Supplementary Information for:

The depletion of wildlife mass migrations

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1. Extended Materials and Methods

Defining species migrations

Drawing on established frameworks (Dingle, 2014), we defined migration as *persistent, directed, and ecologically driven movement between spatially separated habitats*. Such movements may occur on seasonal, annual, or irregular timescales, and encompassing both return and one-way displacements. Beyond the behavioural aspects, this definition aims to recognise that various forms of large-scale movement—including seasonal migrations, permanent relocations, and nomadism—can influence ecosystem processes such as nutrient transport and carbon fluxes. We acknowledge that the inclusion of some taxa (e.g., *Gorilla gorilla*) reflects classifications from conservation databases (UN-CMS) that may incorporate geopolitical or management criteria in addition to ecological ones. To account for this limitation, we resolved for further refining our definition of migrations into subgroups.

First, we define *to-and-fro* migrations as regular, seasonal movements typically between breeding and wintering grounds, and occasionally involving moulting sites as well. This category includes many of the most well-known migrations, such as those of great whales, large ungulates (e.g., *Rangifer tarandus*), salmon runs, and temperate–tropical bird migrations that follow well-established migratory routes.

Second, we describe *loop* migrations as those that, while often seasonal, involve movements across altitudinal or bathymetric gradients, between offshore and inshore, or coastal and inland locations. These migrations generally retain a regular frequency and are frequently associated with breeding activity (e.g., *Caretta caretta*, *Alces alces*), but exhibit greater variability in routes and destinations compared to to-and-fro migrations and are more dispersed.

Finally, *nomadic* migrations are characterised by irregularity in timing, routes, and destinations, distinguishing them from more predictable migratory behaviours. This category helped capture the dynamics of species such as *Loxodonta africana*, which exhibited nomadic movement patterns (Sianga et al., 2024). Importantly, the nutrient, biomass and propagule fluxes for these species should be interpreted slightly differently. In these species, the fluxes still move from feeding areas into non-feeding areas, but these are less well defined spatially. Generally, however, non-feeding areas tend to be more nutrient-depleted, where feeding is less likely. For example, *Physeter macrocephalus* is a nomadic species that hunts for food in deep waters and rest in surface waters (Watwood et al., 2006). For *Loxodonta africana*, dispersal works in a similar way, along the tracks between feeding groups (Chibeya et al., 2021; Poulsen et al., 2021). Such effects are important both at large spatial and temporal landscapes, contributing to the redistribution of nutrients (Doughty et al., 2013) – and likely propagules as well.

Identifying migratory species and obtaining biomass estimates

Using the definition of migration above, we compiled a dataset of 5,519 migratory species from multiple databases (CMS, 1979; Dunn et al., 2019; Miller et al., 2018; Riede, 2000; GROMS, CMS, MiCO, EPBC), peer-reviewed studies and review works (Chowdhury et al., 2021; Dingle, 2014; Holland et al., 2006; Russell et al., 2005; Shuster & Sekiguchi, 2009) and the manual review of the IUCN extinct species list (International Union for Conservation of Nature (IUCN), 2025). This approach ensured maximising taxonomic and geographic coverage. Species names were standardised to resolve taxonomic inconsistences by first finding all synonyms for each given taxon and then removing any repeated instances (Chamberlain & Szöcs, 2013). Subspecies designations were also removed, as not all migratory species were classified to the subspecies level. Species taxonomy was obtained with *taxize* (Chamberlain & Szöcs, 2013) and migratory information was extracted from GROMS (http://www.groms.de) and rfishbase (Boettiger et al., 2012) databases. After, all species were categorised into major taxonomic groups based on migratory information specifying their migration into freshwater and information on the genus, family and order they belonged to: terrestrial and marine mammals oceanodromous and freshwater fish terrestrial and seabirds terrestrial and marine invertebrates, reptiles, amphibians and sea turtles (Supplementary Materials). We also excluded species presenting Diel Vertical Migration, as these are widely distributed across the globe, have been extensively studied and -accounting for mesopelagic fish and zooplankton – represent biomass at least an order of magnitude higher (10^{16} grams) (Hernández-León et al., 2020; Irigoien et al., 2014).

We then estimated species biomass using available abundance and biomass data (Greenspoon et al., 2023; McRae et al., 2014; Ricard et al., 2012; Santini et al., 2018), obtaining data for a total of 2522 species or 44% of the dataset. Direct biomass data were used for marine and terrestrial mammals, while for other taxa, we

converted abundance estimates by multiplying abundance by species-specific body weights from the *rfishbase* and AVONET databases (Boettiger et al., 2012; Hays & Scott, 2013a; Tobias et al., 2022). Sea turtle body size estimates were derived under the assumption of an even sex ratio in population assessments, whereas fish body size data were manually verified when inconsistencies were detected in *rfishbase* estimates, particularly for *Morone saxatilis* and *Carcharhinus limbatus*. All biomass data were transformed to grams and reported with 95% confidence intervals where possible. Finally, to identify species contributing disproportionately to migration fluxes, we defined 'mass migrations' as the group of species accounting for >90% of the total migratory biomass within each taxonomic group (Supplementary Materials Section 4).

Obtaining information on migration distance, migratory routes and trophic groups

To assess shifts in migration distance, migratory routes and trophic groups, we compiled data on migration distances, routes and trophic group from IUCN Red List (https://www.iucnredlist.org), Birds of the World (https://birdsoftheworld.org), Fishbase (https://www.fishbase.org) and peer-reviewed articles (see Supplementary Materials for a full list of all individual articles consulted). Migration distances were recorded as linear displacement, total distance travelled over a given period, or the spatial extent of movement. Since these estimates varied in sample size, geographic coverage, and population representation, we prioritised species-level values derived from the broadest available datasets. For species exhibiting partial migration patterns, we quantified variability by calculating the standard error in movement distances when possible. Where species performed multiple migrations annually—such as distinct breeding and moulting migrations in birds—we used the largest annual movement to ensure a standardised comparison across taxa.

Migratory type and routes were defined for each species classified into 'mass migrations' based on peer-reviewed reports of their annual movements. Due to the current most accepted definition of migration not fitting all types of migrations in the database (Dingle & Drake, 2007), we identified three different types of movements: to-and-fro, nomadic and loop movements. To-and-fro are bi-directional movements between two distant sites. For example, cetacean migrations between feeding sites and breeding sites (Acevedo et al., 2017). Nomadic movements consist of non-bidirectional movements in search of resources or shelter within an area, where the destination may differ across years and resources tend to be ephemeral and scarce (Sach et al., 2019; Stratmann et al., 2021; Teitelbaum & Mueller, 2019). For example, elephant movements looking for water and food. Lastly, loop movements were considered when animals moved away from a given site for a period before returning (usually seasonally), and when animals displayed dispersal dynamics when young and returned to breeding areas as adults. Loop movements would be, for example, moving from higher to lower altitudes in winter, from inshore to offshore areas, or from coastal to inland areas (Hsiung et al., 2018; Murase et al., 2019). When representing migration routes, only the routes for which we could describe the specific route, and the biomass apportioned to it were represented. More detail on species migratory routes is provided in Supplementary Materials.

Modelling population trends across species

We compiled data from the Living Planet and RAML datasets (RAM Legacy Stock Assessment Database, 2018; Ricard et al., 2012; WWF & ZSL, 2022), extracting population-level abundance estimates, the year of observation, species names, site (sampling location), region (broader spatial grouping), and the units of each metric (see Supplementary Materials Section 6 for detailed metric selection). For the Living Planet Database, we included only vertebrate time series that met some standards (Living Planet Index, 2016), requiring at least two years of data, accepted abundance metrics (counts, densities, indices, biomass, proxies such as breeding pairs or CPUE, samples, or occupancy), consistent methods and spatial coverage (with any changes treated as separate entries), and traceable sources, while excluding experimental studies, survival or recruitment only, uncorrected changes in method or area, and unstandardised catch or hunting data. For the RAML database, we filtered the 74 available metrics to exclude those lacking ecological relevance to population size (e.g., aquaculture biomass, mortality, recruitment loss), driven primarily by management targets or external factors (e.g., reference points), or statistically dependent on other variables (e.g., ratio-derived metrics). We retained core abundance measures—total biomass (TB), total abundance (TN), and spawning stock biomass (SSB)—and, for harmonisation with LPD and prior reporting (UNEP-WCMC, 2024a), included catch-per-unit-effort (CPUE) despite known technological biases (Ye & Dennis, 2009), while adding closely related metrics (e.g., SSB for males, TBbest) only if the main ones were unavailable and excluding CPUE whenever another primary metric was present. When multiple metrics existed for the same species and location, we prioritised TB, TN, or SSB to minimise redundancy. Finally, we merged the two datasets and harmonised taxonomic information using a species synonym list to ensure consistency with other datasets in the study.

To specifically target mass migrations species across time, we selected species that potentially presented biomass above 10^{11} grams (<0.01% of total current migratory biomass) at some point in time. To do so, we first computed the log-response ratio from population abundance data, dividing all dates in the time series by the population abundance data on the first date of each time series. Using this ratio, we estimated putative biomass over time per species and kept all species that presented putative biomass above 10^{11} grams at least at one point across all their time series. As a result, we kept a dataset with 383 species for modelling, which we divided into each taxonomic group for data analysis: terrestrial mammals (25 spp.), marine mammals (36 spp.), marine fish (82 spp.), diadromous fish (5 spp.), terrestrial birds (151 spp.), seabirds (60 spp.), marine invertebrates (16 spp.) and sea turtles (7 spp.). We did not apply further filters to the overall dataset, regarding minimum length of each time series and maximum number of missing data, since our goal in the analysis was not to find an overall trend across species but to account for variability across populations and metrics to obtain population trends per species.

To estimate species-level trends, we used Bayesian multilevel generalised additive models that accounted for spatial and temporal correlations, and variability across metrics. We specified a smooth (k=6) for the general time trend in the model, and another smooth (k = 4) to model individual species' time trends, using Year in both cases as a variable for time. We incorporated spatial dependencies (e.g., due to shared environmental conditions and dispersal) by including a covariance matrix accounting for Haversine distances across sites, which helped better explain further uncertainty in population size and variability of residuals linked to Site. Given the high clustering of bird populations in some regions and their general large mobility, we resolved to cluster sites within 100km to allow for a larger focus on spatial autocorrelation at larger scales. A first-order autoregressive correlation structure per time series was included to model temporal autocorrelation. Finally, we included a random intercept for metric type. Models were specified and fitted using brms (Bürkner, 2021) in R v 4.5.1. For more details on model specification and assumptions, see S7 and S8. This modelling approaches allowed enough flexibility to model species with disparate trends and avoided overfitting to high-frequency variability. Using this approach, we were able to obtain estimates at the start and end of each time series which were representative of the species population trend.

Modelling biomass to propagate uncertainty

To ensure we propagated uncertainty across all species, we modelling species biomass while explicitly accounting for species-level variance, so as to provide a measure of uncertainty for species with missing data (i.e., mainly fish species). We first compiled a unified dataset of mass migratory species that integrated multiple data sources, including primary biomass estimates (from RAM, Greenspoon, Callagher, and literature datasets), trait data (body mass, trophic level, and range size) from AVONET for birds (Tobias et al., 2022) and FishBase for fishes (Froese & Pauly, 2024), and complementary ecological attributes such as IUCN conservation status, migration type, and migration system. Missing trait data (<150 cases for body size and <50 for range size) were filled manually using trait database means for closely related taxa.

We fitted a Bayesian multilevel model with log-transformed biomass as response variable. As predictors, we specified a smooth function of species' body mass and geographic range size, including both global smooths and taxon-specific deviations using thin-plate spline terms. Taxon-specific body size and range-size variation was incorporated through factor-smooth interactions and random effects on slopes and intercepts across taxonomic groups, trophic levels, IUCN categories, migration types and migratory system (i.e., the ecosystems where migration was performed e.g. offshore to inshore). Crucially, we introduced observation-level error by including the variance observed per species through a log-linear variance function. For cases where uncertainty was missing, species-level variance was imputed as the mean across species, thus allowing to generate predictions with uncertainty. Priors were weakly informative, including Student-t and exponential distributions for intercepts and standard deviations. Models were specified and fitted using brms (Bürkner, 2021) in R v 4.5.1. For more details on model specification and assumptions, please read the sections 'Description of model variables and model specification' and 'Model diagnostics'.

Posterior sampling was performed using four chains of 12,000 iterations each. Convergence and model adequacy were confirmed through posterior predictive checks, and visual inspection of residual and fitted distributions. Model performance was evaluated using approximate leave-one-out cross-validation (LOO-CV) and the an R^2 of 0.8. For each species, we generated 12,000 posterior draws of expected biomass by back-transforming predictions to the natural scale.

Obtaining biomass estimates for the '1950 benchmark' and the '1800 benchmark'

We quantified biomass estimates relative to two temporal baselines: the '1950 benchmark'—which aligns with most biodiversity and migratory assessments—and the '1800 benchmark', representing the earliest available historical records (typically <1950 and often ~1800 or earlier) for each species. To generate these estimates, we combined three complementary sources of information: (a) biomass predictions from Bayesian multilevel models, obtaining 12,000 posterior samples per species, (b) population change predictions from Bayesian multilevel models fit using brms, from which we drew 4,000 posterior samples per species and year to estimate predicted population abundance trajectories across years; and (c) manually compiled historical biomass values (i.e., the earliest available records per species), including population size records for extinct species. In all three cases, we log-transformed the values, estimated the mean and standard deviation, and generated 4,000 log-normal bootstrap samples per species and year, assigning zero present-day biomass to fully extinct taxa. We computed biomass change calculations for each one of the 4,000 iterations and computed the means and credible intervals afterwards. For 0 estimates and estimates without uncertainty, SD was defined as 0. Notably, 92.3% of species had time series data that fell within the 1950 benchmark, while only 7.7% had records that extended back to the 1800 benchmark, reflecting the relative scarcity of older data across taxa.

To reconstruct biomass at the 1950 benchmark, we first separated species with predictions up until before and after 1950. For those with predictions before 1950, we computed a species-specific population change ratio for each posterior draw so that all population change ratios were either after or on 1950. To transform pre-1950 population change ratios we used the following formula

$$\hat{r}_{1950} = \widehat{N}_{1950}/\widehat{N}_{\text{recent}}, \quad (1)$$

where $\hat{r}_{1950}$ represents the population change ratio at 1950, calculated as the ratio of the log-back-transformed population size in 1950 ($\widehat{N}_{1950}$) to that of the most recent year ($\widehat{N}_{\text{recent}}$), both originally expressed relative to the earliest available population size record. For species lacking direct pre-1950 coverage, we used the earliest available model time point to approximate $\hat{r}_{1950}$ or, when historical biomass observations existed, used the bootstrapped historical biomass replicate instead. Once all population change ratio were harmonised to changes at 1950 and later, biomass estimates at year 1950 were obtained by rescaling the present-day biomass replicate

$$B_{1950}^{(d)} = B_{\text{recent}}^{(d)} \times \hat{r}_{1950}^{(d)}, d = 1, \ldots, 1000, \quad (2)$$

where $B_{1950}^{(d)}$ was the estimated biomass at year 1950 per replicate *d*, $B_{\text{recent}}^{(d)}$ was the most recent biomass estimate per replicate and $\hat{r}_{1950}^{(d)}$ in the population change ratio per replicate *d* for the 1950 benchmark. For each species, there were 1000 replicates (*d*).

For the 1800 benchmark, we first checked whether the earliest biomass estimates had been collected manually, or were they based on model projections. When both manual and model estimates were available for a given species and year, we prioritised model estimates to facilitate harmonisation with with previous LP projections. To estimate biomass at the 1800 benchmark using model projections, we considered that $\hat{r}_{1800} = \widehat{N}_{\text{recent}}$ since the latter consider the log-backtransformed ratio between the most population size estimate and the earliest population size estimate. Then, we applied the following formula

$$B_{1800}^{(d)} = B_{\text{recent}}^{(d)} \times \hat{r}_{1800}^{(d)}, d = 1, \ldots, 1000, \quad (3)$$

where $B_{1800}^{(d)}$ was the estimated biomass at year 1800 per replicate *d*, $B_{\text{recent}}^{(d)}$ was the most recent biomass estimate per replicate *d* and $\hat{r}_{1800}^{(d)}$ in the population change ratio per replicate for the earliest date on each time series. For each species, there were 1000 replicates (*d*).

Computing Biomass Change across groups (taxonomic, trophic and migratory) and species

Biomass change across groups

For each replicate d, we summed species-level biomass within the focal grouping (taxonomic group, trophic group, or migratory system) to obtain group-level biomass at present**,** and for1950 and 1800 baselines. Biomass change was then expressed as the proportional difference:

$$\Delta B^{(d)} = \frac{B_{\text{present}}^{(d)} - B_{\text{baseline}}^{(d)}}{B_{\text{baseline}}^{(d)}}, \quad (4)$$

where ΔB was the biomass change defined per replicate d as the proportional biomass increase or decrease relative to the 1950 or 1800 benchmark, B_{present} was the biomass estimate at present per replicate d, B_{baseline} was the biomass present either at the 1950 or the 1800 baseline, per replicate d. We summarized uncertainty across the 1,000 replicates (d) by reporting the mean and standard deviation of ΔB, and 95% credible intervals derived from the replicate. Importantly, this workflow accounted for both the original uncertainty of biomass estimates (B_{present}; via log-normal bootstrapping of estimated biomass) and model projections (B_{baseline}; via posterior sampling from brms), ensuring uncertainty propagation.

Biomass change across species

Given recent reports of migratory species recovery (Barker et al., 2022; Miller et al., 2019) and the significant depletion of migratory biomass observed in the early stages of this study, we further examined the temporal dynamics of both biomass decline and a potential posterior recovery. Specifically, we investigated whether the proportional decrease in migratory biomass was more accentuated in older dates, and whether recovery trends became more pronounced in more recent datasets.

To estimate biomass change at the species level, we first identified four key timepoints in each species' biomass trajectory: (i) the year of minimum biomass, (ii) the year of maximum biomass, (iii) the year preceding the biomass minimum with the highest biomass (if any), and (iv) the most recent year with available data – resulting with a maximum of three trends per species (but often only one or two trends could be extracted). Trends were derived from posterior draws of predicted biomass, averaged across replicates per year. We then computed three proportional biomass changes across these landmark years, per species and replicate: 1) between the previous peak (iii) and the minimum year (i) (ΔB_1), 2) between the minimum (i) and maximum (ii) year (ΔB_2), between the minimum (i) or maximum (ii) year (whichever occurred later) and the most recent year (iv) (ΔB_3). Each change was calculated as a proportional difference between biomass values at the two corresponding years:

$$\Delta B^{(d)} = \frac{B_{\text{after}}^{(d)} - B_{\text{before}}^{(d)}}{B_{\text{before}}^{(d)}}, \quad (5)$$

where $B_{\text{before}}^{(d)}$ and $B_{\text{after}}^{(d)}$ were species-level biomass estimates from posterior predictions at the respective years, per replicate d. We excluded short intervals (≤ 3 years) to reduce the influence of stochastic fluctuations and retained only meaningful temporal contrasts. To summarize uncertainty, we computed the mean and 95% credible intervals of ΔB across posterior samples. Additionally, we expressed biomass changes in absolute terms (i.e., biomass differences in tonnes) and in annualised rates (ΔB divided by the number of years between estimates).

