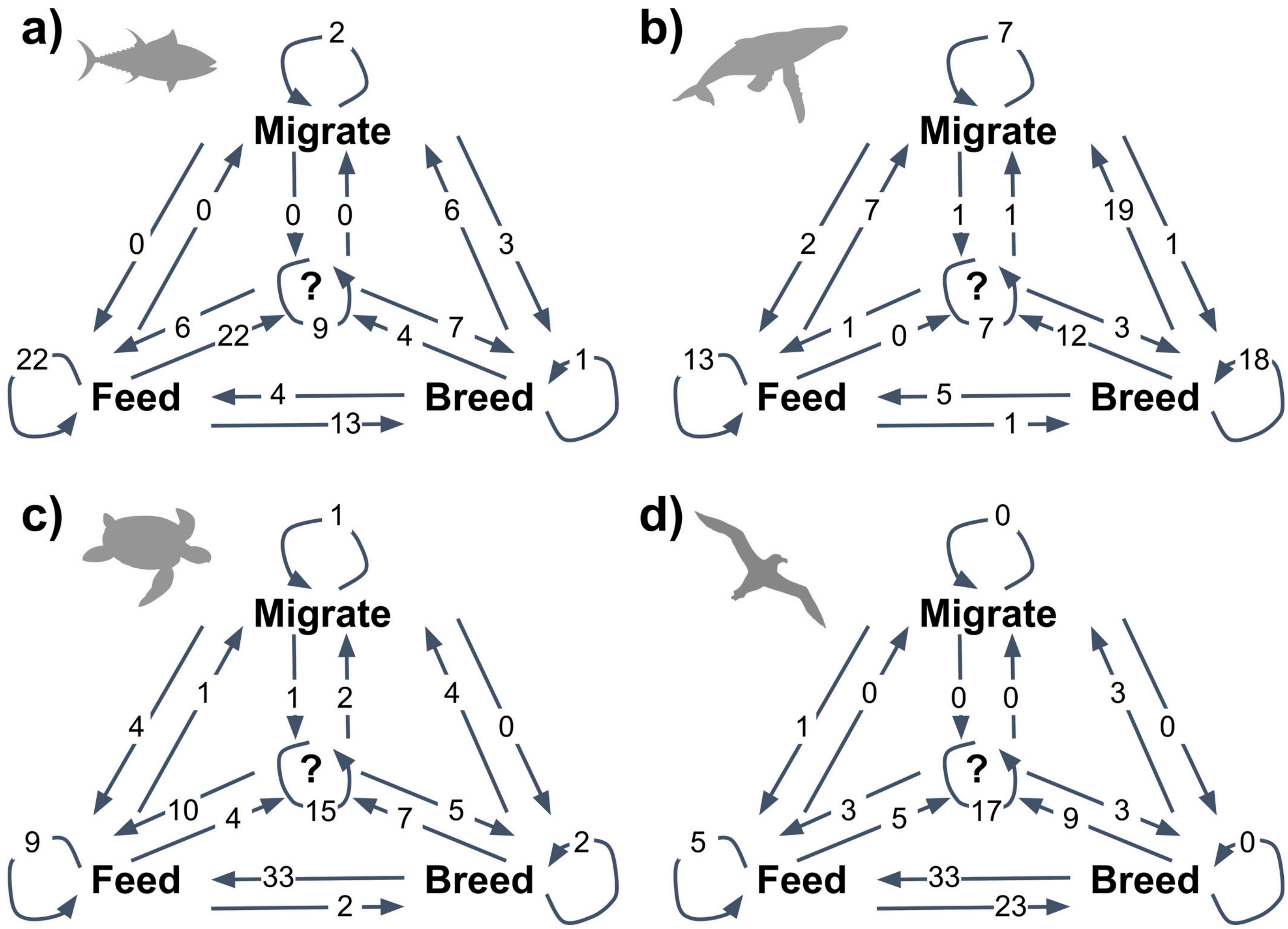

Fig. 6. The percent of each type of route described in the included references, within each species, for a) Atlantic bluefin tuna (n = 107 routes), b) humpback whale (n = 111 routes), c) loggerhead sea turtle (n = 504 routes), d) wandering albatross (n = 90 routes).

Data availability was noted for all case study species, with the exception of Atlantic bluefin tuna. Only two wandering albatross references identified the availability of the data within project-specific archives, while three humpback whale references identified where data could be accessed (Dryad, $n = 2$; OBIS, $n = 1$). These databases were noted in humpback whale and wandering albatross references published between 2013 and 2016. Nearly a third of loggerhead sea turtle references ($n = 36$) identified the repositories where data was archived; the STAT repository was most frequently noted (n = 34), with a single mention of OBIS and MoveBank each. These repositories were noted in included loggerhead sea turtle references published between 2006 and 2016.

For our literature review on the case study species, included references were published within 86 different sources. The top three journals most frequently included were the same top three journals found for reviewing all marine species: Marine Biology, Marine Ecology Progress Series, and PLOS ONE (Appendix B). These top three sources accounted for 29 % of all 223 references included with information just for the case study species, compared to 23 % of the 981 references included for all marine species we reviewed. Other journals that were highly ranked with information on area-use and connectivity, for the case study species, included the Biological Conservation journal, followed by the International Commission for the Conservation of Atlantic Tunas Collective Volume of Scientific Papers journal, and Journal of Experimental Marine Biology and Ecology (Appendix B). The Marine Ecology Progress Series and Biological Conservation journals were the only two of all 86 unique sources that contained area-use or connectivity information for all four case study species. The Marine Biology journal was also the greatest source for relevant telemetry data collected on loggerhead sea turtle and the greatest number of described sites and routes collected for all case study species except for humpback whale (Appendix B). The International Commission for the Conservation of Atlantic Tunas Collective Volume of Scientific Papers journal published the greatest number of references on Atlantic bluefin tuna, and the Marine Ecology Progress Series journal had the greatest number of references for wandering albatross and humpback whale. The top six journals identified were also among the top 15 % of sources that described the greatest number of sites and routes, across case study species (Appendix B).

The top six journals most frequently found with area-use or connectivity data for all marine species we reviewed, including the case study species, currently have open access policies that ranged from being fully open and accessible online (i.e., Endangered Species Research, International Commission for the Conservation of Atlantic Tunas Collective Volume of Scientific Papers, PLOS ONE) to a hybrid where authors can choose to publish articles with open access or only available to subscribers (i.e., Biological Conservation, Journal of Experimental Marine Biology and Ecology, Marine Biology, Marine Ecology Progress Series, Marine Mammal Science). These journals also had different data sharing levels that included: 1) not having a policy for including any data availability statement (i.e., Endangered Species Research, International Commission for the Conservation of Atlantic

Tunas Collective Volume of Scientific Papers, Marine Mammal Science), 2) not requiring data sharing, allowing for data to be available “upon request” (i.e., Biological Conservation, Journal of Experimental Marine Biology and Ecology, Marine Biology, Marine Ecology Progress Series), or 3) requiring data to be publicly available at the time of publication, without restriction (i.e., PLOS ONE).

4. Discussion

4.1. Marine connectivity research

We reviewed over 25 years of references on marine migratory animals to provide an overview of how their tracked movements showed ecological connectivity, the limitations of the information published within the references, and insights for how to best synthesize data on movement ecology to facilitate integration into conservation planning. We presented a snapshot of available information within the references, acknowledging the potential that more information not captured here was due to limited resources. Our literature search showed a significant increase in the number of initial references found over time, while the number of references that included relevant data on area-use or connectivity increased at a slower rate, if at all. However, these trends may change with increased improvements in technology, more efficient methods for studying area-use or connectivity, better ways for sharing knowledge, and the effects of pressing conservation priorities.