Changes in migratory distance across taxonomic groups

To estimate the change in migratory distance over time, we summed biomass per taxonomic group and temporal benchmark (i.e., 2020, 1950, 1800). Then, we divided each species biomass at a given temporal benchmark by the corresponding summed biomass. We multiplied migratory distance by the resulting weighting factor, and summed the resulting weighted distance per taxonomic group and temporal benchmark to obtain the group-level weighted-average distance per taxonomic group and temporal benchmark. Finally, we computed the change in migratory distance as

$$\Delta D^{(d)} = \frac{D_{\text{after}}^{(d)} - D_{\text{before}}^{(d)}}{D_{\text{before}}^{(d)}}, \quad (6)$$

where $D_{\text{before}}^{(d)}$ and $D_{\text{after}}^{(d)}$ were group-level average distance estimates from posterior predictions at the respective years, per replicate d. To summarise uncertainty, we computed the mean and 95% credible intervals of ΔD

across posterior samples. In this case, uncertainty estimation was not possible due to the scarcity migratory distance uncertainty in our dataset.

2. Description of data sources and data compilation for all analyses

Finding migratory species in the literature

To identify migratory species, we performed an initial exploration of definitions and databases. As a result, we identified a few big databases listing species of interest that showed migratory behaviours, but also species which national transboundary movements were of interest for conservation (e.g. *Gorilla gorilla*, CMS). Given that these movements did not strictly fit the definitions for migrations (Dingle & Drake, 2007), we resolved for classifying species into different types of movements (i.e., to-and-fro, nomadic and loop movements,) so that these distinctions could be later made if needed.

We obtained most migratory species from the GROMS database (Table S1), which was complemented with the CMS database, the MiCO database, the EPBC database and the rest were obtained from the literature. While this approach ensured capturing most species of migratory interest, it still failed to appropriately include invertebrates and extinct species. Thus, we made an explicit effort to include these by manually examining marine invertebrate species in the RAML database and the IUCN RedList for extinct species to find evidence of migratory behaviour (IUCN, 2025). As a result, we were able to include a few important extinct migratory species (e.g., *Ectopistes migratorius*) and marine invertebrates (e.g., *Pandalus borealis*). Nonetheless, both terrestrial and marine invertebrates remain largely unreported in terms of identifying migratory species, although considerable efforts have been made for butterflies (Chowdhury et al., 2021).

To join all databases, we first obtained all synonyms for each species of each database. To do that, we first removed the subspecific epithet to ensure equal resolution across all species. Then, we found all synonyms for each species and database, obtaining > 10 synonyms in some cases. We removed again subspecific epithets and created a 'library' dataset which linked all possible synonyms of a given species to a single name (Chamberlain & Szöcs, 2013). We manually checked the list to correct for cases where a single synonym was given to multiple species. We then used that dataset to harmonise species names across all databases and obtained a final dataset with 5519 species.

Table S1. Summary of sources used to obtain the list of migratory species for the mass migrations database.

Source	Number of Species	Rationale
GROMS (http://groms.de)	4431	Global Register of Migratory Species (GROMS) provides a comprehensive database of migratory species across taxa, compiled from various international sources.
CMS (https://www.cms.int)	655	The Convention on the Conservation of Migratory Species of Wild Animals (CMS) lists species with transboundary migrations that require international conservation efforts.
MiCO (https://mico.eco)	900	The Migratory Connectivity in the Ocean (MiCO) system compiles marine species migration data, integrating telemetry and genetic studies.
EPBC (http://www.environment.gov.au)	158	The Australian Environment Protection and Biodiversity Conservation (EPBC) Act lists species of national conservation concern, including migratory species.
Dingle 2014	228	This book provides an extensive review of migration across multiple taxa, including birds, mammals, insects, and marine species.
Chowdhury et al. 2021	568	This study synthesises global patterns of butterfly migration, providing a species-level perspective on insect movement.
Russell et al. 2005	89	This paper reviews migratory patterns in amphibians and reptiles, discussing orientation mechanisms and ecological drivers of movement.
Other peer-reviewed references	34	Grouper species included based on spawning aggregation studies, highlighting the importance of monitoring these migrations for conservation.
Other peer-reviewed references	95	Includes invertebrate species with well-documented migrations, such as horseshoe crabs and cuttlefish, which undertake seasonal movements for reproduction and environmental conditions.

Finding biomass estimates in the literature

We identified databases available to contribute biomass information to our dataset. Among them, we found readily available published databases for mammals and birds (Table S2). For fish and marine invertebrates, we resolved to use the RAML database, which contains information on fish catch data around the world and provides biomass and abundance data. For birds, only abundance data was provided, which was converted to

biomass by multiplying for body weight provided by the AVONET database (Tobias et al., 2022). For fish and marine invertebrates, biomass information was missing in some instances – since data varied largely depending on e.g. geographic region or commercial interest for a given species. For these cases, we used abundance data and converted it to biomass by multiplying for body weight data in FishBase (Boettiger et al., 2012). It is worth noting, however, that body weight data in FishBase is biased toward large individuals and this could have introduced a bias for species growing very large as adults. We corrected for this bias by checking resulting biomass estimates per species and corrected the cases of *Morone saxatilis* and *Carcharhinus limbatus* since we detected inconsistencies with that data. No biomass data was found for freshwater fish or for terrestrial invertebrates.

Table S2. Summary of sources used to obtain biomass data for the mass migrations database.

Taxonomic group	Current biomass	Historical biomass estimates	Body Weight
Terrestrial mammals	Greenspoon et al. (2023)	WWF & ZSL (2022)	-
Marine mammals	Greenspoon et al. (2023)	WWF & ZSL (2022)	-
Terrestrial birds	Callaghan et al. (2021)	WWF & ZSL (2022)	Tobias et al. (2022)
Seabirds	Callaghan et al. (2021)	WWF & ZSL (2022)	Tobias et al. (2022)
Marine fish	RAM Legacy Stock Assessment Database (2018)	RAM Legacy Stock Assessment Database (2018)	Boettiger et al. (2012)
Diadromous fish	RAM Legacy Stock Assessment Database (2018)	RAM Legacy Stock Assessment Database (2018)	Boettiger et al. (2012)
Marine invertebrates	RAM Legacy Stock Assessment Database (2018)	RAM Legacy Stock Assessment Database (2018)	Boettiger et al. (2012)
Sea turtles	de Castilhos et al. (2022); Department of Climate Change Energy the Environment and Water (2008); Mortimer et al. (2020); NOAA (2025a-d) New York State Department of Environmental Conservation (2013); Sato (2017)	WWF & ZSL (2022)	Georges & Fossette (2006); Hays & Scott (2013b); Limpus (2007); Renaud (1995)
Extinct Species	-	IUCN Red List (2025)	Bucher (1992); Garcia (2000); Li et al. (2021); Marine Geospatial Ecology Lab at Duke University (2025); Montevecchi & Kirk (2020); Morrow & Monfort (1998)

We reviewed the literature again to find abundance and biomass records for the terrestrial and marine mammal mass migrations. In some cases, estimates went back only 10 or 20 years (1950 benchmark), while in other instances in went as far as 200 or 300 years back (1800 benchmark). To estimate historical global abundance, we extracted data from ecological literature reporting either (a) direct historical abundance estimates or (b) relative changes in population size (e.g., proportional declines such as 0.5) (Table S3). These relative changes were either reported directly or calculated by comparing historical and current abundance values provided in the same study. When only relative changes were available, we applied them to current abundance estimates to reconstruct historical values. Notably, when multiple population estimates were found, we opted to include the most conservative one (60 vs 30 million *Bison bison*; (Lott, 2002; McHugh, 1979).

Standard errors (SEs) were inconsistently reported across studies, so a consistent method for propagating uncertainty was needed. When only confidence intervals (CIs) were reported, we assumed a normal distribution and used the upper and lower bounds to estimate the mean and approximate SE. To obtain standard errors (SEs) for reconstructed historical abundances, we computed SE using the stanrdard formula. When enough information was not available, we applied several variants of the delta method depending on the type of information provided in each study. First, when a study reported only a mean and its 95% confidence interval (CI), we assumed a normal distribution and converted the CI to an SE using

$$\mathrm{SE}(X) = \frac{U - L}{2 \times 1.96} \qquad (7)$$

When historical abundance was estimated as the product of current abundance X and a proportional population change R, the SE of the product was approximated with the two-variable delta method,

$$\mathrm{SE}(XR) \approx XR\sqrt{\left(\frac{\mathrm{SE}(X)}{X}\right)^2 + \left(\frac{\mathrm{SE}(R)}{R}\right)^2} \qquad (8)$$

For cases where a study reported a quotient of two uncertain quantities, we used the delta-method approximation for ratios,

$$\mathrm{SE}\left(\frac{X}{Y}\right) \approx \left|\frac{X}{Y}\right| \sqrt{\left(\frac{\mathrm{SE}(X)}{X}\right)^2 + \left(\frac{\mathrm{SE}(Y)}{Y}\right)^2} \qquad (9)$$

In the few cases where the historical estimate depended on a composite function involving both an uncertain numerator and denominator—specifically a term of the form $H = X(A/B)$—we applied the multivariate delta method,

$$\mathrm{SE}(H) \approx \sqrt{\left(\frac{X}{B}\right)^2 \mathrm{Var}(A) + \left(\frac{-XA}{B^2}\right)^2 \mathrm{Var}(B)} \qquad (10)$$

In these equations, X denotes the current abundance estimate, R the proportional historical change applied to reconstruct historical values, and H the resulting historical abundance. The symbols A and B are numerator and denominator terms in composite ratios reported in the literature; Y represents a second uncertain variable for ratio formulations; k is any fixed scaling constant; U and L are the upper and lower limits of a reported 95% CI.

Table S3. Sources of the earliest abundance records per terrestrial and marine mammal species included in the mass migrations list. Non-bold references are cited within bold ones. Species for which data were not found are indicated with NA.

Species	Estimate ± SE (Year)
Terrestrial mammals	
Loxodonta africana. The 1814 abundance estimate was obtained by calculating the ecological carrying capacity of Africa for elephants using White's (1983) vegetation map, historical reports of elephant presence (e.g. Bryden 1903), and density estimates from more recent studies (e.g. Barnes 1989; Burrill & Douglas-Hamilton 1987). Vegetation types were classified as suitable or unsuitable elephant range, and maximum densities were applied to estimate a pristine carrying capacity of approximately 27 million elephants (**Milner-Gulland & Beddington, 1993**).	26913000 (1814)
Odocoileus hemionus. The authors used roadside count indices from 1964 (72.7 deer/1.6 km) and 1989 (15 deer/1.6 km) to estimate population size change over time. These two points were used to infer historical abundance (**Peek et al., 2002**).	21276077.58 ± 2226077.58 (1964)
Alces alces	NA
Cervus elaphus	NA
Loxodonta cyclotis. The authors obtained the 1937 abundance estimate by using a conservative historical density of 0.5 forest elephants per km² applied across the full 2.2 million km² extent of Central African forest, resulting in a projected population exceeding one million individuals. This non-conservative estimate was based on assumed densities in areas with little or no poaching. In contrast, a conservative estimate of 500,000 elephants was used in the context of IUCN Red List criteria and derived from earlier modelling by Michelmore et al. (1994), which back-calculated historical populations using known densities from low-poaching sites **(Maisels et al., 2013).**	500000 (1937)
Rangifer tarandus. The authors obtained the 1980 estimate of 935,000 caribou from Bergerud (1980), who compiled population data across North America based on surveys and census records available at the time. The historical abundance estimate of 3 to 5 million caribou was inferred from earlier literature. The comparison between these figures is used to infer population change globally (**Luensmann, 2007**).	9274042.78 (<1800)
Connochaetes taurinus. The authors estimated the 1977 abundance of resident wildebeest in the Masai Mara at approximately 119,000 individuals using aerial survey data. By comparing it with subsequent surveys conducted during non-migratory periods, they identified an 81% decline to about 22,000 individuals by 1997. This estimate was used to infer global trends for the species **(Ottichilo et al., 2001).**	8157894.73 (1977)
Eidolon helvum. The 1962 estimate by Mutere placed the Eidolon helvum population in Kampala at over 200,000 individuals. While the authors highlight a sharper drop based on the October 2002 count (~23,000 bats), a more conservative comparison can be made using the March 2003 estimate of approximately 43,000—the highest value recorded near the end of the monitoring period—representing a ~79% decline over 40 years. This long-term decline was used to infer broader patterns of population reduction potentially occurring at global scale **(Perpetra & K., 2009).**	5319443172.09 (1962)
Equus quagga. A 25% decline in Plains Zebra abundance was calculated by comparing the 1992 global population estimate of 671,000 individuals (Duncan and Gakahu 1992) with the 2016 estimate of approximately 500,000, based on similar survey methods. This change was used to infer a global decline in abundance across the species' range **(King & Moehlman, 2016)**.	666666.66 (1992)
Elephas maximus. The study cites an early global abundance estimate of 41,410–52,345 wild Asian elephants from Sukumar (2003), based on expert opinion and historical records, and a more recent estimate of 4,189–6,999 from Williams et al. (2020), drawn from updated field data and IUCN assessments. I used these two sources, as reported in the study, to infer the scale of global population decline over time (**Htet et al., 2021**).	275460.57 ± 964.74 (2003)
Giraffa camelopardalis. The authors derived the 1970s–1985 abundance estimates for giraffes by compiling the best available data per subspecies closest to 1985 (roughly three generations ago), using aerial and ground surveys, photographic capture-recapture, interviews, and expert estimates. Two global estimates for that period ranged from 151,702 to 163,452 individuals, compared to 97,562 individuals in 2015, indicating a 36–40% decline in mature individuals across the species' range **(Muller et al., 2018).**	157577 ± 1149.01 (1970)
Kobus kob. The 2000 population estimate of Buffon's kob in Faro National Park was approximately 42,524 individuals, based on previous surveys by Gomsé & Mahop, with the species comprising nearly half of the park's total mammalian abundance. In 2018, a new survey using distance sampling across 145 transects estimated the population at 4,094 ± 1,303 individuals—an ~80% decline. This relative change was used to infer the global abundance of Buffon's kob in the year 2000 (**Kondasso Taïga et al., 2021**).	11016977.48 (2000)
Rousettus aegyptiacus	NA
Ovibos moschatus. The authors inferred the 1998 global abundance (~157,100) by aggregating regional survey data, including 87,800 Muskoxen on Banks and Victoria islands, which accounted for 61% of Canada's Muskoxen. This value was compared to the 2019 global estimate of 127,102 individuals, resulting in a proportional change of –0.081 (i.e., an 8.1% decline over the three-generation period) **(Gunn & Forchhammer, 2022).**	251045.80 (1998)
Rousettus angolensis	NA

Ursus arctos	NA
Phyllostomus hastatus	NA
Gorilla gorilla. They estimated the ancestral abundance of Cross River gorillas around 1691 using coalescent-based demographic modelling informed by microsatellite genotypes from both ~100-year-old museum specimens and contemporary samples. Their analysis revealed a ~60-fold decline in effective population size starting ~320 years ago, decreasing from ~16,260 to an estimated 271 individuals by the time of study (2011), largely driven by habitat fragmentation and intensified anthropogenic pressure (**Thalmann et al., 2011**).	19200000 (1691)
Procapra gutturosa. The authors obtained the 1994 abundance estimate for the Mongolian gazelle using unpublished data from an aerial survey (**Milner-Gulland & Lhagvasuren, 1998).**	2670000 (1994)
Equus kiang.	NA
Vicugna vicugna. Multiple sources indicate that there had been at least 2 million before the Spanish conquest, and with potentially much larger numbers **(Cueto & Ponce, 1985; Hofmann et al., 1983; Wawrzyk & Vila, 2013; Wheeler & Domingo Hoces, 1997).**	2000000 (1500)
Bison bison. The estimate of 32 million bison is based on historical eyewitness reports describing vast herds spanning miles, which researchers converted into population numbers by estimating herd size, area covered, and animal density, then combining these across regions (**McHugh, 1979**).	32000000 (<1800)
Pan troglodytes. An estimate of over 50% chimpanzee population decline across three generations (approximately 20–30 years) is based on multiple lines of evidence, including Walsh et al. (2003). This includes steep declines in nest encounter rates, such as a 90% drop in Côte d'Ivoire between 1989–1990 and 2007, extensive habitat loss documented by satellite data, and severe local population crashes from hunting and disease outbreaks like Ebola **(Chapman et al., 2020)**.	805358 (1990)
Equus hemionus.	NA
Marine mammals	
Balaenoptera physalus. For fin whales, the earliest abundance estimate (~360,000 individuals) was derived using coalescent models applied to mitochondrial DNA (mtDNA) diversity from 235 North Atlantic individuals. This method infers a long-term historical population size averaged over thousands of generations, not tied to a specific year, but rather representing conditions prior to major human exploitation (likely millennia before the 19th century). In contrast, the most recent abundance estimate (~56,000 individuals) is based on contemporary survey data from the late 20th century, likely around the 1990s, using visual or acoustic census methods cited from IWC and related sources **(Roman & Palumbi, 2003)**.	642857.14 ± 105685.13 (1850)
Physeter macrocephalus. The earliest abundance estimate for sperm whales in 1711 (1.95 million) was reconstructed using a modified theta-logistic population model that incorporated historical catch records, spatial subpopulation dynamics, and demographic impacts of social disruption from whaling. The model was calibrated to match a 1993 global estimate (736,053 whales) derived from extrapolated survey data using habitat suitability modelling. This approach allowed the authors to back-calculate the pre-whaling population size despite the lack of direct historical abundance data **(Whitehead & Shin, 2022)**.	1949698 ± 335054 (1711)
Megaptera novaeangliae. For humpback whales, the earliest abundance estimate (~240,000 individuals) was inferred from mitochondrial DNA diversity using coalescent models that estimate long-term effective population size over evolutionary timescales, not a specific historical year. This genetic estimate reflects an average population size over tens of thousands of years, not necessarily just before whaling began. In contrast, the most recent abundance (~9,300–12,100 individuals) refers to modern population estimates from the late 20th century, based on direct observational data such as surveys and mark-recapture studies **(Roman & Palumbi, 2003)**.	1884112.14± 1945841.29 (1850)
Balaenoptera bonaerensis. The 1780 estimate for Antarctic minke whale abundance (~319,000 individuals) was obtained through ecosystem modelling of krill–predator interactions over 220 years. It relied on fitting simulations of population trajectories to observed catch records and recent abundance data using biologically plausible constraints and predator–prey dynamics (**Leaper & Miller, 2011**).	670000 ± 195959.59 (1780)
Balaenoptera acutorostrata. For North Atlantic minke whales, the earliest abundance estimate (~265,000 individuals) was derived using coalescent models based on mitochondrial DNA (mtDNA) diversity, representing long-term average population size over evolutionary timescales—not a specific historical year, but spanning thousands of years prior to industrial whaling. The most recent estimate (~149,000 individuals) refers to modern population counts from the late 20th century, based on survey and observational data (likely from the 1980s–1990s, e.g., Smith et al. 1999) **(Roman & Palumbi, 2003)**.	355704.69± 81838.10 (1850)
Balaenoptera musculus. The earliest estimate—239,000 whales in 1905—was obtained by fitting a Bayesian logistic population model to historical catch data and post-whaling sightings, allowing the model to reconstruct the pre-exploitation abundance as the population's carrying capacity. The most recent estimate—1,700 whales in 1996—was derived from a Bayesian exponential model calibrated with current sightings data (IDCR/SOWER, JSV, JARPA) and used to track post-whaling population recovery. The proportional change across these two estimates was extrapolated to global abundance **(Branch et al., 2004)**.	1.05E+06 ± 345299.69 (1905)
Lobodon carcinophaga. The 15 million crabeater seal estimate by Laws (1984) was derived from a compilation and upward adjustment of Erickson's 1968–1973 regional survey data. It is widely cited but should be interpreted as a best guess minimum, not a robust statistical estimate. Laws himself considered it conservative and noted that the real number could be 2–3 times higher, though this remains unverified **(Southwell et al., 2012)**.	15000000 (1970)
Balaenoptera edeni	NA
Pagophilus groenlandicus. The estimate of ~11 million harp seals in the early 1800s was derived by fitting a population model to historical commercial catch records dating back to the 18th century. The model assumed density-dependent growth and a carrying capacity of 12 million, projecting backward from modern data on pup production, reproductive rates, and human removals. This reconstruction assumes environmental conditions at that time were similar to today, providing an estimate of pre-exploitation abundance **(DFO, 2012)**.	11000000 (1800)
Balaena mysticetus. Around 1800, the East Greenland–Spitsbergen population of Balaena mysticetus was already in significant decline due to intensive commercial whaling that began in the early 1600s. Historical sources cited in Christensen et al. (1992), particularly Reeves (1980), suggest the stock may have originally numbered between 20,000 and 30,000 whales, though by 1800 the actual abundance was likely considerably lower. No precise population estimate exists for that year, but whaling records indicate the population was still large enough to sustain catches, albeit shrinking (**Christensen et al., 1992**).	25000 ± 2551.02 (1800)
Balaenoptera borealis. The earliest abundance estimate for Balaenoptera borealis (sei whale) dates to 1929 and was derived using demographic modelling based on historical catch data and assumptions about population decline. The estimate suggests a pre-whaling abundance of less than 100,000 individuals, but it is not endorsed by the IWC due to substantial uncertainties and the fact that it reflects only the mature portion of the population (**Leaper & Miller, 2011**).	100000 (1929)

Globicephala melas. The 1987 estimate of long-finned pilot whale abundance was based on a ship survey using single-platform visual observations with no correction for detection bias and likely overestimated group sizes, especially by Faroese observers. In contrast, the 2015 estimate used improved methods, including independent double platforms and standardized group definitions, yielding a higher and more reliable estimate. Despite differences in methodology, both estimates were derived from the same core survey area (6-SIR) using conventional distance sampling. These two estimates were used to infer historical abundance (**Pike et al., 2019**).	45320.46 ± 31577.71 (1987)
Hyperoodon planifrons	NA
Globicephala macrorhynchus. The earliest reliable abundance estimate for the northern form of the short-finned pilot whale was obtained in 1985 through a dedicated line transect survey with seven primary sightings, resulting in estimates ranging from 6,287 to 8,646 individuals depending on how school size was adjusted. The most recent estimate in 2006, using a similar survey and updated detection models, showed a marked decline to 2,431–3,879 individuals. These two estimates were used to infer historical abundance (**Kanaji et al., 2011**).	1805539.67 ± 5045336.45 (1985)
Mirounga leonina	NA
Delphinus delphis	NA
Eschrichtius robustus. The estimate of ~96,000 pre-whaling Eastern gray whales comes from Alter et al. (2007), who used nuclear microsatellites and mitochondrial DNA to model historical population size via coalescent simulations. Their analysis suggested that the population prior to industrial whaling (early 1800s or earlier) was significantly larger than today, with a 95% confidence interval of 76,000–118,000 individuals (**Brüniche-Olsen et al., 2018**).	96000 ± 10606.06 (1800)
Arctocephalus pusillus. To generate the estimates, the authors used an age- and sex-structured population model fitted to six aerial pup count surveys (1972–1993) and detailed harvest records by age and sex starting in 1901. Demographic parameters such as survival and pregnancy rates were informed by empirical studies, while key unknowns (initial pup production in 1901, density-dependence threshold, and territorial bull survival) were estimated by minimizing the mismatch between modelled and observed pup counts. The resulting population trajectory, including mean and 90% confidence interval, was extracted from Figure 3a and used to estimate historical abundances (**Butterworth et al., 1995**).	125875.00 ± 30553.55 (1973)
Pusa hispida.	NA
Halichoerus grypus. The earliest estimate of Baltic grey seal abundance (~90,000 seals around 1900) was reconstructed from historical hunting records, adjusted for unregistered kills such as unrecovered carcasses. The most recent estimate (~19,400 seals in 2003) was derived by combining regional moulting-season counts with a mark-recapture estimate from 2000, then projecting forward using a documented annual growth rate of 7.5% (**Harding et al., 2007**).	1465979.38 (1900)
Odobenus rosmarus. Taylor et al. (2017) presented modelled Pacific walrus population sizes from 1975 to 2015, derived using a Bayesian integrated population model. This model combined aerial survey estimates, subsistence harvest data, age structure, and reproductive information to reconstruct annual abundance while accounting for observation error and process uncertainty. I used the estimated population sizes for 1975 and 2005 from Figure 3 to calculate the relative change in abundance and infer historical population size (**Taylor et al., 2018**).	314062.49 ± 73161.63 (1975)
Extinct species	
Ectopistes migratorius. The historical abundance estimate of 3–5 billion passenger pigeons in the 1800s was derived from qualitative accounts and observations by naturalists. These anecdotal records were synthesized to approximate population sizes, providing a rough but widely cited census estimate prior to the species' rapid decline **(Hung et al., 2014**).	4000000000 (1800)
Melanoplus spretus. The 1875 abundance estimate was based on eyewitness reports describing a locust swarm that stretched over 198,000 square miles. Scientists used standard density estimates of about 27.5 locusts per square meter to extrapolate a total of roughly 3.5 trillion insects in that swarm. Manual calculations done with the figures from the paper reveal a conservative estimate, but the methods on how this estimate was obtained are not given (**Lockwood, 2004; Lockwood, 2010**).	3500000000000 (1875)
Neomonachus tropicalis. The earliest abundance estimates for the Caribbean monk seal were reconstructed using historical records of sightings, hunting, and colony sizes across 13 locations in the Caribbean. These data were combined to estimate a total population of 233,000 to 338,000 seals (**McClenachan & Cooper, 2008**).	285500 ± 26785.71 (1688)
Oryx dammah. The figure of about one million scimitar-horned oryx was obtained from historical ecological literature, such as Dixon & Jones (1988), which documented the species' widespread presence and formation of large migratory aggregations across the Sahara's arid steppes. These records, based on traveler reports, naturalists' observations, and early wildlife surveys, provided estimates of population sizes by describing herd numbers and range extent before major declines (**Bassett, 1975; Gilbert et al., 2012**).	1000000 (1936)
Pinguinus impennis. The 1718 abundance estimate for the Great Auk originates from historical records and anecdotal accounts describing colony sizes and hunting pressure during that period. This figure was reconstructed by analyzing early observers' reports combined with estimates of breeding densities, often inferred from comparisons to related species and nesting behaviors. As no direct scientific counts existed, the 1718 estimate reflects an informed approximation based on qualitative descriptions of colony extent and density at known breeding sites like Funk Island (**Birkhead et al., 2021**).	500000 (1718)
Zalophus japonicus. The 1850 population estimate of 30,000 to 50,000 Japanese sea lions was derived from historical and bibliographic records, including fishermen's accounts, archaeological findings, and traditional place names indicating sea lion presence along the coasts of Korea and Japan. These sources provided qualitative evidence of abundant sea lion populations before intensive commercial hunting began (**Lee et al., 2022**).	40000 ± 5102.04 (1850)

Finding information on the migratory and trophic ecology of relevant migratory species

After identifying mass migrations as the most important global migrations around the world (see Methods and Supplementary Materials Section 3), we collected relevant migratory and trophic data per species to assess the functional consequences of depleting and recovering migrations. We manually reviewed the literature to collect information on the migratory route, migration distance and trophic group per species. We surveyed the literature to identify studies that tracked migratory movements for each species, and compared studies in terms of their comprehensiveness, data coverage and possible biases. For example, studies using GPS tracking across multiple populations across the world was deemed more informative that other studies not using any form of tracking and relying only on occurrences or tracking few individuals of only one population. Using these best sources available, we compiled a dataset describing the important migration areas (breeding, resting, overwintering, feeding) and the route followed across these areas. We also reviewed these studies to identify the best data

We also compiled data on trophic group, migration ecology and migration distance data (Table S3). This was obtained from peer-reviewed literature, IUCN, FishBase and peer-reviewed references in Birds of the World, as well as other online databases. We used this information to classify species into migration types (to-and-fro, nomadic, loop migrations) and trophic categories (herbivore, consumers, omnivores and detritivores). Planktivorous such as most great whales were considered consumers, since their diet comprised a mix of phytoplankton and zooplankton organisms.

Table S4. Summary of information and references collected on Mass Migrations.

Species	Information
Terrestrial mammals	
Loxodonta africana	Nomadic populations in Central Africa migrate in response to ecological factors like water availability, temperature, and elevation. During the dry season, they move to locate essential resources such as water and food. Migration Distance (MD) obtained from the weighted average of distance values across individuals within a population. Grazer. Browser. (IUCN 2025; Hines et al. 2023; Purdon et al. 2018)
Odocoileus hemionus	Mule deer migration is a seasonal movement between high-elevation summer ranges and lower-elevation winter ranges, driven by food availability and weather changes. While some remain year-round, migratory deer travel over 100 miles, using stopovers to forage. The longest recorded migration spans 240 miles from Wyoming's Red Desert to Idaho. Migration routes are learned from mothers and followed for life. MD from the average distance across 19 individuals. Grazer. Mixed Feeder (Grazer). (IUCN 2025; van de Kerk et al. 2021; Mule Deer Foundation; Ortega et al. 2023)
Alces alces	Migration is primarily driven by snow thickness, which affects foraging and predation risk. Most animals move from higher summer ranges to lower winter ranges, though deep valley snow may reverse this pattern. Migrations often follow river basins, with larger basins supporting longer migrations. Some make only short elevational or horizontal movements, and the proportion of migratory individuals increases at higher latitudes. MD per population in Sweden and in Canada, averaging across individuals. Browser. (IUCN 2025; Mauer 1998; Sweanor & Sandegren 1988; Sandegren & Sweanor 1988; Safronov 2009)
Cervus elaphus	Red deer migration is driven by snow thickness, resource availability, energy conservation, and predation risk. They breed at higher altitudes in spring-summer and migrate to lower altitudes in winter. In predator-free lowlands, they remain non-migratory, while in mountainous regions with strong seasonal resource variation, they migrate regularly. Migration helps compensate for winter food shortages and allows prolonged access to high-quality forage. A snow depth of 20–25 cm typically triggers downhill migration. While migration reduces predation risk, it also introduces new dangers. Both migratory and non-migratory strategies coexist within populations, influenced by environmental conditions and individual differences. MD from average a cross individuals in Western Carpathians. Mixed Feeder (Grazer). (IUCN 2025; Kropil et al. 2015)
Loxodonta cyclotis	Migration in Central Africa is driven by access to healthy food, predator avoidance, mating, and social organization. Movements follow a nomadic pattern, closely linked to rainfall, which influences resource availability and migration routes. MD obtained from averaging distance covered by males and females, respectively, over a period of time. Browser. (IUCN 2025; Beirne et al. 2021; Mills et al. 2018)
Rangifer tarandus	These ungulates migrate to escape harsh winter conditions and find resources, breeding in the Arctic and wintering in the south. The extreme seasonal shifts in the Arctic drive migration, with pregnant Rangifer moving from wintering grounds to traditional calving areas in spring. Average MD (in a straight line) across multiple populations. Mixed Feeder (Grazer). (IUCN 2025; Joly et al. 2021; Joly et al. 2019)
Connochaetes taurinus	Migrates seasonally, spending the dry season in Central Africa (north) and the wet season towards South Africa (south), following rainfall patterns and green grass. Different herds may exhibit varied movement patterns. MD based on distance cover by a population in the Serengeti (straight line). Grazer. (IUCN 2025; Torney et al. 2018; Holdo et al. 2009; Joly et al. 2019)
Eidolon helvum	Moves into savanna zones during the rainy season. Following the birth of young in February, males and females migrate progressively along a south-north axis, reaching at least the Niger River basin by mid-wet season (July). MD obtained from the average distance across individuals tracked over different time spans. Grazer. (IUCN 2025; CMS 2025; Richter & Cumming 2008)
Equus quagga	Returns to dry grasslands after the rainy season. Partial migration depends on factors such as water availability, vegetation composition, disease spread, predation, and competition. MD obtained by averaging the distance covered by 2-5 individuals per population, across 2 populations. Grazer. (IUCN 2025; Bartlam-Brooks et al. 2011)
Elephas maximus	Migrates northward during the dry season or year-round in search of greener pastures. Migration is triggered by extreme hot-dry climates causing habitat degradation, as well as increasing elephant populations and competition. Although Bonhof & Pryor (2022) described movements to some extent, it was not deemed reliable for quantification due to the goals of the study diverging from the quantification of migration distance. Browser. (IUCN 2025; Wang et al. 2021; Bonhof & Pryor 2022)
Giraffa camelopardalis	Moves along river basins and to greener areas, with males traveling long distances in search of forage and mates. Giraffe migrations are transboundary, covering vast areas, though their patterns remain poorly understood. MD obtained by averaging travelled distance across multiple individuals equipped with GPS trackers. Browser. (IUCN 2025; Brown & Bolger 2020; CMS 2025)
Kobus kob	Spends the wet season in the west and the dry season in the east. Moves north during the dry season for food and south in the wet season to avoid floods and access more nutritious grasses. Migration follows distinct seasonal patterns. MD based on the distance between relevant migration areas. Grazer. (IUCN 2025; Marjan 2014; Fryxell & Sinclair 1988)
Rousettus aegyptiacus	Moves to food-rich areas during the wet season, but migration is limited by available roosts. Seasonal fruit abundance drives movement, with some individuals relocating long distances. MD from a reiview citing studies indicating that species travel 32km, and record a female travelling as far as 500km Grazer. (IUCN 2025; Kwiecinski & Griffiths 1999)
Ovibos moschatus	Moves to mountain slopes in winter and areas near water in summer, avoiding deep snow for easier foraging. Winter precipitation influences distribution, with migration to south-facing slopes where snow is shallower. MD from averaged distance between males and females at low and high ranges. Grazer. (IUCN 2025; Forchhammer & Boertmann 1993; Tener 1960)
Rousettus angolensis	Migrates to more productive areas during the rainy season in search of food, though movement is restricted by roost availability. No information on MD was found. Grazer. (IUCN 2025; Bergmans 1997)

Ursus arctos	Home-ranging movements are driven by opportunistic feeding behavior, seasonality, and habitat selection. MD obtained from GPS tracking one individual. Tracking is hindered by conservation status and the low number of individuals. Omnivore. (IUCN 2025; Pop et al. 2018; CMS 2025)
Phyllostomus hastatus	Moves between roosting and feeding sites, wandering in search of ephemeral food sources. MD from GPS tracking individuals from different social groups. Omnivore. (IUCN 2025; O'Mara & Dechmann 2023)
Gorilla gorilla	Expands home range and travels farther when food is scarce. Males without mates travel even more extensively. Home range size varies due to food availability and mating competition. MD obtained from a range of methods, including nesting or sleeping site counts, direct observations and GPS tracking. Omnivore. (IUCN 2025; CMS 2025)
Procapra gutturosa	Engages in partial migration but is often prevented by artificial barriers. Exhibits nomadic long-distance movements in response to unpredictable grassland dynamics. MD from GPS tracking individuals. Grazer. (IUCN 2025; Dejid et al. 2022; CMS 2025)
Equus kiang	Spends summers at higher or less accessible altitudes and moves seasonally between habitats. No fixed migration pattern but disperses in small groups to hilly areas in summer and flat terrains in winter. MD information not found. Grazer. (IUCN 2025; Equids.org 2025)
Vicugna vicugna	Winters in areas with water and, during dry El Niño years, moves in search of water. Seasonal food and water availability strongly influence habitat selection. MD information not found. Grazer. (IUCN 2025; Torres & Puig 2012)
Bison bison	Migrates seasonally, spending summers at higher altitudes and winters at lower elevations. Migration distance varies by herd location, with more localised movements in northern populations. MD from a round trip migration distance (linear distance between migration areas). Grazer. (IUCN 2025; Jones et al. 2010; Soper 1941; Joly et al. 2019)
Pan troglodytes	Home range size depends on resource availability, with larger ranges in areas where food is scarce and dispersed. Mating competition can also influence movement patterns. MD from GPS tracking data used to estimate home ranging dynamics. Omnivore / Tertiary Consumer. (IUCN 2025; Newton-Fisher 2003; Martínez-Íñigo et al. 2021)
Equus hemionus	Exhibits nomadic movements influenced by unpredictable foraging resources. Travels long distances with no distinct migratory pattern, driven by water availability, habitat conditions, and competition. Human activities such as infrastructure and poaching impact movement and population viability. MD from GPS telemetry. Grazer. (IUCN 2025; Nandintsetseg et al. 2016; Joly et al. 2019)
Marine mammals	
Balaenoptera physalus	This species follows a classic migratory pattern, breeding in warmer waters and feeding in colder, nutrient-rich regions. Fin whales in the Southern Hemisphere breed in Australian waters, escaping Antarctic ice, and migrate south to feed. North Atlantic populations migrate between Svalbard, Morocco, and other regions, while Mediterranean fin whales are more nomadic, adjusting their movements based on seasonal productivity rather than fixed migration routes. MD based on different techniques depending on the geographic area, and varied between GPS telemetry and passive accoustics data. Primary Consumer. (IUCN 2025; Lydersen et al. 2020; di Sciara et al. 2016; Panigada et al. 2017; Sepúlveda et al. 2018; Aulich et al. 2022)
Physeter macrocephalus	Sperm whales travel to minimise disruptions caused by fluctuating food resources. They engage in deep vertical migrations (DVM), feeding at lower depths and transporting carbon and nutrients to shallower waters. Their long lifespan and low reproductive rate necessitate careful tracking of environmental variation to sustain population sizes. MD obtained from GPS tracking data, and using machine learning algorithm to estimate MD. Tertiary Consumer. (IUCN 2025; NAMMCO 2025; Chambault et al. 2021)
Megaptera novaeangliae	Humpback whales undertake extensive seasonal migrations between tropical breeding grounds and polar feeding areas. In the Southern Hemisphere, they breed in warm waters near Australia, Madagascar, Brazil, and the West Indies, while feeding in Antarctica or the Southern Ocean. In the North Pacific, different populations overwinter in locations such as Hawaii, Mexico, and Japan, feeding in Alaska, the Arctic, or the North Pacific. MD from satellite monitoring tags and state-space models. Primary Consumer. (IUCN 2025; Gales et al. 2009; Trudelle et al. 2016; Rosenbaum et al. 2014; Thouless 2021; Lagerquist et al. 2008; Mate et al. 1998; Palacios et al. 2019)
Balaenoptera bonaerensis	This species migrates from temperate waters in the winter to Antarctic feeding grounds in summer. They have a circumpolar distribution and have been observed as far north as Surinam and Madagascar, though their migration patterns are variable and less predictable compared to other baleen whales. MD not found in the literature. Primary Consumer. (IUCN 2025; CMS 2025; Towers et al. 2013; Víkingsson & Heide-Jørgensen 2012; Double et al. 2014; Hucke-Gaete et al. 2018; Mate et al. 1999; Bailey et al. 2009; Prieto et al. 2013)
Balaenoptera acutorostrata	North Pacific populations exhibit distinct migration routes. Some travel between Hawaii and Alaska, while others migrate from the Sea of Japan to the South China Sea. These whales are generally assumed to migrate to high latitudes in summer to feed and move to lower latitudes in winter for breeding. MD based on photo-identification techniques between multiple sites of interest. Primary and Secondary Consumer. (IUCN 2025; CMS 2025)
Balaenoptera musculus	Blue whales migrate between productive feeding grounds and lower-latitude breeding areas, though their movements are influenced by oceanographic conditions. Some populations move between Perth and Indonesia, others between the Galápagos and Chile, while North Pacific populations migrate from Oregon and British Columbia to Panama. MD obtained from satellite tagging multiple individuals. Primary Consumer. (Double et al., 2014; Hucke-Gaete et al., 2018; Bailey et al., 2009; Mate et al., 1999; Silva et al., 2013; IUCN 2025.; SeaLifeBase; International Whaling Commission)
Balaenoptera borealis	Sei whales migrate between the Arctic and North Atlantic, and from the Southern Ocean into South Africa. Their movement patterns are not fully understood, but they tend to favor deep offshore waters in summer and warmer breeding grounds in winter. Primary and Secondary Consumer. (IUCN 2025; Prieto et al. 2012; Best & Lockyer 2002)
Balaenoptera mysticetus	Bowhead whales are adapted to Arctic conditions and migrate between Greenland, northern Canada, and the Labrador Gulf. They move between ice edges and fjords seasonally, with migrations influenced by ice coverage and seasonal feeding opportunities. Primary and Secondary Consumer. (IUCN 2025; Heide-Jørgensen et al. 2003)
Lobodon carcinophaga	These seals are closely associated with Antarctic sea ice, using it for breeding, molting, and resting. Their movements are primarily dictated by the distribution of krill, their primary food source. MD obtained from information on satellite-linked dive recorder averaged across multiple individuals. Primary and Secondary Consumer. (IUCN 2025; Nachtsheim et al. 2017)
Balaenoptera edeni	This species follows a migratory pattern between warm and cold waters but remains within the 20° isotherm, making their migration shorter than other baleen whales. In the North Pacific, Bryde's whales feed in subarctic-subtropical transition areas near Japan during summer and migrate southward into lower latitudes (0°–10°N) during winter. Some individuals, however, remain in mid-latitudes year-round. MD based on satellite-monitored radio tag data from two individuals. Primary and Secondary Consumer. (IUCN 2025; Murase et al. 2016; CMS 2025)
Pagophilus groenlandicus	Harp seals migrate seasonally between the Arctic and subarctic waters, moving from Newfoundland and Greenland to Svalbard. Their migrations are closely linked to sea ice conditions, which play a critical role in their breeding and molting cycles. MD from 38 juveniles from two populations in Greenland and NW Atlantic using satellite-linked telemetry tags. Primary and Secondary Consumer. (IUCN 2025; Grecian et al. 2022)