Along with an increased collection of electronic telemetry data and the variety of methods to analyze the data, studies on marine connectivity have continued to expand to cover more species and regions over time (Hart and Hyrenbach, 2010; Bryan-Brown et al., 2017; Abecasis et al., 2018; Harcourt et al., 2019). Global assessments using telemetry data for marine mammals (e.g., Johnson et al., 2022; Reisinger et al., 2022), seabirds (e.g., Bernard et al., 2021), sea turtles (e.g., Kot et al., 2022a), marine fish (e.g., Queiroz et al., 2016; Matley et al., 2022), and a combination of multiple marine taxa (e.g., Sequeira et al., 2018) have advanced our understanding of seasonal and regional movements of migratory animals. These studies demonstrated that management measures need to take critical ecological connections into account for effective conservation. However, this assessment of marine connectivity data, collected by studying migratory animal area-use and movements within the published literature, identified several outstanding scientific knowledge gaps that can inform how we should prioritize research, disseminate findings, and reformat data into more actionable knowledge.

When comparing across the four taxa we reviewed, there was a greater number of references included for our literature review that contained relevant connectivity data for sea turtles, compared to marine fish, marine mammals, and seabirds. Donaldson et al. (2014) also found that the number of biodiversity conservation studies on sea turtle species (and European eel) was much greater than other species considered as “Threatened” (species categorized as “Critically Endangered,” “Endangered,” or “Vulnerable” by the IUCN Red List). Furthermore, we did not find any site or route information in our literature review for humpback whales in the Caribbean-Gulf of Mexico, Mediterranean Sea, or East Indian Ocean regions. Humpback whales have occasionally been observed feeding in the Mediterranean region (see Frantzis and Nikolaou, 2004; Espada Ruíz et al., 2018; Violi et al., 2021) and wintering in the Caribbean-Gulf of Mexico region (Martin et al., 1984). These regions were identified as part of the “secondary range” of humpback whales (Jefferson et al., 2015; Clapham, 2018), though more research is still needed on area-use and activities within these regions, along with identifying connections from these regions to areas within their primary range. The eastern Indian Ocean contains areas identified as the primary, secondary, and possible ranges for humpback whales (Jefferson et al., 2015; Clapham, 2018) and recently published telemetry data by Bestley et al. (2019) showed that humpback whale movements connected breeding grounds in coastal waters near western Australia to the Southern Ocean feeding grounds. Studies have shown that humpback whales migrate from breeding grounds in the southern Atlantic, southern Pacific, and western Indian Ocean regions to feeding grounds in the Southern Ocean, but relatively less is known for the eastern Indian Ocean (Murphy et al., 2021). Until existing biases in taxonomic and geographic research are corrected, marine ecological assessments used to determine priority conservation measures and resources may be hindered (Donaldson et al., 2014; Di Marco et al., 2017). More attention is needed for marine connectivity research, especially for the taxa and regions still lacking in information (Bryan-Brown et al., 2017). Furthermore, better information can be presented for the development of policies when evidence syntheses are inclusive, rigorous (with minimal bias), transparent, and accessible (Donnelly et al., 2018; Sutherland et al., 2019; Christie et al., 2021).

As was found in other recent reviews, scientific research on marine animals has been spatially biased towards the northern hemisphere (Kaschner et al., 2011; Selig et al., 2014). Studies have attributed this to sampling bias, the natural distribution of species, and availability of habitats (Powell et al., 2012; Higgs and Attrill, 2015; Chaudhary et al., 2016). However, this geographic bias could be advantageous for prioritizing mitigation strategies in northern regions that were most affected by stressors of high human impact (Halpern et al., 2008; Tittensor et al., 2010; Selig et al., 2014; Stock et al., 2018) and the threats to marine migratory animals affecting northern populations more than southern ones (see Sydeman et al., 2021). Based on the number of references with telemetry data found in our review, the North Pacific and North Atlantic Ocean regions have the greatest potential to support a multi-taxa approach to conserving connectivity. Three of the four case study species presented here had more data on North Atlantic feeding sites and connectivity of feeding sites to or from other areas, providing more support for the need to conserve connectivity within area-based management plans here compared to other regions and animal behavior activities. In the southern hemisphere, the south Indian Ocean has been identified as highly impacted by humans (Halpern et al., 2015, 2019), a region that had the greatest number of references for wandering albatross and, therefore, the most potential for applying connectivity data towards area-based management for this species. Mott and Clarke (2018) reported more intensive seabird research in the northern hemisphere, but also found many studies concentrated in the southern hemisphere within the sub-Antarctic region (southern Atlantic and Indian Oceans). Based on our results, another potential region in the south for supporting multi-taxa analyses was the South Pacific region, which had the most references for the combined, broader list of marine species and included data for all four taxa combined. Our summarized activities, by broad ocean regions, point to initial areas that are still in need of more fine-scaled data collection and analysis efforts. Multi-taxa assessments should be utilized when data are available to provide a comprehensive view of priorities for more cost-effective conservation (Lehtomäki et al., 2019; Critchlow et al., 2022).