Globicephala melas	This species exhibits seasonal inshore movements during the summer, though their migration patterns are not well understood. During mating seasons in May–June and October–November, multiple pods interact for cross-mating. MD from a group of 80 individuals, checking short-term movement using satellite-linked time-depth recorders. Tertiary Consumer. (IUCN 2025; CMS 2025; Bloch et al. 2003)
Hyperoodon planifrons	These whales follow a north-south migratory pattern, spending summers in Antarctic waters and moving northward in winter, possibly reaching South America. Stranding records suggest individuals may travel over 1,000 km to reach warmer waters. Tertiary Consumer. (IUCN 2025; Sekiguchi et al. 1993)
Globicephala macrorhynchus	Unlike their long-finned relatives, short-finned pilot whales exhibit year-round site fidelity to oceanic islands rather than long-distance migrations. However, some wide-ranging movements have been documented, indicating possible exploratory behaviors. MD obtained from photo-identification of the same individuals at different locations. Tertiary Consumer. (IUCN 2025; Alessandrini 2016)
Mirounga leonina	These seals breed and molt on sub-Antarctic islands but travel long distances into Antarctic and South American waters to forage. MD obtained by attaching satellite-linked tracking devices to 10 adults and 2 juveniles during moulting season. Tertiary Consumer. (IUCN 2025; Chua et al. 2022)
Delphinus delphis	Migration patterns are not well-documented, but seasonal movements have been observed in regions like the Alboran Sea and around Malta. These dolphins are highly mobile and likely cross national boundaries regularly. MD obtained from photo-identifiaction of individuals at different locations. Tertiary Consumer. (IUCN 2025; CMS 2025; Genov et al. 2012)
Eschrichtius robustus	Gray whales migrate from the Bering Sea to breeding grounds in Baja California. This is one of the longest migrations among mammals, with distinct Eastern and Western North Pacific populations. MD based on satellite-monitored tags on multiple individuals. Secondary Consumer. (IUCN 2025; Mate et al. 2015)
Arctocephalus pusillus	While not known for long-distance migrations, South African fur seals exhibit extensive movement between colonies in Angola and South Africa, particularly among juveniles. MD based on the recovery of tagged individuals. Most dispersal occurs after weaning. Secondary Consumer. (IUCN 2025; Oosthuizen 1991)
Pusa hispida	Ringed seals inhabit Arctic waters and display highly variable movement patterns. They migrate from the high Arctic to lower latitudes depending on sea ice conditions. Their extensive diving and foraging behaviors make them a key indicator species for environmental changes. MD based on satellite telemetry averaged across multiple individuals. Secondary Consumer. (IUCN 2025; Ogloff et al. 2021)
Halichoerus grypus	Gray seals move between breeding colonies across the northeast and northwest Atlantic, as well as the Baltic Sea. Seasonal migrations depend on feeding and breeding requirements. MD based on satellite telemetry averaged across multiple individuals. Secondary Consumer. (IUCN 2025; Pinnipeds.org 2025; Huon et al. 2015; Vincent et al. 2002)
Odobenus rosmarus	Walruses migrate between Arctic waters and ice-free regions. Pacific walruses move from the Bering Sea to the Chukchi Sea in summer, while Atlantic walruses migrate between the Arctic Circle, Bering Sea, and Svalbard. MD based on satellite telemetry averaged across multiple individuals. Secondary Consumer. (IUCN 2025; Dietz et al. 2014; Marine Mammal Science 2025; ADFG 2025)
Marine fish	
Engraulis ringens	This small pelagic fish inhabits the Humboldt Current System off the coasts of Peru and Chile, migrating seasonally in response to oceanographic changes. During summer and winter, anchoveta remain closer to the coast, while in spring and autumn, they move offshore following the current. Their distribution is highly sensitive to environmental changes, such as temperature and salinity fluctuations, which influence their movement both horizontally and vertically. MD based on distribution and relative abundance between feeding and spawning areas. Primary and Secondary Consumer. (Froese & Pauly 2025; Castillo et al. 2021; Caballero et al. 2024)
Clupea pallasii	Pacific herring migrate seasonally between offshore feeding areas and inshore spawning grounds. They overwinter near the Pribilof Islands before migrating to the Alaska coast for spawning in spring. After spawning, they move offshore for feeding, returning in fall to deeper overwintering grounds. Their migration patterns are influenced by ocean temperature and ice-edge dynamics. MD based on distribution and relative abundance between feeding and spawning areas. Primary and Secondary Consumer. (ADFG 2025; Tojo et al. 2007)
Pseudopleuronectes americanus	This species exhibits seasonal migrations, moving inshore to spawn in winter before returning to deeper offshore areas as temperatures rise in spring. Two distinct groups exist: one migratory, residing offshore most of the year, and one resident, remaining in coastal bays with limited movements. MD based on tag-return data across locations. Secondary Consumer. (Froese & Pauly 2025; Ziegler et al. 2019; Howe & Coates 1975)
Scomber japonicus	This species spawns in the South China Sea and southern Japan, with key spawning grounds in the East China Sea. After spawning, juveniles migrate to nursery grounds near Cheju and the Tsushima Strait. Feeding occurs primarily in the South Sea of Korea and the northern China Sea, with seasonal variations in diet and feeding intensity. MD based on biologgers recording temperatures. Secondary Consumer. (Froese & Pauly 2025; Yasuda et al. 2023; Li et al. 2012; Perrotta et al. 2001; Kaneko et al. 2017; Yamada et al. 1998; Jianshen 2014; Kume et al. 2021; Yoon et al. 2008; Li et al. 2014)
Katsuwonus pelamis	Skipjack tuna migrate between tropical and temperate waters, wintering in warm tropical areas and moving north to temperate waters in summer. Their migration is influenced by oceanographic factors such as temperature barriers, particularly the 18°C thermal limit. Their movement patterns also align with prey availability in deeper waters. MD from reviewed literature in the species' ecology and migration. Tertiary Consumer. (Froese & Pauly 2025; Kiyofuji et al. 2019)
Hippoglossoides platessoides	While not engaging in extensive migrations, this species moves from shallow spawning areas to deeper waters in winter. In areas like the Gulf of St. Lawrence, fish shift into deeper channels, though lateral movement is generally limited. MD from 17 tagging studies in the Bay of Fundy. Secondary Consumer. (Froese & Pauly 2025; Dery 1988; Fowler 2013)
Micromesistius poutassou	This species primarily spawns west of Ireland in spring and undertakes vertical daily migrations—remaining near the surface at night and deeper during the day. Feeding grounds are south of spawning areas, while nursery grounds are farther north, indicating a northward migration. Tertiary Consumer. (Froese & Pauly 2025; Payne et al. 2012)
Scomber scombrus	Spawning occurs in waters north and west of the British Isles. Larger individuals migrate longer distances between feeding and spawning areas, with some traveling westward into Icelandic waters or following the main route north into the Norwegian Sea. These migrations impact their arrival times in wintering areas. MD from using Passive Integrated Transponder on multiple individuals/ Primary and Secondary Consumer. (Froese & Pauly 2025; Ono et al. 2022)
Gadus morhua	Cod migrate between distinct spawning, feeding, and overwintering grounds, with movements largely constrained within their respective stocks. Long-distance migrations exceeding 200 km are rare, though seasonal shifts in distribution are observed. MD based on capture-recapture for >5000 individuals around Iceland across 17 years, and used depth and temperature loggers. Tertiary Consumer. (Froese & Pauly 2025)
Brevoortia tyrannus	Adults move southward to spawn, while juveniles redistribute northward. Spawning occurs offshore, with young spending their first summer in estuaries before migrating out in autumn. Their distribution varies along the U.S. east

	coast, with recruitment affecting commercial fisheries. MD based on tag recovery across locations. Primary Consumer and Detritivore. (Froese & Pauly 2025; Kroger & Guthrie 1973)
Sardinops sagax	These sardines migrate seasonally, moving north to British Columbia in summer and traveling south to central California for spawning. In the southern hemisphere, they migrate along the east coast of South Africa. Their distribution shifts seasonally based on food availability and water temperature. MD based on distribution and relative abundance between feeding and spawning areas. Primary Consumer. (Froese & Pauly 2025; Demer et al. 2012; NCBI 2025)
Sardina pilchardus	This species migrates inshore to spawn, with spawning occurring in regions such as the southern Adriatic Sea and the South of Biscay Bay. They return to northern waters in winter. Atlantic populations also enter the Alboran Sea for spawning. MD information obtained from data on ecosound surveys, pelagic egg distribution, taggin experiments, fisheries landing and statistical catch analysis. Primary and Secondary Consumer. (Froese & Pauly 2025; Caballero-Huertas et al. 2022; Škrivanić & Zavodnik 1973; Planque et al. 2007; FAO 2025)
Thunnus albacares	Yellowfin tuna follow complex migratory patterns linked to feeding and spawning. They winter in locations such as Venezuela and Argentina, with spawning occurring off the Caribbean Sea and southern Brazil. Some populations winter in the mid-Atlantic and spawn in the Bay of Biscay. In the Pacific, they spawn near Japan and spend summer and fall in American waters. MD based on archival tag data across individuals. Tertiary Consumer. (Froese & Pauly 2025; Beardsley 1969; Schaefer et al. 2007; Childers et al. 2011; Artetxe-Arrate et al. 2021)
Engraulis anchoita	This species migrates seasonally between coastal and offshore areas in South America. Northern populations reproduce in South Brazil during winter before migrating south and offshore in autumn for feeding. A smaller southern population moves between Isla Escondida for spawning and winters in Golfo San Matías and Golfo Nuevo. MD based on distribution and relative abundance between feeding and spawning areas. Primary Consumer. (Froese & Pauly 2025; Hansen 2004)
Gadus macrocephalus	Moves offshore to spawn in deeper waters (100-250 m) from late summer to mid-winter, then returns inshore (30-60 m) after spawning. Spawning occurs once per year. MD obtained from pop up archival satellite tags, which produced data fed to a hidden Markov model to ultimately define movement pathways in the Aleutian Islands, with other tagging and modelling performed in Korea to the same end. Tertiary Consumer. (Froese & Pauly 2025; Bryan et al. 2021; Lee et al. 2015)
Cololabis saira	Migrates between the subtropical Kuroshio region and the subarctic Oyashio region, following the Kuroshio–Oyashio Transition Zone. Migration is influenced by environmental factors such as sea surface temperature, salinity, and chlorophyll-a concentration. MD based on environmental factors affecting the distribution of the species. Secondary Consumer. (Froese & Pauly 2025; Liu et al. 2022)
Trachurus murphyi	Spawns offshore in the high seas near Chile, with larvae distribution influenced by the Subtropical Front. Spawning extends westward towards New Zealand and beyond 150°W, with seasonal shifts based on ocean currents. MD based on satellite data defining the subtropical front, which location and variability was used to define the migration patterns for the species. Secondary Consumer. (Froese & Pauly 2025; Belkin & Shen 2023)
Engraulis encrasicolus	Moves inshore to spawn during summer and retreats offshore in winter. It tolerates a wide range of salinities and sometimes enters estuaries, lagoons, and lakes. Spawning occurs from April to November, peaking in warmer months. No information found on MD. Primary Consumer. (Froese & Pauly 2025)
Pollachius virens	Moves inshore to spawn in spring and returns to deeper offshore waters in winter. Highly active and migratory, it frequently shifts between coastal and deep-sea habitats. MD from tagging data across individuals. Tertiary Consumer. (Froese & Pauly 2025; Homrum et al. 2013)
Reinhardtius hippoglossoides	Migrates to spawning areas in spring and returns to feeding areas in summer. Spawning occurs in specific deepwater locations around the coast and in offshore regions. Secondary Consumer. (Godø & Haug 1989)
Thunnus obesus	Migrates across the Atlantic, Indian, and Pacific Oceans. In the Atlantic, it spawns near the equator, with seasonal peaks in both hemispheres. In the Indian Ocean, spawning occurs year-round in warm equatorial waters. In the Pacific, spawning is limited to areas with sea surface temperatures above 23-24°C. MD based on a tag attrition model and tagging to obtain information on the species movements/ Tertiary Consumer. (Froese & Pauly 2025; Arregui et al. 2019; Aquadocs 2025)
Sprattus sprattus	Exhibits diel vertical migration (DVM) and seasonal movement from the NW to SW Baltic due to oxygen conditions. In summer, some move into sea lochs, while others overwinter inshore or remain offshore. Spawning occurs both in coastal and offshore waters, peaking between May and June. No MD found in the literature. Primary Consumer. (Froese & Pauly 2025; ICES 2025; Helcom 2025)
Mallotus villosus	Moves inshore in large schools to spawn in spring, often entering brackish or freshwater. Males typically arrive first. This species is semelparous, meaning individuals spawn once before dying. No MD found in the literature. Primary Consumer. (Froese & Pauly 2025)
Melanogrammus aeglefinus	Moves into spawning grounds along the Scandinavian coast, NW Scotland, E England, and Newfoundland. It is a batch spawner and undergoes extensive migrations in the Barents Sea and Iceland. No MD found in the literature. Secondary Consumer. (Froese & Pauly 2025; González-Irusta & Wright 2016; Johannesen et al. 2025; Skjæraasen et al. 2015; Begg 1998)
Paralichthys dentatus	Moves into coastal and estuarine waters in spring and summer, then migrates offshore in fall for spawning along the continental shelf. Most of the population resides in the Mid-Atlantic Bight. No MD found in the literature. Secondary Consumer. (Sackett et al. 2007)
Thunnus alalunga	Juveniles aggregate around New Caledonia and French Polynesia, while adults migrate between these regions and deeper waters to feed. Movement between spawning and feeding grounds is influenced by ocean currents. In summer, they move into spawning areas before returning to feeding grounds. MD information from data-logging devices tracking location, depth and temperature in juveniles. Tertiary Consumer. (Kimura & Sugimoto 1997; Macdonald et al. 2013; Childers et al. 2011)
Sebastes mentella	Migrates to East Greenland for spawning and North Norway for feeding. Other spawning grounds exist in Northeast Scandinavia, with juveniles drifting into the Barents Sea and Svalbard areas, particularly around Bear Island Channel. MD obtained from underwater tagging. Tertiary Consumer. (Karamushko & Christiansen 2021; FAO 2025; Sigurdsson et al. 2006)
Trachurus trachurus	Divided into two stocks. The West stock spawns between the Bay of Biscay and Ireland in early spring, migrating north and east to Norway and the northern North Sea. The North Sea stock spawns in the southern North Sea in summer and migrates to central North Sea, Skagerrak, and Kattegat. MD from echosounder and sonar data to track distribution and thus infer movement patterns. Tertiary Consumer. (Froese & Pauly 2025; Holst & Iversen 1992)
Pleuronectes platessa	Moves into shallower sandbanks for spawning in spring. Generally stationary, but tagging experiments show long-distance spawning migrations. MD from tagging and recapture data. Secondary Consumer. (Froese & Pauly 2025; Jones et al. 1979)

Thunnus maccoyii	Spawns south of Java, with juveniles spending their first year in South Australia before migrating via two routes to New Zealand and South Africa. Adults move across southern Australia and return to spawning grounds near Indonesia, with migrations influenced by food availability and oceanic conditions. MD from archival and satellite tags, fisheries data analysis and aerial and acoustic surveys to infer movement patterns and migratory areas of interest (e.g., spawning grounds). Tertiary Consumer. (Froese & Pauly 2025; Hobday et al. 2015)
Merluccius hubbsi	Migrates inshore in spring and summer to spawn and moves offshore to deep wintering areas post-spawning. Undertakes diel vertical migrations. MD information not found in the literature. Secondary Consumer. (Froese & Pauly 2025)
Macruronus magellanicus	Migrates southward in spring and summer and northward in winter. Larger fish move to coastal waters for late winter spawning, with juveniles and young adults performing north-south migrations before distributing across their habitat. MD information not found in the literature. Tertiary Consumer. (Froese & Pauly 2025; Giussi et al. 2016; Cubillos et al. 2009, 2014)
Hippoglossoides elassodon	Spawns inshore in the Bering Sea, with larvae displaying reverse diel vertical migrations. Juveniles use bays along the Alaska Peninsula and Kodiak Island as nursery areas. MD information not found in the literature. Secondary Consumer. (Froese & Pauly 2025; Porter & Ciannelli 2018; Porter 2005; Abookire & Norcross 1998)
Engraulis japonicus	Spawns inshore in the Yellow Sea from June to August. Migrates north and northwest during spawning, then moves south toward wintering grounds in the Yellow Sea and East China Sea from November to March. MD from habitat modelling and remote sensing data, fisheries catch models and climate and oceanographic models. Primary Consumer. (Froese & Pauly 2025; Liu et al. 2020)
Anoplopoma fimbria	Exhibits diel vertical migration (DVM) and home-ranging behavior along the Alaskan coast. MD from tagging and recapture data, modelled to understand movement and population dynamics. Secondary Consumer. (Froese & Pauly 2025; Sigler & Echave 2019; Kimura & Shavy 1998)
Trachurus japonicus	Spawns off northern Taiwan and migrates north to Japan for feeding. Migration patterns vary based on water temperature and food availability, with an estimated maximum migration distance of 800 km. MD from catch data and environmental correlation analysis to understand changes in distribution and infer movement patterns. Tertiary Consumer. (Baeck et al. 2024; Sassa et al. 2009)
Sardinella aurita	Migrates between Gambia (spawning) and South Morocco (feeding). Spawns year-round but peaks in summer (June-September). After spawning, physical condition declines, and the species migrates south in winter, influenced by seasonal sea surface temperature changes. MD information not found in the literature. Primary Consumer. (Froese & Pauly 2025; Ter Hofstede et al. 2007)
Diadromous fish	
Morone saxatilis	Migrates from nearshore environments into deltas and estuaries along the North American coast and the Gulf of Mexico. Populations at mid-latitudes return to rivers to spawn, while those at the northern and southern range limits may complete their entire lifecycle in rivers. MD from reviewing previous tagging and tracking studies, as well as environmental modelling. Secondary Consumer. (Froese & Pauly 2025; Coutant 1985; Lucas & Baras 2008)
Carcharhinus limbatus	Overwinters off Southeast Florida and migrates north to North Carolina and Georgia in summer. Aggregates in shallow waters, with migration influenced by water temperature, photoperiod, and prey availability. In some areas, comes inshore in summer to feed and reproduce. MD from aerial surveys tracking changes in shark distribution over time. Tertiary Consumer. (Froese & Pauly 2025; Kajiura & Tellman 2016; Capapé et al. 2004)
Oncorhynchus gorbuscha	Spawns in coastal rivers from June to September, traveling up to 300 miles upstream. Spawning occurs between mid-July and late October, with peak activity in cooler water temperatures. MD from tagging studies and observational records on the changing distribution of individuals, along with catch records and indigenous knowledge to infer movement patterns. Secondary Consumer. (Froese & Pauly 2025; Scott 1973)
Oncorhynchus keta	Spawns from Hokkaido to Alaska. Spawning migration timing varies by location, with northern populations arriving as early as July and southern populations spawning from September to early January. Has distinct autumn and summer runs. MD from isotope analyses used to identify area of origin and infer movement patterns. Secondary Consumer. (Froese & Pauly 2025; Scott 1973; Matsubayashi et al. 2020)
Oncorhynchus nerka	Migrates from coastal areas into rivers for spawning. Juveniles first stay nearshore before moving offshore, feeding on plankton and small fish. Adult sockeye return to their natal streams for spawning in summer and fall, sometimes as late as December. MD based on telemetry marking and smoltification markers to infer movement patterns. Secondary Consumer. (Froese & Pauly 2025; Bassett et al. 2018)
Arripis trutta	Migrates from eastern Australia to Western Australia for spawning in austral autumn (March-May). Larvae are distributed along the coast by ocean currents. The species is targeted by commercial and recreational fisheries. MD based on tagging recapture data and modelling. Secondary Consumer. (Froese & Pauly 2025; Cappo et al. 2000)
Thaleichthys pacificus	Spawns in coastal rivers. Spends most of its life at sea before returning to freshwater streams, with evidence of natal homing. Migration can extend up to 160 km upstream. MD based on recorded occurrence. Primary Consumer. (Lewis et al. 2002; Froese & Pauly 2025)
Salmo trutta	Migrates from coastal waters into rivers to spawn. Juveniles spend 1-5 years in freshwater before moving to saltwater for 6 months to 5 years. Spawns in rivers and streams with swift currents, often more than once. MD from telemetry, mark-recapture studies and physiological assessments to infer movement patterns. Secondary Consumer. (Froese & Pauly 2025; Birnie-Gauvin et al. 2019)
Trichiurus lepturus	Moves from coastal waters into estuaries for feeding and spawning. Found over muddy bottoms, with juveniles feeding on planktonic crustaceans and small fish, while adults consume fish, squids, and crustaceans. MD based on literature review in FishBase. MD based on genetic analysis and demographic history modelling. Secondary Consumer. (Froese & Pauly 2025; Hsu et al. 2022)
Ethmalosa fimbriata	Spawns along the West African coast from Mauritania to Angola during the cold season (January-June). The species inhabits marine, brackish, and freshwater environments and is commercially important in fisheries. MD based on otolith microchemistry, spawning site surveys and energetic analysis to identify movement patterns and migratory areas of interest. Primary Consumer. (Froese & Pauly 2025; Baldé et al. 2019; Döring et al. 2019)
Mugil cephalus	Migrates from estuaries and rivers to coastal waters for spawning. Adults form large schools offshore, while juveniles migrate inshore for protection and feeding. MD information not found in the literature. Scavenger. (Froese & Pauly 2025; FAO 2025; MNHN 2025)
Platichthys stellatus	Spawns in estuaries, moving inshore into very shallow waters in summer and deeper waters in winter. Young and adults can migrate up to 120 km upstream, avoiding highly saline waters. MD based on recorded occurrence. Secondary Consumer. (Morrow 1980; Froese & Pauly 2025)
Terrestrial birds	

Branta canadensis	A medium- to long-distance annual migrant, some populations winter within their breeding range while others migrate to mid-latitude North America. Northern populations travel long distances from Arctic and subarctic Canada and Alaska to southern U.S. states, while southern populations migrate shorter distances. Smaller geese tend to migrate farther than larger ones, and some populations have lost their migratory habits altogether. Reverse migrations occur in response to adverse weather, and nonbreeding individuals undergo a northward molt-migration. MD from satellite telemetry across individuals from the same population. Grazer. (Mowbray et al. 2020; Giles et al. 2013)
Anser caerulescens	A medium-distance complete migrant, with no populations wintering in their breeding range. Migration consists of long stopovers combined with rapid, high-altitude flights along specific migratory corridors. They rely on established staging and wintering areas. Geese that do not breed in the summer undergo a northward molt-migration. Individuals found in breeding grounds outside their normal season are usually sick or injured. MD from population surveys and harvesting records across the migratory range. Mixed Feeder (Grazer). (Mlodinow et al. 2024; Lefebvre et al. 2017)
Anser anser	Most populations migrate south to wintering sites in central and southern Europe, though some remain sedentary (e.g., in Scotland). Harsh winters can cause irregular movements, and nonbreeders may travel to traditional molting sites. Migration has been delayed in recent decades, likely due to climate change. Scandinavian birds move through Denmark and the Netherlands, some reaching France, Spain, Portugal, and Morocco. The wintering range has shifted northward, with more birds wintering in the Netherlands rather than Spain. MD from ring recovery and observations across European populations. Mixed Feeder (Grazer). (Carboneras & Kirwan 2020; Podhrázský et al. 2017)
Pelecanus onocrotalus	Northern populations migrate, arriving in the Danube Delta in spring and leaving in autumn. Their precise European wintering grounds are uncertain but likely in Africa. Many Asian breeders winter in Pakistan. Large numbers migrate through Bulgaria and Turkey, using staging areas before continuing their journey. Some birds are resident in tropical and southern temperate areas. Pelicans can travel long distances daily for feeding, and occasional vagrants have been recorded in several European countries. MD from satellite telemetry across individuals. Tertiary Consumer. (Elliott et al. 2020; Izhaki et al. 2002)
Anser albifrons	A long-distance migrant moving between Arctic breeding areas and temperate North America and Eurasia. Migration relies on key staging areas for feeding and resting. Much knowledge about their migration comes from population counts and tracking data. Banding studies have provided insights into migration corridors, particularly for Pacific Flyway populations. MD from satellite telemetry across populations in China. Mixed Feeder (Grazer). (Ely et al. 2024; Deng et al. 2019)
Cygnus atratus	Generally sedentary but congregates on permanent water bodies during droughts. Young and nonbreeding adults wander widely, likely searching for breeding areas. While some populations show little movement, others travel long distances, including interchange between the North and South Islands of New Zealand. Migration is linked to rainfall in southwestern Australia, where they breed in summer and leave in autumn. Introduced populations in Europe may also disperse widely. MD from banding across populations in New Zealand. Grazer. (Carboneras & Kirwan 2020; Williams 1980)
Grus grus	A well-known migratory species with multiple flyways. Birds from Scandinavia and northern Europe migrate through western Europe to winter in France, Spain, and North Africa. Eastern European cranes follow routes through central Europe and Italy to winter in North Africa. Populations from Russia and western Siberia travel via the Black Sea region to winter in the Middle East and East Africa. Cranes breeding in China migrate to the Yangtze River Basin for the winter. MD from GPS/GSM tracking across 36 individuals. Omnivore. (Archibald et al. 2020; Ojaste et al. 2020)
Phoenicopterus roseus	A highly dispersive but philopatric species. Migration patterns vary by population. Northern Asian birds migrate south to winter along the Caspian Sea, while Middle Eastern and European birds are partially migratory, with some moving to North Africa and the Arabian Peninsula in autumn. Breeding populations in the Rift Valley lakes are largely resident, with local movements between lakes. MD from banding records across multiple populations and locations in the Western Palearctic. Secondary Consumer. (Salvador et al. 2024; Johnson 1989)
Columba palumbus	A partial migrant with intracontinental and local movements. Some populations winter in southern Europe and North Africa, while others remain year-round in urban or farmland areas. Migration flyways in Europe include an Atlantic route to Spain and Portugal, a Mediterranean route through Italy and southern France, and a Black Sea route. Many individuals leave urban areas in summer to forage in farmland but return in winter. Some populations have adapted to feeding in urban areas year-round. MD from GPS tracking across individuals and populations in Europe. Mixed Feeder (Grazer). (Baptista et al. 2020; Schumm et al. 2022)
Struthio camelus	A non-flying bird with nomadic movements driven by food and water availability. In North Africa, they move seasonally, traveling north during rains and south during dry periods. Some individuals remain in the same region for years, particularly in moister habitats. In drier areas, ostriches may travel long distances in search of resources, with seasonal movements seen in West Africa. MD not found in the literature. Omnivore. (Folch et al. 2020)
Grus monacha	Migrates south for winter, primarily through northeastern China. Important staging areas include the Russian-Chinese border, with large autumn concentrations recorded. Most of the population crosses the Korean Peninsula to winter in southern Japan, with smaller groups wintering in South Korea and China. Some individuals migrate to the Yangtze River Basin. Occasional vagrants have been recorded in Taiwan and Bhutan. MD from satellite telemetry across individuals. Omnivore. (Folch et al. 2020; Bird Research Japan)
Corvus frugilegus	Northern and eastern populations are migratory, while western and southern populations are resident. Many birds from the Baltic and the Netherlands winter in eastern England, while eastern European birds migrate to central Europe. Ukrainian and Russian birds travel to regions such as Hungary, Bulgaria, and Italy. Some Kazakh birds winter from Iran to Uzbekistan, with others reaching Pakistan. East Asian populations winter in China and Japan, while introduced populations in New Zealand disperse widely. MD not found in the literature. Omnivore. (Birds of the World)
Anas platyrhynchos	A partial migrant with short- to medium-distance movements. Some populations, especially in North America and western Europe, are sedentary. Migration occurs along specific corridors, with individuals typically using the same route for both autumn and spring migration. Mallards exhibit varied migration patterns, with northern populations not necessarily wintering farther south than their southern counterparts. Urban populations may remain in place year-round or move only short distances when water freezes. MD from banding data across multiple individuals and years in Sweden. Omnivore. (Drilling et al. 2020; Söderquist et al. 2013)
Coragyps atratus	Black Vultures exhibit short-term, local movements in response to winter weather. While some individuals remain in their breeding range year-round, others migrate southward from mid-October to mid-November and return between late February and early March. Migration patterns vary, with some birds overwintering in southern regions while others stay near breeding areas. MD from banding data across multiple individuals and locations in USA. Scavenger. (Buckley et al. 2022; Parmalee & Parmalee 1967)
Cygnus columbianus	Tundra Swans migrate from northern North America to mid-latitude regions during winter. They travel in family groups along traditional flyways, primarily wintering in temperate coastal areas. During severe winters, some individuals move further south, while others remain in typical wintering grounds. MD from satellite transmitter across individuals. Grazer. (Limpert et al. 2020; Wei et al. 2023)

Pelecanus erythrorhynchos	American White Pelicans migrate from northern breeding areas to southern wintering grounds, primarily along the Gulf of Mexico and the Pacific Coast of Mexico. Those breeding east of the Rockies move southeast, while western populations migrate southward. Some remain in wintering areas, while others make return journeys to traditional breeding locations. MD from GPS tracking across two populations and multiple years. Secondary Consumer. (Knopf & Evans 2020; Ogawa et al. 2022)
Cathartes aura	Turkey Vultures are partial migrants, with northern breeders typically migrating southward, while some populations remain resident in warmer regions like Florida and the Gulf States. Western populations tend to migrate more than eastern ones. In tropical areas, they exhibit nomadic behavior rather than strict migratory patterns. MD from multiple individuals across four populations over 10 years. Scavenger. (Kirk & Mossman 2020; Dodge et al. 2014)
Pelecanus occidentalis	Brown Pelicans are mostly resident but exhibit seasonal movements. Along the Atlantic Coast, some disperse northward post-breeding before migrating south for winter. Gulf Coast populations tend to remain year-round, while some individuals travel southward along the Pacific Coast or across the Gulf of Mexico. MD from satellite transmitter across 18 individuals for two years. Secondary Consumer. (Shields 2020; King et al. 2013)
Sturnus vulgaris	European Starlings display regionally variable migration, with some populations being sedentary and others migratory. In North America, birds in the midwestern and northeastern regions migrate southward in winter, while southern breeders remain resident. European populations exhibit a similar pattern, with northern birds traveling greater distances. MD from geolocators and accelerometers across individuals for a year. Omnivore. (Cabe 2020; Vīgants et al. 2023)
Phoenicopterus ruber	American Flamingos are partially migratory and highly dispersive, moving in response to seasonal water availability. Some populations migrate southward post-breeding, while others remain resident in tropical areas. Large-scale movements have been observed between breeding and foraging sites, with occasional dispersal to new regions. MD not found in the literature. Omnivore. (del Hoyo et al. 2020)
Anas acuta	Northern Pintails undertake annual migrations between breeding and wintering areas, with some making long-distance transoceanic flights. Birds from Alaska may migrate as far as Mexico, while others winter in the southern U.S. and Central America. Migration routes often cross major water bodies, including the Pacific Ocean and the Gulf of Mexico. MD from satellite telemetry across individuals over six years. Omnivore. (Clark et al. 2020; Hupp et al. 2011)
Cygnus cygnus	Whooper Swans migrate from northern breeding areas in Iceland, Russia, and Europe to wintering grounds in temperate regions. Their migration is influenced by weather conditions, with movements ranging from short-distance shifts to extensive journeys. Climate change is affecting migration timing, with earlier spring arrivals and longer stays at stopover sites. MD from satellite tracking inidividuals, comparing multiple studies. Omnivore. (Carboneras & Kirwan 2020; Lee et al. 2023; Ao et al. 2020; Shimada et al. 2014; Stenschke et al. 2019)
Ciconia ciconia	White Storks are highly migratory, traveling in large flocks between European breeding grounds and sub-Saharan Africa. Western populations migrate via the Strait of Gibraltar, while eastern populations travel through the Middle East. Some storks remain in Iberia during winter, and climate change has increased overwintering trends in southern Europe. Md from satellite telemetry and observations across individuals in European populations. Omnivore / Scavenger. (Elliott et al. 2020; Berthold et al. 2001)
Cygnus olor	Mute Swans are facultative migrants, with movements driven by ice-free water availability. In milder winters, many remain resident, while harsh conditions trigger migrations of up to 1,700 km. Some populations engage in short-distance molt migrations, and increasing sedentariness has been observed in parts of Europe. MD from satellite telemetry and observations, aggregating data from two studies in China and Europe. Grazer. (Wood et al. 2024; Jia et al. 2024)
Cygnus buccinator	Trumpeter Swans primarily migrate short distances, moving to ice-free waters during winter. While some populations remain year-round in northern areas, others historically migrated further south. Habitat restoration efforts are expanding their range and creating new migration routes. MD from banding and resighting, covering multiple individuals and populations over 23 years in USA. Grazer. (Mitchell & Eichholz 2020; Handrigan et al. 2016)
Phoenicopterus minor	Lesser Flamingos are highly dispersive and exhibit seasonal movements based on water availability. They travel long distances between breeding and feeding areas, sometimes moving hundreds of kilometers. Some individuals migrate between East and South Africa, and occasional long-range movements to West Africa and India have been documented. MD from GPS/GSM tracking from 12 individuals from one population over five years. Primary consumer (Planktivore/Herbivore). (del Hoyo et al. 2020; Pretorius et al. 2020)
Antigone canadensis	Sandhill Cranes exhibit both migratory and non-migratory behaviors depending on their population. While birds in Cuba, Florida, and Mississippi remain resident year-round, all other populations—including those in the Eastern Flyway, Mid-Continent, Rocky Mountain, Lower Colorado River Valley, and Central Valley—migrate seasonally. These cranes travel from northern breeding grounds to warmer southern regions during winter, following well-established migratory routes. However, off-route individuals have been observed throughout the continental U.S. MD from GPS transmitters across seven individuals from different populations over six years. Omnivore. (Gerber et al. 2020; Fronczak et al. 2017)
Dromaius novaehollandiae	Emus are generally sedentary but can be nomadic, depending on local food and water availability. In Western Australia, they exhibit seasonal north-south movements, often following rainfall patterns. Although primarily terrestrial, emus have been observed crossing shallow bays to reach coastal islands when necessary for foraging or dispersal. MD from banding across multiple individuals and locations, over three years. Omnivore. (Folch et al. 2020; Davies et al. 1971)
Gyps fulvus	Eurasian Griffon Vultures are primarily dispersive, with juveniles traveling long distances while adults show more localised movements. Migration is mainly southward in autumn, with young birds crossing the Mediterranean via the Straits of Gibraltar and the Bosphorus before continuing into the Sahel. Juveniles from Israel migrate to East Africa or southern Arabia, while those from the Caucasus head toward the Middle East, Pakistan, and India. The migratory behavior of Asian populations is less understood, but movements have been recorded from October to mid-April. MD based on GPS tracking of a single individual. Tertiary Consumer (Scavenger / Carnivore). (Salvador 2024; Arkumarev et al. 2019)
Aythya collaris	Ring-necked Ducks are highly migratory, with Canadian and northern U.S. breeders moving south to winter in the southern U.S., Mexico, and the Caribbean. Some birds remain in portions of the western Rocky Mountains year-round, though turnover between breeding and wintering individuals is unclear. Migration begins in mid-September, peaking in October–November, with some individuals making transoceanic flights to Bermuda, Cuba, or the Yucatán Peninsula. Wintering populations can be highly mobile and unpredictable. MD from satellite telemetry across multiple individuals over two years. Omnivore. (Roy et al. 2020; Mezebish 2019)
Bubulcus ibis	The Western Cattle Egret exhibits both migratory and dispersive tendencies, with young birds traveling long distances from natal colonies. Some populations migrate from cooler regions to warmer areas, while others, such as those in Florida, coastal Louisiana, and Egypt, remain resident. European populations exhibit partial migration, with some birds moving to North Africa in winter. The species has also been observed making transoceanic crossings between Africa and South America. MD from ring-recovery data across multiple individuals and populations in Africa over 13 years. Omnivore. (Telfair II 2023; Siegfried 1970)