Our literature review also emphasized the lack of information for certain sexes, age classes, and connectivity for areas used during migrations. In general, the included references we reviewed have been limited in identifying important areas for a population and their different cross-sections (i.e., grouped by sex, age class, behavior) because of a combination of the small number of tagged animals and the potentially large variation in intraspecific movements (Hebblewhite and Haydon, 2010; Sequeira et al., 2019; Webster et al., 2022). The collection of data can also depend upon the type of device that can be successfully deployed, with restrictions based on taxa and life-stage, related to the habitats frequented, body size, and attachment methods (Hazen et al., 2012). Relatively little data found on migrations, or more extensive movements from one discrete area to another, may have also resulted from the difficulty of accessing marine animals during these periods, when they typically utilize more remote habitats and require more expensive technologies that could collect data over longer durations (Luschi, 2013; Ogburn et al., 2017). Our results conflicted with a review by Shaw (2020), where more studies were found when using the term "migration" compared to "foraging," "dispersal," or "nomadism." However, the great number of studies published on the topic of migration can point to its general popularity, but may not be directly correlated with the relevant connectivity data for our study's objectives, as shown by our final, relatively smaller collection of included references. Holyoak et al. (2008) conducted a similar search, using more search terms compared to our methods, and concluded that behavior was rarely known in studies of movement, dispersal, or migration. Greater investments towards sampling underrepresented sexes, age classes, and during migratory behaviors would yield more accurate estimates of the distribution and area-use on the population level, particularly for the migrations of highly mobile, long-lived marine fish, marine mammals, sea turtles, and seabird populations that require different habitats throughout their life-cycle. Because the literature was limited in publishing data during migration, scientific collaborations should be leveraged to fill the existing gaps on area-use and ecological connectivity by combining telemetry datasets, or connectivity data collected using other research methods, while minimizing costs for improved management decisions (Dunn et al., 2019; Sequeira et al., 2019; Brownscombe et al., 2022).

4.2. *Information for bridging the gap*

A multi-taxa literature review for connectivity information was challenging to synthesize because many studies used different methods to analyze and present results from tracking animal movements. Although we found that most references did not mention archiving data in a repository within the references, knowledge exchange could still be accelerated with greater accessibility to connectivity data, which can occur when data are made more transparent within publications or made available through other sources. Within the peer-reviewed literature, connectivity data can be presented in various formats using different terminologies (Beger et al., 2010; Bryan-Brown et al., 2017; Dunn et al., 2019; Beger et al., 2022) and the resources needed for procuring, organizing, and assessing the quality of information for 173 marine species was considerable. Adjustments were needed for all five steps of our literature review, described by Khan et al. (2003) as: 1) framing the research question, 2) identifying what is relevant (screening), 3) assessing the quality of studies, 4) summarizing the evidence, and 5) interpreting the results. Much effort was needed for filtering (steps 2 and 3), to select a relatively small subset of included references that had the minimum requirements (i.e., geographic information presented from telemetry data) from a large collection (>10,000 references). The number of hours and the proportion of time we spent filtering, before recalibrating our scope to one that was more feasible given our time constraints, were comparable to other meta-analyses of similar size (see Allen and Olkin, 1999). During the data extraction phase of the process (step 4), we conservatively estimated that over 2000 person-hours were spent on reviewing the included literature, noting details in the datasheet template, refining the parameters for the information collected, and controlling for differences among the 13 reviewers by using frequent communication and other quality-assurance/quality-control methods and tools.