Milvus migrans	The Black Kite is primarily migratory but shows nomadic and dispersive tendencies in some populations. The nominate subspecies migrates to sub-Saharan Africa, while others winter in the Middle East, South Asia, and Southeast Asia. The South African subspecies migrates northward after breeding, and populations in China and Japan are partially migratory. Movements are influenced by seasonal rains and food availability, with some individuals exhibiting erratic dispersal patterns. MD from GPS/SMS/GPRS telemetry data across multiple nestling in Western Siberia. Tertiary Consumer. (David et al. 2021; Literák et al. 2022)
Tadorna ferruginea	Ruddy Shelducks migrate from their breeding grounds in eastern and central Asia to southern Asia for winter. Populations in West Asia and Eastern Europe move to the Black and Azov Seas, Iran, Iraq, and the Caucasus. Some individuals remain in breeding areas year-round, as seen in Kazakhstan, where birds fitted with transmitters have overwintered. Their wintering behavior varies across populations, with some displaying partial migration. MD from satellite telemetry on 15 individuals across 2 populations on the Tibetan Plateau over four years. Omnivore. (Salvador & Amat 2024; Takekawa et al. 2013)
Anthropoides virgo	Demoiselle Cranes are long-distance migrants, with birds from Western Eurasia traveling to sub-Saharan Africa, particularly Sudan and Ethiopia. Central Asian and Mongolian populations winter in the Indian subcontinent, while small populations from the Black Sea region also migrate to Africa. Some vagrants have been recorded as far as North America, Japan, and the Philippines, though their migration patterns remain mostly well-defined. MD from satellite telemetry from one population. Omnivore. (Archibald et al. 2020; Ilyashenko et al. 2022)
Fulica atra	Eurasian Coots exhibit both migratory and sedentary behaviors, with northern populations migrating southward in winter. European birds move to North Africa and the Middle East, while Asian populations winter in South and Southeast Asia. Moult migrations occur in summer, often involving non-breeding adults. Australian populations are highly dispersive, responding to changes in water levels rather than following a strict seasonal migration pattern. MD from mark-recapture data from a population. Omnivore. (Taylor & Kirwan 2020; Perdeck 1987)
Mergus merganser	Common Mergansers are primarily short- to medium-distance migrants, with North American and most European populations moving between breeding and wintering areas. Coastal populations tend to migrate shorter distances, while interior birds travel farther. Migration occurs along rivers, lake chains, and coastlines, often at night. Males may undertake separate molt migrations, moving northward to large lakes and coastal bays to undergo feather replacement. Md from band recovery from five locations over 31 years. Secondary Consumer. (Pearce et al. 2020; Pearce et al. 2005)
Branta leucopsis	Barnacle Geese undertake moderate-distance migrations between Arctic breeding colonies in Greenland, Russia, and western Siberia and wintering areas in Western Europe, from Ireland to Estonia. Migration is characterised by direct, non-stop flights or routes with minimal interruptions. Some birds winter further south during harsh winters, but most follow established flyways between traditional breeding and wintering grounds. MD from GPS tracking across three populations and three years. Grazer. (Mlodinow & Boesman 2023; Shariatinajafabadi et al. 2014)
Casmerodius albus	The Great Egret exhibits both migratory and dispersive movements depending on location. Populations in North America migrate from northern breeding grounds to warmer southern regions, with wintering numbers influenced by temperature and water conditions. Birds from temperate regions may reach as far as Alaska, Hawaii, and the British Isles, while tropical populations are largely sedentary. Post-breeding dispersal is common, particularly among juveniles, with individuals occasionally traveling across large bodies of water to the West Indies and Middle America. MD from mark-recapture for one population over 16 years. Secondary Consumer. (McCrimmon Jr. et al. 2020; Włodarczyk et al. 2020)
Anser fabalis	The Taiga Bean-Goose is a long-distance migrant, traveling from breeding areas in northern Eurasia to wintering grounds in southern Europe, Central Asia, and East Asia. Migration routes are influenced by climate change, with birds increasingly wintering further north. Western populations primarily winter in northwestern Europe, while eastern populations migrate to China, Korea, and Japan. Some individuals have been recorded as vagrants in North America, the Middle East, and Africa. MD from GPS tracking data from three subpopulations in East Asia. Mixed Feeder (Grazer). (Kirwan et al. 2024; Meng et al. 2022)
Gavia immer	The Common Loon is a complete migrant, moving from freshwater breeding lakes in northern North America to coastal marine environments in winter. Migration distances vary widely, from 60 to over 3,000 km. While most birds winter in saltwater, some remain at inland lakes. Juveniles may stay at wintering sites year-round, delaying their return to breeding areas until they reach maturity. Md from GPS tracking 13 moulting individuals acrossthree different locations. Secondary Consumer. (Paruk et al. 2021; Gray et al. 2014)
Pelecanus conspicillatus	The Australian Pelican is highly nomadic, with movements influenced by drought and storm conditions. Large irruptions occur during extreme droughts, with birds traveling great distances in search of water bodies. Some individuals reach Indonesia, New Guinea, and Pacific islands such as Vanuatu and Fiji. While generally sedentary, these pelicans occasionally undertake long-distance dispersal events. MD from band recovery data across multiple locations and over 38 years. Secondary Consumer. (Elliott et al. 2020; Johnston et al. 2015)
Gyps himalayensis	The Himalayan Vulture is mostly sedentary, though juveniles often move to lower altitudes in winter. Some individuals reach the plains of northern India, and there are increasing records from Southeast Asia, particularly Myanmar, Thailand, and Malaysia. Rare vagrants have been recorded as far west as Afghanistan and the Middle East. MD from observations across multiple countries. Tertiary Consumer (Scavenger / Carnivore). (Clark et al. 2020)
Corvus monedula	Western Jackdaws are mostly resident or short-distance migrants in Europe, with some populations moving to lower altitudes in winter. Northern birds migrate to southwestern Europe and North Africa, while others disperse across Central Europe. Occasionally, large-scale movements occur, such as a massive displacement event in the UK in 1984. Vagrants have been reported as far as North America and Japan. MD from banding multiple individuals across multiple locations in Denmark since 1917. Omnivore. (Madge & de Juana 2020)
Pelecanus crispus	Dalmatian Pelicans display a mix of migratory and dispersive behaviors. European populations move short distances, often wintering in the eastern Mediterranean. Asian breeders undertake long-distance migrations to South Asia and China. Some birds follow coastal migration routes, while others use inland river systems. Vagrants have been recorded as far as the Philippines, Japan, and northern Europe. MD from GPS tracking of individuals in Greece. Secondary Consumer. (Elliott et al. 2020; Efrat et al. 2019)
Turdus migratorius	American Robins migrate seasonally across North America, moving from breeding grounds in Canada and the northern U.S. to wintering areas in the southern U.S. and Mexico. While most individuals migrate, some remain year-round in milder climates. Overwintering numbers fluctuate based on food availability, with some robins forming large migratory flocks in response to fruit abundance. MD from banding and radio telemetry across multiple populations and years. Omnivore. (Vanderhoff et al. 2020)
Corvus corax	Common Ravens are primarily sedentary, though some populations move southward in winter. Northernmost birds, such as those in Greenland and Siberia, travel significant distances to find food. Juveniles tend to wander more than adults, occasionally forming large but temporary groups. While ravens do not exhibit regular migration, some populations show seasonal shifts in response to food scarcity. MD from banding and observations in one population across multiple years. Omnivore. (Boarman & Heinrich 2020; Mahringer 1970)

Haliaeetus leucocephalus	The Bald Eagle's migration patterns vary based on age, location, and food availability. Northern breeders migrate southward in winter, while some southern and coastal populations remain resident. Immature birds tend to disperse more widely than adults. Migration is primarily solitary, though temporary concentrations occur at key feeding sites. Some populations are shifting their migratory timing due to climate change. MD from GPS telemetry across multiple populations. Tertiary Consumer. (Buehler 2022; Wheat et al. 2017)
Passer domesticus	The House Sparrow is mostly sedentary, though some populations at high latitudes or altitudes migrate to milder areas in winter. Limited juvenile dispersal occurs in autumn, but once individuals establish breeding territories, they rarely move beyond a small range. Some Central Asian subspecies are migratory, moving between Turkestan and South Asia in response to seasonal temperature changes. MD from genetic tracking and banding, covering multiple populations and years. Omnivore. (Lowther & Cink 2020; Ranke et al. 2024)
Corvus brachyrhynchos	American Crows are partial migrants, with northern populations traveling south for winter while others remain resident. Migration distances vary, with some crows traveling over 1,000 km. Even within resident populations, some individuals move seasonally. Large communal roosts form in winter, with thousands of crows gathering in favorable locations. Some individuals return to traditional breeding sites in spring. MD from GPS telemetry, stable isotopos and molecular markers, across multiple populations and years, Omnivore. (Verbeek & Caffrey 2021; Townsend et al. 2018)
Chloephaga picta	Birds from the southernmost range migrate north in the austral winter, reaching Buenos Aires Province, Argentina, and occasionally Uruguay and southern Brazil. They leave Tierra del Fuego in late April or early May, traveling nocturnally along the eastern Andes or coast, returning between late August and September. Some may reach the Falklands in winter, though records are scarce. On wintering grounds, the barred morph is more coastal, while the white-breasted morph is inland. Falklands populations are mostly sedentary, moving up to 75 km at most. MD from GPS telemetry across multiple individuals. Grazer. (Carboneras & Kirwan 2020; Pedrana et al. 2018)
Anas penelope	Migrates south in winter, reaching western and central Europe, the Mediterranean, the Middle East, northern and northeastern Africa (to Tanzania), the Indian subcontinent, and East Asia. Some populations, like British birds, are mostly sedentary but move short distances. Migration timing is influenced by climate. Post-breeding, birds move to moulting sites in Estonia, southern Sweden, Denmark, and the Netherlands. Scandinavian and Russian birds migrate west, Siberian birds winter around the Caspian and Black Seas. Vagrants occur as far as the Azores, Cape Verde, Bermuda, and the West Indies. MD from satellite telemetry across multiple individuals and years. Omnivore. (Carboneras et al. 2020; Doko et al. 2019)
Ardea cinerea	Northern populations migrate south, while southern ones disperse. Post-breeding dispersal begins in September–October. Birds in Iberia, Britain, and Ireland are mainly sedentary, though some British individuals migrate to Spain, Gambia, and western Europe. Eastern European and Siberian birds migrate southwest to sub-Saharan Africa. East Asian birds winter in southern China, Taiwan, the Philippines, and Borneo. African, Indian, and Southeast Asian populations are mostly resident. Vagrants have reached Greenland, North America, the Caribbean, Australia, and New Zealand. MD from GPS/GSM telemetry across individuals of one population and multiple years. Secondary Consumer. (Martínez-Vilalta et al. 2020; Tiunov et al. 2022; Ye et al. 2018)
Phoenicopterus chilensis	High-altitude Andean populations migrate to lower latitudes and altitudes in winter, moving to the Pacific coast, Argentina's central plains, and Chile's coastal wetlands. Birds abandon Junin (Peru) from February to May and migrate north from Tierra del Fuego in September. Wintering populations are found in Uruguay, southern Brazil (Rio Grande do Sul), and increasingly in Paraguay. A nomadic visitor to Ecuador, it occasionally reaches the Falklands. MD not found in the literature. Primary Consumer. (del Hoyo et al. 2024)
Fulica americana	Migration is variable. Northern populations migrate long to medium distances, while southern and West Coast birds are often resident or migrate only in severe winters. Some winter within breeding ranges, but it is unclear if they are permanent residents or replacements from further north. Southeastern U.S. populations seem to be increasing. Some mountain populations migrate altitudinally. Males and nonbreeders may move to large lakes post-breeding before heading to wintering grounds. MD from banding and telemetry across populations and multiple years. Omnivore. (Brisbin Jr. & Mowbray 2020)
Cygnus melanocorypha	Falklands and northern populations are mostly sedentary, while those from higher latitudes migrate to lower ones in winter (March–April), sometimes reaching the Tropic of Capricorn. Chilean populations are highly mobile, sometimes moving thousands of kilometers. El Niño events influence migration, with birds staying year-round in some areas. Seasonal water level changes drive movements, with swans congregating in permanent waterbodies during dry periods. Vagrants have been recorded on Antarctic islands and the Antarctic Peninsula. MD not found in the literature. Omnivore. (Carboneras et al. 2024)
Turdus merula	Migration varies by latitude. Northern European populations are partly migratory, leaving breeding grounds in late September and moving south in October–November. Scandinavian birds winter in Britain, Ireland, and mainland Europe; central European birds winter in France, Iberia, and Italy. Russian birds migrate southwest. North African, Middle Eastern, and South Asian subspecies are mostly resident but show some seasonal movements. Spring migration begins in late February, peaking in March. Vagrants have reached Greenland, North America, and South Asia. MD from banding and morphometric analysis across multiple populations and over 85 years of data. Omnivore. (Collar & Christie 2020; Németh 2017; Csörgő et al. 2017)
Gavia stellata	A medium-distance migrant, it does not overwinter on breeding lakes. Breeding adults use freshwater in summer but switch to marine habitats for the rest of the year. Juveniles remain at sea year-round. In Alaska, breeders migrate either to East Asia or down the Pacific Coast of North America. Atlantic birds use a loop migration pattern, returning via Hudson Bay and the Great Lakes. Eurasian birds winter in the North Sea and migrate to northern Russia, Norway, Greenland, and Svalbard. MD from satellite telemetry and geolocation on multiple individuals across populations in Alaska and Europe. Secondary Consumer. (Rizzolo et al. 2020; McCloskey et al. 2018; Kleinschmidt et al. 2022)
Clangula hyemalis	A short- to medium-distance migrant, though resident populations exist in Alaska and Hudson Bay. Large coastal gatherings occur before spring migration, with birds flying at high altitudes or overland in Alaska. Spring migration follows ice leads into the Arctic. Southward migration after moulting is less understood but likely occurs in smaller groups at night. MD from satellite telemetry averaged across populations in Canadian Arctic and Barents Sea. Secondary Consumer. (Robertson & Savard 2020; Bartzen et al. 2017; Quillfeldt et al. 2022)
Mycteria americana	Not a true migrant, it moves based on food availability. After breeding, it disperses southward in late fall and winter. In years of breeding failure in Florida, many move north before summer rains. Caribbean populations are likely resident. Soaring thermals facilitate long-distance movements, but overwater travel is limited. Movements in Mexico and Central/South America are poorly understood, but many populations disappear from breeding sites during the rainy season. MD from GPS telemetry across individuals in south USA over multiple years. Secondary Consumer. (Coulter et al. 2020; Picardi et al. 2020)
Pelecanus rufescens	Primarily dispersive, with juveniles moving north into sub-Saharan steppes during the wet season. Local movements depend on water conditions and breeding cycles. Less reliant on thermals than P. onocrotalus. Increasing reports from Europe since the 1980s, reaching Spain, France, England, the Netherlands, Scandinavia, and Poland, particularly