Based on the updated collection of >1000 potential references published between 2017 and 2022 that we initially found for the case study species, and an estimate of effort needed to complete a meta-analysis by Allen and Olkin (1999), it would take about 1000 h to complete an update to this literature review. Within this update process, an estimated 300 h would be necessary to thoroughly review and extract information from the collection of over 100 relevant references, based on our experience of about 2.5 h spent per reference. Although the task for updates may seem labor-intensive, especially in growing fields such as movement ecology, here we have developed the protocols for selecting the final collection of references that were included in our review, and these references could be used to analyze future trends in connectivity research for marine megavertebrates. Our thorough review has also identified the included studies with the basic terms and concepts frequently used to analyze connectivity, serving as a baseline for classifying keywords that could facilitate more efficient screening of new references. Currently, approaches for automation techniques to expedite systematic reviews are still being refined and not yet widely adopted by practitioners (O'Mara-Eves et al., 2015; Marshall and Wallace, 2019; O'Connor et al., 2019). If better protocols or text mining tools could be used to assist with future reviews, documenting the details and effort for each step in the process would aid others in implementing improvements and managing expectations (Pham et al., 2018).

A large collection of published references does not necessarily directly relate with the amount of insight on a topic, especially when incomplete collections of data remain unpublished or are not reusable (Campbell et al., 2015; Roche et al., 2015, 2022). As a standard, more comprehensive descriptions of the data collected for connectivity studies should be published and available in different formats, with information that can be discerned as missing versus unknown to guide future studies in filling true gaps whenever possible (i.e., incorporate methods to determine sex, age class, or animal behavior). Within the references included in our literature review, studies frequently omitted key details (because they were unknown, not collected, or excluded) or results were summarized in a way that prevented further analyses. For example, when the season, sex, age class, or specific behavior (i.e., breeding, feeding, migrating) were unknown for tracked animals, we determined that it would be inappropriate to aggregate data across studies when movements were known to differ because of these characteristics. As shown by the case study species, migratory routes and movements of juveniles and adult males were not well-represented within the literature, but this may be the result of underreporting when the authors collected this information but did not disclose sampling details within the publication.

Along with the call for more transparency, sharing data and the reproducible methods for data filtering and processing should be required reporting for all tracking data studies (Hart and Hyrenbach, 2010). The easiest way to minimize potential loss of data was to present standardized information within the main text or supplemental materials of peer-reviewed journal articles, along with dedicating effort to disseminate information to broader audiences by leveraging online data archives or repositories. Utilizing standardized metadata templates for archived data would further improve data reuse (Nguyen et al., 2017; Sequeira et al., 2021; Kot et al., 2022b), but our literature review showed that most studies did not report this within their publications. Further, we acknowledge that data could be archived separately, without a direct connection to a publication, but it was beyond the scope of our study to search data repositories for area-use and connectivity data as primary sources of information. Numerous studies continue to report on the desire to improve data sharing and collaboration (e.g., Gomes et al., 2022; Kaiser and Brainard, 2023; Nuijten et al., 2023), but how this has translated to changes in data release trends, especially in relation to any recent mandates for making data publicly available and reusable within and beyond specific disciplines, remains to be evaluated (e.g., Sholler et al., 2019; Bellard et al., 2022; Bratt, 2022). If data become accessible within a repository or elsewhere post-publication, details from the available data should be directly linked to the original reference and addendums should be included for readers to provide access to the data from the original reference.

For our collection of included references, accessibility of articles and data sharing policies ranged widely. Besides archiving and publishing data in public repositories, scientific research could extend its reach when sharing data within fully open access articles (Clements, 2017). Better support for open access publishing or promoting research outside of peer-reviewed publications would help mitigate existing research biases within the conservation science literature (Wilson et al., 2016). Within the peer-reviewed journals, different options for data sharing levels may be declared at the time of publication, but Tedersoo et al.