	Germany. Early records were suspected escapees from zoos, but later studies suggest genuine vagrancy based on population trends and climatic factors. MD not found in the literature. Secondary Consumer. (Elliott et al. 2020)
Anseranas semipalmata	Non-migratory but highly mobile, moving in response to food and water availability. Disperses widely in the wet season and concentrates in dry-season refuges such as South Alligator River and Nourlangie Creek in Kakadu National Park. Satellite telemetry shows movements up to 114 km, influenced by seasonal changes. Occasionally found outside its usual range, including Tasmania, with some interchange between northern Queensland and southern New Guinea via the Torres Strait. Satellite telemetry across individuals in northern Australia to study seasonal movements across multiple years. Grazer. (Carboneras & Kirwan 2020; Traill et al. 2010)
Dendrocygna viduata	Movements are influenced by water availability, with large aggregations forming in permanent wetlands during the dry season, such as Zambia's Kafue Flats (24,000 birds recorded in September 1971). Most movements are within a few hundred kilometers, though some birds travel up to 1126 km, including interchange between mainland Africa and Madagascar. Occasional vagrants reach the eastern Andes, the Caribbean, the Canary Islands, and Florida. In South America, it is an erratic visitor to Peru, with a few records from the 19th century and recent sightings in 2009–2010. MD from satellite telemetry across individuals over multiple years. Omnivore. (Carboneras & Kirwan 2024; Takekawa et al. 2015)
Melanitta americana	Migrates from coastal wintering areas to inland breeding sites in North America. In late June, males and some females undergo a molt migration to northern coastal sites before returning south in the fall. On the East Coast, populations stage in the St. Lawrence Estuary and Newfoundland during migration. Some individuals undertake cross-continental migration. MD from banding and telemetry across individuals and populations in USA, with long-term records. Secondary Consumer. (Bordage & Savard 2020)
Somateria mollissima	A partial migrant, with some populations sedentary and others moving south in response to ice formation. Males and immatures leave breeding areas for moulting sites in June–July. Most North American birds winter along the Atlantic and Pacific coasts, rarely appearing inland. Some immatures summer within wintering grounds. Migration patterns vary, with facultative movements occurring when ice conditions change. MD from telemetry and banding across multiple individuals in Europe and North America. Secondary Consumer. (Goudie et al. 2020; Mallory et al. 2020; Swennen 1990; Baillie & Milne 1989)
Anser brachyrhynchus	Migratory, with Greenland and Icelandic populations wintering mainly in Scotland, northwest and eastern England, and smaller numbers in Ireland. Birds leave breeding grounds in late August, sometimes staging in Iceland before reaching the UK in October. Spring migration peaks in April, with return movements to Iceland continuing into May. Svalbard birds winter along the North Sea coasts of Denmark, Germany, the Netherlands, and Belgium, using Norway as a stopover. Recent trends suggest an earlier spring migration and longer stopovers in Norway, potentially due to climate change. MD from GPS telemetry and observational surveys, with multiple individuals being studied at their stopover sites. Grazer. (Carboneras & Kirwan 2020; Jensen et al. 2016)
Ardea herodias	Both migratory and non-migratory populations exist. Resident in the Pacific Northwest, southern Florida, and the Galápagos. Northern breeders migrate south in winter, sometimes covering vast distances, reaching as far as the Caribbean. In mild winters, some remain in Canada where ice-free conditions persist. MD not found in the literature. Secondary Consumer. (Vennesland & Butler 2020)
Nycticorax nycticorax	Migration varies with climate and food availability. Movements range from short dispersals (10–100 km) to long migrations, such as Massachusetts to Florida and Alberta to Cuba. Extensive post-breeding dispersal reaches up to 1200 km in Europe, regularly up to 800 km. Tropical populations undertake seasonal dispersive movements. MD from banding and telemetry across multiple populations worldwide. Secondary Consumer. (Hothem et al. 2020)
Mergus serrator	Breeds at boreal latitudes and migrates south in fall to winter in temperate coastal waters. Present year-round in parts of northwest Europe, Iceland, and Greenland. Most inland breeders migrate to coasts, with some flying overland to the Great Lakes. Males undergo a mid-summer molt migration. Large concentrations occur in the Gulf of St. Lawrence and Danish waters, with males wintering further north than females or immatures. MD from banding and morphometric analysis across multiple individuals in north Eurasia. Secondary Consumer. (Craik et al. 2020; Robinson 1999)
Streptopelia decaocto	Generally resident but shows altitudinal movements in the Himalayas (Pakistan, northern India), descending to lower elevations from November to March. Summer visitor to Afghanistan. Spring (April–May) and autumn (October–November) movements reported at Eilat, Israel. Most young disperse under 300 km from their hatching site, with rare cases of over 1,000 km. MD not found in the literature. Mixed Feeder (Grazer). (Romagosa & Mlodinow 2022)
Anser indicus	Highly migratory, wintering in northern India and adjacent regions, with some also moving south and east in China. Crosses the Himalayas at altitudes up to 6,000 m, typically in a single day. Birds use different spring and autumn routes and show considerable individual variation in timing. Major stopover sites include Qinghai Lake, Tibet, and the Ruoergai Marsh. Some birds tracked from Kyrgyzstan followed different migration routes to Pakistan, India, and Uzbekistan. MD from satellite telemetry across individuals following different migration routes. Grazer. (Carboneras & Kirwan 2020; Guo-Gang et al. 2011; Hawkes et al. 2013; Zhang et al. 2011)
Haliaeetus albicilla	Migratory in northern and eastern parts of the range, sedentary elsewhere (Greenland, Iceland, Norway). Juveniles are more dispersive and can form large winter flocks (up to 100 birds). Winters south of breeding areas, reaching central Europe and occasionally the Middle East, China, and Japan. Adults migrate later (October) and return earlier (February–April). MD from GPS telemetry on first-year dispersal over multiple years. Tertiary Consumer. (Orta et al. 2023; Rymešová et al. 2021)
Anser cygnoides	Migratory, wintering mainly in eastern China and Korea, with past records in Japan. Migration begins in late August, with birds forming flocks before moving south in mid-September to early October. Spring migration starts in late March, with arrival on breeding grounds in April. Migration routes are not well understood, but recent data suggest an eastward shift due to climate change. MD from GPS telemetry across multiple individuals and years. Grazer. (Carboneras & Kirwan 2020; Damba et al. 2021)
Zenaida macroura	Mourning Dove is a complete migrant in the northern breeding range, a partial migrant in mid-latitude areas, and a non-migrant in the south, wintering across the U.S., Mexico, and Central America. Eastern birds migrate down the Atlantic coast, central birds move south to Texas, Mexico, and Central America, while western birds migrate to southern states but rarely reach Mexico. Immatures migrate earlier than adults. MD not found in the literature. Omnivore. (Otis et al. 2020)
Melanitta perspicillata	Medium-distance migrant, moving from breeding areas in northern Canada and Alaska to wintering areas along Pacific and Atlantic coasts. Some overlap between populations in the eastern Northwest Territories and Hudson Bay. Major spring staging areas include Washington, British Columbia, southeast Alaska, and St. Lawrence Estuary. MD from satellite telemetry and banding across multiple individuals and years. Secondary Consumer. (Anderson et al. 2020; De La Cruz et al. 2009)
Somateria spectabilis	King Eider is fully migratory with no resident populations, departing breeding areas between August and October, often in large flocks exceeding 10,000 individuals. Spring migration starts early, between March and April, following open water leads in sea ice. Western Arctic birds nest from the Bering Sea to the Northwest Territories, while Eastern Arctic

	birds breed in the Canadian Arctic Archipelago. MD from satellite telemetry and banding across multiple individuals and years. Secondary Consumer. (Powell & Suydam 2020; Bentzen & Powell 2015)
Aegypius monachus	Cinereous Vulture juveniles disperse widely, with some returning to breeding areas as adults. Migration routes include movements from Mongolia to South Korea, from Türkiye and the Caucasus to the Middle East, Arabian Peninsula, and northeast Africa, and from Western Europe to the Sahel via the Strait of Gibraltar. Increasing numbers of juveniles from France and Spain now migrate to Africa. MD from satellite telemetry and banding across multiple individuals and years. Tertiary Consumer (Scavenger / Carnivore). (Salvador 2024; Castaño et al. 2015; Yamaç & Bilgin 2012)
Anastomus oscitans	Seasonal movements depend on water availability. Thai birds migrate west to the Ganges and Brahmaputra deltas during the wet season, though some remain resident. Some Cambodian birds move to the Mekong Delta in the dry season. Birds from northwest India may move east to Bangladesh. Occasionally reaches Malaysia and Laos. MD from satellite telemetry over multiple individuals and years. Secondary Consumer. (Elliott et al. 2020; Wang et al. 2020)
Plectropterus gambensis	Seasonal movements related to water availability. Congregates to moult north of breeding range (e.g., Lake Chad, Senegal Delta). Large numbers (60,000–90,000) recorded in Zambia's Kafue Flats. Likely intra-tropical migrant in Ethiopia, with records in Sudan. Occasionally wanders to higher altitudes and has been reported in Egypt, Mauritania, and Morocco. MD from banding across individuals and years. Omnivore. (Carboneras & Kirwan 2020; Oatley & Prys-Jones 1986)
Buteo buteo	Migratory in Scandinavia and Russia, partially migratory in central Europe, and mostly sedentary in Britain, southern Europe, and the Caucasus. Some winter in Africa, Israel, and Arabia. B. b. vulpinus is a long-distance migrant, traveling up to 13,000 km to winter in sub-Saharan Africa. Birds cross into Africa via the Bab al Mandab Strait in autumn and return via Suez in spring. Swedish satellite-tracked birds migrated 425–1,449 km, wintering in Denmark, Germany, the Netherlands, and Belgium. MD from banding and observations across individuals and years. Secondary Consumer. (Orta et al. 2022; Martín et al. 2014)
Pelecanus thagus	Pelecanus thagus (Peruvian Pelican) is mostly resident and dispersive, with offshore movements for feeding. Some individuals have been recorded far from their typical range, such as in São Paulo, Brazil, and Tierra del Fuego. MD across individuals and years. Secondary Consumer. (del Hoyo et al. 2020; Zavalaga et al. 2011)
Eremophila alpestris	Eremophila alpestris (Horned Lark) is a partial migrant, with northern populations migrating south or to lower elevations in winter, while southern populations are mostly sedentary. Some alpine breeders move to lowlands in winter, and desert populations in the southern U.S. migrate short distances to northern Mexico. MD not found in the literature. Omnivore. (Beason 2020)
Corvus corone	Corvus corone (Carrion Crow) is mostly resident, but birds from interior Europe migrate southeast, south, and southwest in winter, occasionally reaching Spain, Gibraltar, and northern Africa. The eastern race, orientalis, is a partial migrant, with northern birds wintering in southern China and Mongolia. Some individuals migrate to Vietnam and Iran, with occasional vagrants recorded in Japan and the Ryukyu Islands. MD not found in the literature. Omnivore. (Madge 2020)
Anas americana	Anas americana (American Wigeon) is a short- to medium-distance migrant, with some populations wintering within their breeding range in western North America. Migration follows all four major North American flyways, with males and nonbreeders migrating earlier than females and juveniles. Males undergo post-breeding molt migration. MD not found in the literature. Omnivore. (Mini et al. 2020)
Threskiornis aethiopicus	Threskiornis aethiopicus (African Sacred Ibis) is nomadic or migratory, moving several hundred kilometers to breed during the rainy season. Birds north of the equator move north, while those south of the equator move south, returning at the start of the dry season. Ringing studies show long-distance movements, with birds from South Africa found in Angola and Zambia. Some populations are present year-round in the Middle East. MD not found in the literature. Secondary Consumer. (Matheu et al. 2020)
Aythya fuligula	Aythya fuligula (Tufted Duck) is partially or wholly migratory, departing breeding areas between September and November and returning between February and May. Winters in Central and Northwest Europe, the Mediterranean, sub-Saharan Africa, the Middle East, and Asia. Different breeding populations have distinct wintering areas, with shifts in migration timing linked to climate change. Some individuals reach North America, Hawaii, and Micronesia as vagrants. MD from banding across individuals, locations and years. Omnivore. (Carboneras & Kirwan 2020; Gourlay-Larour et al. 2012)
Gavia pacifica	Gavia pacifica (Pacific Loon) is a short- to medium-distance migrant, moving from Arctic freshwater breeding sites to wintering coastal marine habitats along the Pacific Coast. Most North American birds winter in Mexico. Some nonbreeding individuals remain in wintering areas year-round. A late-winter molt migration may occur before northward migration. MD from observations of individuals moving along the seashore over multiple years. Secondary Consumer. (Russell 2020; Russell & Lehman 1994)
Coscoroba coscoroba	Coscoroba coscoroba (Coscoroba Swan) is mainly sedentary, but some southern breeders migrate north to about 25°S in winter, sometimes beyond the Tropic of Capricorn. Movements vary by region, with some populations regularly wintering in Uruguay and central Chile. Banding studies show unexpected long-distance movements, with individuals recorded as far north as Brazil and Bolivia. MD not found in the literature. Secondary Consumer. (Carboneras & Kirwan 2024)
Plegadis falcinellus	Plegadis falcinellus (Glossy Ibis) is migratory, nomadic, and dispersive. The American population descended from European immigrants and continues to show transatlantic movement, with individuals traveling from Spain to Bermuda. North American birds migrate south along the East Coast. European populations show strong interconnectivity, with birds moving between Spain, Italy, Algeria, Morocco, and Portugal. MD not found in the literature. MD from banding and GPS telemetry across individuals in the Western Mediterranean basin. Secondary Consumer. (Davis Jr. & Kricher 2020; Samraoui et al. 2023)
Pelecanus philippensis	Pelecanus philippensis (Spot-billed Pelican) is poorly studied, with some local movements while other populations remain sedentary. Birds in southern India arrive at breeding colonies between October and February and leave around May. Migrants have been recorded in Nepal, the Maldives, and Southeast Asia, with increasing numbers in Thailand due to conservation efforts in Cambodia. Some vagrants have been reported in China, Sumatra, and Japan. MD not found in the literature. Secondary Consumer. (Elliott et al. 2020)
Necrosyrtes monachus	Necrosyrtes monachus is mostly sedentary but may range over 200 km when not breeding, particularly juveniles. There are no regular migration patterns except for some wet-season movements into the southern Sahara (June–September). Occasionally recorded in northeastern Sudan and as a vagrant in Morocco. MD from GPS telemetry across individuals in South Africa. Secondary Consumer (Scavenger/Carnivore). (Kemp et al. 2020; Reading et al. 2019)
Platalea leucorodia	Platalea leucorodia has a mix of migratory and resident populations. Northern populations migrate south in winter, with western European birds wintering around the Mediterranean and tropical Africa, particularly at Banc d'Arguin, Mauritania. Eastern populations migrate through Italy or the Balkans to North Africa and the Upper Nile Basin. Some Central European birds winter in Egypt and Sudan. Immatures may stay in wintering areas for years before returning to

	breed. Resident populations exist in India, Sri Lanka, and Mauritania. GPS telemetry across individuals over multiple years. Omnivore. (Matheu et al. 2020; Xi et al. 2021)
Bucephala clangula	Common Goldeneye is a short- to medium-distance migrant, using major rivers, lake chains, and coastlines during migration. Western-breeding birds migrate to the Pacific Coast, while eastern breeders move to the Atlantic. Spring migration follows coastal routes before moving inland to breeding areas. MD not found in the literature. Omnivore. (Eadie et al. 2020)
Aythya marila	Greater Scaup is migratory, with most individuals moving from Alaska and northwest Canada to winter in the northeastern U.S., the Pacific Coast, the Gulf of Mexico, Europe, and Asia. Some winter inland in North America and Europe. Males tend to winter farther north than females and juveniles. Migration timing is influenced by weather and ice conditions. MD not found in the literature. Omnivore. (Kessel et al. 2020)
Melanitta deglandi	White-winged Scoter migrates from breeding areas in northwestern Canada and Alaska to winter along the Atlantic and Pacific coasts, as well as the Great Lakes. Males and nonbreeding individuals leave breeding areas in June–July for molting sites. Some females also leave breeding grounds early, while others molt in their nesting areas. MD not found in the literature. Secondary Consumer. (Brown & Fredrickson 2020)
Podiceps grisegena	Red-necked Grebe is a complete short- to medium-distance migrant, moving from inland freshwater breeding areas to coastal marine wintering sites. Some individuals migrate in small flocks, with post-breeding movements to molting areas before continuing to wintering grounds. Pacific- and Atlantic-wintering populations may have separate breeding ranges, with some birds using a migration corridor through Lake Superior. MD from banding and observations across Europe for multiple years. Secondary Consumer. (Stout & Nuechterlein 2020; Konter & Konter 2006)
Anas rubripes	American Black Duck is a partial short-distance migrant in North America. Northern breeders migrate up to 1,300 km, while mid-Atlantic and coastal populations are mostly resident or move short distances inland. Migration routes are loosely defined due to overlapping breeding and wintering ranges. MD from satellite telemetry and banding across individuals and years. Omnivore. (Longcore et al. 2020; Bowman 2020)
Phoenicoparrus andinus	Andean Flamingo is partially migratory. Some individuals remain at breeding lakes with hot springs that do not freeze in winter, while others move to lower-altitude wetlands in Chile and Argentina. Some birds migrate to the lowland salt lake Mar Chiquita in Argentina, but overall wintering patterns remain poorly understood. GPS telemetry across individuals and locations over multiple years. Primary Consumer. (Roberts et al. 2020; Jahn et al. 2023)
Sturnella neglecta	Western Meadowlark is resident in southern parts of its range (Kansas to Texas, west to California and Oregon) but migratory in northern and central regions. Some populations move to lower elevations or sheltered valleys in winter, though others remain at high elevations irregularly. MD not found in the literature. Omnivore. (Davis & Lanyon 2020)
Numenius arquata	Eurasian Curlew is mostly migratory, though some birds in western Europe are resident. Scandinavian and Baltic populations migrate southwest to western Europe, while others move through the Balkans to winter in the Mediterranean, North Africa, and as far as India. Some Siberian birds winter in West Africa. Most return north between February and April. Some first-year birds remain in wintering areas year-round. Occasionally recorded as a vagrant in North America and Australia. GPS telemetry across individuals and years. Omnivore. (Van Gils et al. 2020; Pederson et al. 2022)
Ciconia abdimii	Abdim's Stork is a trans-equatorial migrant, breeding north of the equator during the rainy season (March–November) and migrating south to tropical Africa (as far as South Africa) for the wet season (November–March). Birds migrate in large flocks and travel up to 456 km per day. Some populations in Eritrea and Yemen are partially resident. MD from satellite telemetry across individuals and years. Secondary Consumer. (Elliott et al. 2020; Jensen et al. 2006)
Agelaius phoeniceus	Red-winged Blackbird is a partial migrant. Northern populations in Canada and the northern U.S. move south in autumn, while those in the southern U.S., Middle America, and the Bahamas are mostly resident. Migration distances vary from 600 km in the Mid-Atlantic states to 1,200 km from the Great Lakes. Migration begins in August–October, with spring return from February–May. MD from banding and observation across two populations and years. Omnivore. (Yasukawa & Searcy 2020; Knittle et al. 1996)
Aythya affinis	Lesser Scaup is a complete migrant, vacating breeding grounds for southern waters. It follows well-documented migration routes and may undertake transoceanic flights, including from Alaska to California, the Pacific Coast to Hawaii, and the Gulf of Mexico to the Yucatán. MD not found in the literature. Omnivore. (Anteau et al. 2020)
Dendrocygna autumnalis	Black-bellied Whistling Duck is mostly non-migratory but moves seasonally in northern parts of its range. Texas populations arrive at breeding sites in March–April and depart in August–October. Some individuals migrate from Texas to Mexico, while Florida populations may travel within the southeastern U.S. MD from banding and observations across individuals and years. Omnivore. (James & Thompson 2020; Cohen et al. 2019)
Gavia arctica	Black-throated Loon is a migratory species, moving south to coastal waters after breeding, often in flocks of up to 50 birds. Some North American breeders winter along the Pacific coast rather than joining Asian populations. MD not found in the literature. Secondary Consumer. (Russell 2020)
Egretta garzetta	Little Egret is a partial migrant. Northern populations disperse widely after breeding, with many migrating south between August and November. European birds winter around the Mediterranean, the Middle East, and tropical Africa, while eastern birds winter in India, Southeast Asia, and the Philippines. Some Australian breeders disperse to New Zealand and New Guinea, while others remain resident. MD from GPS telemetry for two individuals across multiple seasons. Secondary Consumer. (Mlodinow et al. 2024; Pang et al. 2023)
Antigone vipio	White-naped Crane migrates seasonally. Eastern populations migrate through the Korean Peninsula, with some overwintering in the Demilitarised Zone and others continuing to Japan. Western populations move across central and eastern China to winter in provinces such as Hunan and Jiangxi. MD from satellite telemetry across multiple years in East Asia over multiple years. Omnivore. (Archibald et al. 2020; Higuchi 1992)
Aquila nipalensis	Steppe Eagle is mostly migratory. The eastern race leaves breeding areas in August–September, avoiding sea crossings and concentrating in bottlenecks such as Israel and the Bab el Mandeb Strait. It winters in the Middle East, the Arabian Peninsula, and eastern and southern Africa. Some individuals tracked from Saudi Arabia wintered as far south as Botswana and South Africa. The western race is less migratory, mainly wintering in South Asia. MD from satelite telemetry on 16 individuals over multiple years. Tertiary Consumer. (Meyburg et al. 2020; Meyburg & Meyburg 2010)
Mycteria leucocephala	Painted Stork is a resident species with local movements. After breeding, birds disperse widely in search of feeding opportunities, sometimes forming flocks far from known breeding sites. MD not found in the literature. Secondary Consumer. (Elliott et al. 2020)
Aythya nyroca	Ferruginous Duck is a migratory species in northern parts of its range. Southern Europe, northwest Africa, and the Middle East host both breeding and wintering populations. Birds from more northern areas migrate south in winter, but the species does not undertake significant molt migrations. Its precise movements remain poorly understood due to limited tracking data. MD not found in the literature. Omnivore. (Salvador & Amat 2024)
Gyps africanus	White-backed Vulture is mostly sedentary but moves seasonally in West Africa, heading north to less vegetated areas during the wet season (July–September) and south in the dry season. It also disperses widely, particularly as a juvenile, and marked individuals have shown long-distance movements. Some birds may migrate down the Rift Valley of