(2021) found that less than half of the data claimed to be "available upon request" were able to be obtained from authors of different scientific disciplines. Therefore, data sharing upon publication is particularly important, given that studies that made data "available upon request" had a greater potential for losing data and institutional knowledge over time (Tedersoo et al., 2021). Furthermore, there is a growing trend in the number of scientific journals and granting agencies that require data to be archived in public repositories, but the level of accessibility for the archived data varies greatly (Couture et al., 2018; Huh, 2019; Tedersoo et al., 2021). Solely relying on publishers and funding agencies to appropriately enforce data sharing requirements may not be enough to incentivize researchers to provide better access to data, given that there are currently many options available to publish and archive data among and within journals. Mechanisms are necessary to give researchers more recognition for sharing data, such as the practice of using formal citations for the dataset (Tenopir et al., 2011; Faith et al., 2013), promoting rewards or "badges" for open data (Kidwell et al., 2016), or placing more value on contributorship statements that give credit for roles supporting research that may be different than traditionally defined for authorship (Brand et al., 2015; Allen et al., 2019; Devriendt et al., 2022). Discussions on the many benefits for providing accessible data, such as increased funding opportunities, broader community influence and visibility, and more valuable outputs, should be amplified in an effort to encourage and motivate all stakeholders to share and collaborate for better conservation outcomes (Dallmeier-Tiessen et al., 2014; Nguyen et al., 2017; Kot et al., 2022b).

4.3. Marine connectivity management recommendations

In our literature review, a vast amount of area-use and connectivity information existed that could be used in the design of conservation strategies for marine migratory species, but data were collected using a variety of methods and tools and presented as a mix of "raw" and processed data. We searched for information that best demonstrated connectivity and found that animal movements were most clearly communicated by the presentation of telemetry data and derived products that summarized tracked movements. Area-based management decisions and other related processes used to describe important marine areas have frequently been guided by the best available spatial data (e.g., Hays et al., 2019; Flynn et al., 2021; Holness et al., 2022). More specifically, geospatial data or maps derived from empirical observations or expert input, depicting geographic boundaries and areas, can inform marine spatial plans or analyses after collecting information directly from scientists, existing online data portals, or participatory mapping exercises (e.g., Lombard et al., 2019). Currently, the technologies and analyses used to study animal movements continue to evolve without a clear consensus of best-practices within the marine animal tracking data research community. Along with the increased interest in advancing movement models and the need for greater transparency in applying spatial data to systematic conservation planning frameworks (Hays et al., 2019; Lennox et al., 2019; van Zinnicq Bergmann et al., 2022), there is a growing demand for documented details of data collection efforts, reproducible methods, and maintenance of archived datasets to allow others to build upon previous knowledge. Formal guidelines for standardizing pre- and post-processing animal tracking data have been proposed (see Sequeira et al., 2021) and have yet to be widely adopted. Support for standardized methods would make the process of combining and summarizing multiple datasets more straightforward, allowing area-use and connectivity decisions to draw on a larger body of research. Processes that involve marine management decisions should provide critical feedback to scientific researchers on the types of data and knowledge products (e.g., raw versus processed data, types of analyses and metrics, etc.) still needed for broader applications and what is best for the integration of connectivity data into area-based management decisions.

Our multi-taxa assessment showed that marine management decisions based on some marine migratory species that lacked movement data may need a more cautionary approach. Most of the migratory marine species we reviewed still lacked a comprehensive collection of connectivity data within their respective geographic extent, but insufficient data should not preclude proper conservation. The management of species with an acknowledged paucity of data, such as species categorized by the IUCN Red List as "Data Deficient," has been severely hampered but is still imperative (Jarić et al., 2016; Parsons, 2016). Species recognized as needing higher levels of conservation (based on their current IUCN Red List category and decreasing populations) still lacked baseline data on animal movements and area-use; species we reviewed and categorized as "Critically Endangered" did not have significantly more references identified to include than the eight species on our list that were categorized as "Data Deficient" by the IUCN Red List. For example, all ten Mobulid species listed in our literature review were currently considered "Threatened" under the IUCN Red List but only eight included references were found to have relevant telemetry data (Appendix B). A systematic review by Stewart et al. (2018) also found only a few tracking studies for *Mobula mobular* and *M. munkiani*, and did not find any for *M. hypostoma* or *M. kuhlii.* Results from our literature review confirmed that extensive gaps in baseline knowledge continue to be a limitation for determining the best conservation strategy for highly migratory, widely distributed *Mobula* species (Couturier et al., 2012; Lawson et al., 2017; Stewart et al., 2018). Although the movements of Mobulids have been studied with the use of different methods and technologies (Stewart et al., 2018), knowledge gaps may be the result of *Mobula* spp. being seen as less charismatic and thus less of a research priority compared to other large ray species like *Manta* spp. (Lawson et al., 2017). Regardless of the disadvantages for species with little to no connectivity data, the specific gaps that prevent comprehensive species assessments or the development of necessary management policies need to be identified and communicated.

Finally, a proactive approach to support knowledge exchange and better communication among all stakeholders (e.g., research scientists, data brokers, resource managers) would help to overcome the knowledge gaps that inhibit the conservation of migratory marine species (Dunn et al., 2019; Hays et al., 2019). We also found that most of the peer-reviewed articles presenting relevant connectivity data were readily accessible to the public with or without a journal subscription. However, the tremendous amount of resources needed to synthesize the results of systematically reviewing the scientific literature available to us was a major barrier for knowledge exchange. Other marine resource stakeholders (e.g., lawyers, policy makers, and managers) also have a limited capacity for gathering best available evidence in a timely manner and often benefit from direct communication with scientists and other experts (Pullin et al., 2004; Sallenave and Cowley, 2006; Meretsky et al., 2011) or collaboration with boundary organizations that act as liaisons (e.g., Gray, 2016; Soomai, 2017; Karcher et al., 2022). At the same time, research projects need to consider budgets for developing and disseminating connectivity information in appropriate formats more accessible to non-specialists, outside of peer-reviewed publications, such as organizing discussions/workshops, developing visual tools (e.g., maps, figures), producing policy briefs, or serving spatial data (Grorud-Colvert et al., 2010; Weatherdon et al., 2017; Hetherington and Phillips, 2020). These information sharing mechanisms can extend the reach of scientific research, even when they are traditionally considered supplementary to publications and may not typically be included as primary research objectives or sufficiently funded. Impacts at the science-policy interface have been shown to increase with the presentation of evidence-based recommendations based on broader assessment reports and various other types of informal and formal science communication outputs (Arnautu and Dagenais, 2021; Nuijten et al., 2023; Wagner et al., 2023). Wagner et al. (2023) found that several factors can influence the effectiveness of organizations working at the science-policy interface, such as the levels of stakeholder engagement, diversity of experts, interdisciplinary expertise, and ability to communicate complexity and uncertainty. Recommendations to accelerate knowledge transfer have included coordinating effort and funding among stakeholders with synergistic priorities (Dubois et al., 2020; Meretsky et al., 2011), dedicating resources to directly address specific barriers (Cvitanovic et al., 2014, 2015a, 2015b), and providing more recognition for collaborative activities (Gerber et al., 2020).

5. Conclusions

The published connectivity data and collective knowledge of animal movements vary greatly among marine migratory species and significant data gaps still exist that may impede area-based management policies, especially when managing across taxa, species, regions, sex, age classes, and animal behavior activities. Currently, data presented in the scientific literature could be applied to describe species area-use and connectivity, but the use of standardized metadata templates and archived data products would further their utility in future analyses (e.g., studies that combine multiple datasets, a different area of interest, or include other taxa/species). Finally, research could be elevated beyond the scientific literature (peer-reviewed papers) to enable better communication among scientists and policy-makers if they work together on utilizing data discovery tools (updating and leveraging data repositories), broader communication formats (developing and considering appropriate products), and engagement opportunities (mechanisms to provide feedback).

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.

Data availability

The dataset supporting the conclusions is included within the article (and its additional files).

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Supplementary data

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