	Uganda. MD on multiple immature individual in southern Africa over multiple years. Tertiary Consumer (Scavenger / Carnivore). (Kemp et al. 2020; Phipps et al. 2013)
Haliaeetus pelagicus	Steller's Sea Eagle migrates south from breeding areas in October, returning in March–April. Juveniles take longer to migrate than adults. The main wintering sites are in Japan (primarily Hokkaido) and the Russian Far East. Some individuals remain in southern Kamchatka rather than migrating. Satellite tracking shows varied winter ranges, with some birds traveling over 1,800 km. MD from satellite telemetry on juvenile and immature individuals in northern Asia over multipel years. Tertiary Consumer. (Meyburg et al. 2020; McGrady et al. 2003; Ueta et al. 1998)
Ardea purpurea	Purple Heron undertakes post-breeding dispersal, with West Palearctic populations migrating south to winter in Africa (mostly north of the equator). Birds migrate between July and October and return between March and May. Some European birds overshoot to central and northern Europe. Juveniles tracked from France and the Netherlands reached wintering grounds in West Africa, some flying 4,000–5,600 km in just a few days. Asian populations migrate to Southeast Asia and Indonesia, while African and tropical Asian breeders are largely sedentary. MD from GPS tracking individuals post-breeding, during their quick flights over the Sahel. Secondary Consumer. (Martínez-Vilalta et al. 2020; Van der Winden et al. 2010)
Quiscalus quiscula	Common Grackle is a partial migrant in North America. Northern populations move south in autumn, with migration distances averaging 500–550 km. Southern populations, especially in Gulf Coast states, are largely resident. Fall migration peaks in late October–early November and is usually complete by December. Spring migration begins in February, peaking in March, with males arriving before females. MD from banding and observations across locations and years in North America. Secondary Consumer. (Peer & Bollinger 2020; Dolbeer 1982)
Grus japonensis	Red-crowned Crane has both migratory and resident populations. Mainland birds migrate across northeastern China to wintering grounds in the Korean Demilitarised Zone and coastal China (Jiangsu). The Hokkaido population in Japan is mostly resident, with some individuals moving short distances to wintering areas within the island. MD from GPS tracking over multiple individuals and years. Omnivore. (Archibald et al. 2020; Higuchi et al. 1998)
Anas crecca	Eurasian Teal is highly migratory, with nearly all populations moving between breeding and wintering sites. Northernmost breeders migrate south, while birds from temperate regions may be present year-round. Males undergo a molt migration after breeding. Migration patterns are not fully understood due to limited tracking data. MD from satellite telemetry across multiple individuals. Omnivore. (Johnson et al. 2020; Giunchi et al. 2019)
Hirundo rustica	Barn Swallow is a long-distance migrant. European populations migrate to Africa, with different breeding groups wintering in different regions (e.g., western birds in western Africa, eastern birds in eastern Africa). Asian populations migrate to southern Asia, Australia, and occasionally Africa. North American birds winter in Central and South America, traveling up to 12,000 km in 34 days. Spring migration is faster than autumn migration, with birds reaching breeding grounds from February to May. MD from GPS telemetry and observations across indivduals from a tropical Asian population over multiple years. Secondary Consumer. (Brown & Brown 2020; Tian et al. 2024)
Gavia adamsii	Yellow-billed Loon migrates between Arctic breeding areas and coastal wintering sites. Breeding birds from northern Alaska winter off the Asian coast, while those from central Canada migrate south overland to the Pacific coast of North America. Some populations winter in both regions. MD not found in the literature. Omnivore. (Uher-Koch et al. 2020)
Numenius phaeopus	Whimbrel is a long-distance migrant, moving from breeding grounds in the Arctic to wintering sites in coastal and inland wetlands across the tropics. MD from GPS telemetry across multiple individuals. Omnivore. (Skeel & Mallory 2020; Pederson et al. 2022; Carneiro et al. 2019)
Branta bernicla	Brant Goose is highly migratory, undertaking some of the longest migrations among waterfowl. It relies on key staging areas, particularly those with eelgrass meadows. Wintering sites include northwestern Europe, the Yellow Sea, and both Atlantic and Pacific coasts of North America. Failed breeders and nonbreeding individuals migrate to Alaska's North Slope for molting, while other populations molt locally. MD from satellite telemetry, banding and observations, over multiple years, averaged across two studies. Grazer. (Lewis et al. 2020; Boyd et al. 2013; Green et al. 2002)
Jabiru mycteria	Jabiru mycteria is primarily sedentary but undertakes seasonal dispersal. Small groups congregate outside the breeding season, often with other Ciconiiformes. Radio-tracking studies in Brazil's Pantanal suggest movements to Argentina's Chaco region (Nov–June). Rainfall patterns influence dispersal: in Belize, most birds leave in June–July and return in November–December, possibly wintering in Mexico's Campeche region. Occasional crossings of the Andes in Peru. Now largely a vagrant in much of Central America, with sporadic records from Nicaragua's Pacific coastal wetlands, Honduras, Trinidad & Tobago, southeastern Brazil, and the USA (Texas, Oklahoma, Mississippi, Louisiana). MD not found in the literature. Secondary Consumer. (Elliott et al. 2020)
Anas querquedula	Garganey is highly migratory, wintering mainly in sub-Saharan Africa, the Indian subcontinent, and Southeast Asia, occasionally reaching Australia. Autumn migration occurs from late July to October, peaking in August–September. First arrivals in Africa occur in early September, with the bulk reaching West Africa by mid-October. Returns north in February, peaking in March–April, reaching breeding grounds by mid-May. Vagrant records include Botswana, South Africa, Cape Verde, Iceland, Palau, and North America. MD from satellite telemetry across individuals and years. Omnivore. (Carboneras & Kirwan 2020; Cappelle et al. 2011)
Ciconia nigra	Black stork is migratory, with most European birds wintering in sub-Saharan Africa, especially in the Sahel from Mali to the Central African Republic. Iberian birds may overwinter locally, while most European migrants avoid long sea crossings and pass via Gibraltar, the Middle East, or the Bosporus. Some birds winter in Ethiopia, Chad, and Nigeria. Asian populations winter in Iran, India, and China, with occasional records from Southeast Asia. Southern African birds migrate seasonally, moving south to Namibia and South Africa during the wet season. MD from GPS telemetry across populations in Europe and years. Secondary Consumer. (Elliott et al. 2020; Cano & Tellería 2013)
Sarkidiornis melanotos	The Comb Duck is mainly sedentary, but some populations migrate seasonally in response to water availability. In Africa, about 10% are long-distance migrants, moving across the equator. Some birds from Zimbabwe have been recorded as far away as Chad and Sudan. It is found as a non-breeding visitor in Somalia and West Africa, with some movements occurring between mainland Africa and Madagascar. In Asia, local migrations take place, and vagrants have been recorded in Oman, the Seychelles, Malaysia, and Reunion. MD from banding across individuals over multiple years. Omnivore. (Carboneras & Kirwan 2020; Oatley & Prys-Jones 1986)
Haematopus ostralegus	The Eurasian Oystercatcher undergoes seasonal movements, with some shifting habitats due to climate change. European birds migrate south to winter along coasts from Norway to Iberia, with large concentrations in the Wadden Sea and Irish Sea. Some individuals winter as far south as Ghana and Nigeria. Eastern populations winter from East Africa to India, while Asian birds migrate to Southeast Asia, with occasional records in the Philippines and Guam. In New Zealand, populations migrate short distances to coastal areas. MD not found in the literature. Secondary Consumer. (Hockey et al. 2020)
Vultur gryphus	The Andean Condor forages widely, traveling great distances to find food. It has been recorded 100 km from the Andes in Bolivia and observed as a wanderer in Venezuela. However, it is largely resident, with no evidence of migration. MD from GPS tracking two individuals over multiple years. Tertiary Consumer (Scavenger / Carnivore). (Houston et al. 2020; Piana & Vargas 2018)

Oxyura jamaicensis	The Ruddy Duck is a medium-distance migrant in North America. Breeding populations in Canada and the northern United States migrate south to wintering grounds in the southern U.S., Mexico, and Central America. Some birds remain in wintering areas year-round, with migration numbers fluctuating due to changing water conditions in breeding areas. MD not found in the literature. Secondary Consumer. (Brua 2020)
Tadorna tadorna	The Common Shelduck migrates from northern and inland breeding areas to winter at lower latitudes. Asian birds winter around the Caspian Sea, North Africa, the Middle East, and South Asia. European populations winter along coasts, with large concentrations in the North Sea. Some move to West Africa, including Mauritania, Senegal, and Guinea. Vagrants have been recorded in the Russian Far East, the Philippines, and North America. MD from GPS tracking across multiple individuals across Mongolian populations and over multiple years. Omnivore. (Carboneras & Kirwan 2020; Wang et al. 2018)
Plegadis chihi	The White-faced Ibis is highly mobile, with northern populations migrating south. Birds from Utah and surrounding states winter in Mexico. Some east-to-west movements occur, with Utah and Nevada birds recovered in California. Texas and Louisiana populations are mostly resident but may wander after breeding. This species is well adapted to finding new nesting areas when conditions change. MD not found in the literature. Secondary Consumer. (Ryder & Manry 2020)
Eudocimus albus	The White Ibis is highly nomadic, with movements driven by rainfall and food availability. It breeds along the Gulf and south Atlantic coasts, Florida, Cuba, and Central and South America. Wintering occurs in the southern U.S., the Gulf Coast, the Greater Antilles, and coastal Central and South America. Juveniles disperse widely, reaching as far north as New York, the Midwest, and Quebec. Northern birds migrate south along the Gulf of Mexico, with banded individuals from South Carolina recovered in Cuba and Colombia. MD from banding and observations across multiple populations and locations over multiple years. Secondary Consumer. (Heath et al. 2020; Frederick et al. 1996)
Egretta thula	The Snowy Egret is partially migratory, with interior North American and Atlantic coast populations migrating to winter from the southern U.S. to northern South America. Many immatures remain year-round in wintering areas. Some migratory individuals appear as far north as southern Canada in spring and autumn. MD from banding and observations across locations and years. Secondary Consumer. (Parsons & Master 2020; Melvin et al. 1999)
Netta rufina	The Red-crested Pochard follows complex migration patterns. Western European birds winter in France, Spain, Italy, and the Balkans. Birds banded in northern Europe have been recovered in Spain. Iberian birds are mostly resident but move when wetlands freeze, such as in 1981 when many relocated to the Ebro River delta. Eastern European populations winter around the Black, Azov, and Caspian Seas, while Central Asian birds migrate to India, Pakistan, and Myanmar. MD from banding and telemetry across populations and years. Omnivore. (Salvador et al. 2022)
Anas superciliosa	The Pacific Black Duck is mostly sedentary but disperses from inland Australia during droughts, with some movements exceeding 400 km. Some individuals cross Torres Strait into New Guinea, while Australian immigrants also reach New Zealand, where hybrids have spread to nearby islands like Norfolk and Lord Howe. MD from GPS telemetry across individuals and years. Grazer. (Carboneras & Kirwan 2020; McEvoy et al. 2015)
Ajaia ajaja	The Roseate Spoonbill undergoes post-breeding dispersal, moving inland in the Yucatán and Costa Rica when coastal marshes dry out. In Florida, juveniles shift to interior marshes, and Louisiana birds disperse inland to feed in crayfish and catfish ponds. Northward dispersal in the U.S. can be extensive and irruptive, mostly involving immatures. MD not found in the literature. Secondary Consumer. (Dumas 2020)
Aquila chrysaetos	The Golden Eagle varies in migratory behavior. UK populations are non-migratory, while mainland birds often move seasonally. Northern populations migrate over 5,000 km, with Alaskan and Scandinavian birds responding to prey availability. Southwestern North American eagles migrate differently, with pre-adults moving through New Mexico and Texas in winter. MD from GPS and satellite telemetry averaged across multiple studies performed in various areas in the Western Palearctic. Tertiary Consumer. (Katzner et al. 2020; Moss et al. 2014; Miller 2012; Sandgren 2012; Urios et al. 2007)
Lophonetta specularoides	The Crested Duck has varying elevational movements. Patagonian populations are sedentary, while Andean birds in Bolivia and Peru breed in high-altitude lakes and descend in winter to as low as 2,000 meters. Some remain in the central high Andes year-round, even in snowy conditions. MD not found in the literature. Omnivore. (Bulgarella 2020; Bulgarella et al. 2007)
Podiceps nigricollis	The Black-necked Grebe migrates nocturnally, with northern birds moving to wintering areas in southern California and Mexico. Large concentrations stage at the Salton Sea and Great Salt Lake before dispersing to breeding areas. In Asia, many gather at the southern Caspian Sea before migration. MD from banding and observations across multiple locations and years in Europe. Secondary Consumer. (Cullen et al. 2020; Konter & Konter 2006)
Dendrocygna bicolor	The Fulvous Whistling-Duck is mostly sedentary but migrates seasonally in northern areas. Florida populations are partly resident, with banded individuals recovered in Cuba. Louisiana birds leave post-breeding. South American populations show little seasonal movement, while African birds migrate southward during the austral summer. MD from satellite telemetry across three colonies and over multiple years. Omnivore. (Hohman & Lee 2020; Takekawa et al. 2015)
Mycteria ibis	The Yellow-billed Stork is mostly resident but migrates locally. Populations peak in Mozambique, Zimbabwe, Botswana, and Namibia from October to April, indicating intra-African migration. In West Africa, birds move south in the dry season. Some individuals reach Egypt, and vagrants have been recorded in Europe and the Middle East. MD from GPS telemetry and observations across individuals and years. Secondary Consumer. (Elliott et al. 2020; Herring et al. 2015)
Bostrychia hagedash	The Hadada Ibis is largely sedentary but moves to wetter areas during droughts. Small flocks travel several kilometers from roosts. The species has expanded in South Africa and has recently appeared on the Zimbabwean plateau, where it was previously absent. MD not found in the literature. Secondary Consumer. (Matheu et al. 2020)
Gallinula chloropus	The Common Moorhen is resident in southern and western Europe but migratory in northern and eastern regions. Northern European birds winter in Iberia, Italy, the Balkans, and North Africa, with autumn migration from September to December and return migration from March to May. Some Palearctic birds winter in sub-Saharan Africa, while numbers in India and Pakistan increase with winter visitors. The species disperses widely, often at night, and has been recorded as a vagrant in Alaska, Iceland, and São Tomé. MD from radio telemetry and observations, over multiple locations in South America / Caribbean over multiple years. Omnivore. (Taylor et al. 2020; Takano 2003)
Lagopus lagopus	The Willow Ptarmigan varies from resident to long-distance migrant. In British Columbia, most individuals winter within 20–45 km of their breeding sites, though some travel up to 90 km. In Alaska, movements typically range from 30–50 km, but some females migrate up to 160 km. Manitoba birds have been recorded wintering 800 km south of tundra breeding grounds. Scottish populations remain local, while Scandinavian and Siberian birds migrate up to 300 km. Snowfall triggers migration, sometimes resulting in mass movements. MD from radio telemetry and banding across multiple populations and years. Grazer. (Hannon et al. 2020)
Aquila heliaca	The Eastern Imperial Eagle is mostly migratory, wintering in Turkey, the Middle East, and South and Southeast Asia, including India, Vietnam, and Malaysia. Migration begins from mid-September to November, with birds returning from

	February to May. Many migrate through Israel, Egypt, and Jordan, with peak numbers recorded in the Suez region. Satellite tracking shows individuals wintering in Saudi Arabia, Central Asia, and as far south as Kenya. Vagrants have been recorded in Western Europe and sub-Saharan Africa. MD from GPS and satellite telemetry across individuals and years. Tertiary Consumer. (Meyburg & Kirwan 2020; Poessel et al. 2018; Ueta & Ryabtsev 2001)
Histrionicus histrionicus	The Harlequin Duck is a short- to medium-distance migrant, with some coastal populations making minimal movements. In Alaska, broods migrate downriver to wintering sites. In eastern North America, migration is overland and rapid. Some birds stage at coastal sites before molting, while others migrate directly. Greenland-bound males stop in northern Labrador. Some yearlings remain at wintering sites year-round. MD from banding and observations across individuals and years. Secondary Consumer. (Robertson & Goudie 2020; Iverson & Esler 2006)
Pluvialis squatarola	The Black-bellied Plover is a long-distance migrant, breeding in the Arctic and wintering widely from coastal North America to South America. Migration occurs over a broad front, with most birds following coastal routes. Some winter inland, while others cross the Atlantic. Females tend to winter farther south than males, and immatures migrate farther than adults. Some yearlings remain on wintering grounds. MD from satellite telemetry and banding across individuals and over multiple years. Secondary Consumer. (Poole et al. 2020; Serra et al. 2001; Exo et al. 2019)
Neophron percnopterus	The Egyptian Vulture is migratory in northern regions but largely sedentary in Arabia, the Canary Islands, and the Indian Subcontinent. European birds migrate from March to September, with most crossing into Africa at Gibraltar, Suez, and Bab al-Mandab. Some juveniles remain in Africa for a second year. Migration is slow and dispersed, with birds relying on thermals. A few individuals winter in southern Spain. MD from GPS telemetry across individuals and years. Omnivore / Scavenger. (Orta et al. 2020; García-Ripollés et al. 2010)
Himantopus himantopus	The Black-winged Stilt follows varied migration patterns. Tropical populations are mostly sedentary, while northern populations in Europe and Asia migrate south, some reaching the Sahel and Maghreb. Birds banded in France have been recorded wintering in Mauritania, with others traveling up to 4,200 km to Guinea-Bissau. Some migrate through the Himalayas at altitudes of 3,500 m. In Portugal, non-migratory populations have increased. MD not found in the literature. Secondary Consumer. (Maleko et al. 2023)
Ciconia maguari	The Maguari Stork is nomadic rather than strictly migratory, moving in response to wet and dry seasons. It breeds in Venezuela with the onset of rains and departs when the area dries. Seasonal movements occur in the Brazilian Pantanal, and the species has been recorded as high as 3,700 m in Bolivia. Some migrate north in Bolivia and appear as vagrants in Peru, Chile, Trinidad, and the Falklands. Waterbird surveys in Argentina found seasonal abundance linked to water levels. MD not found in the literature. Secondary Consumer. (van Dort 2022)
Aechmophorus occidentalis	The Western Grebe migrates nocturnally, with post-breeding movements to molting sites before reaching wintering grounds. Northern birds migrate west to the Pacific coast from September to November, returning to breeding areas from April to May. Some southwestern U.S. populations are resident. Banding data shows individuals migrating between Manitoba and the Pacific, as well as between Utah and California. MD from GPS telemetry across individuals and years. Secondary Consumer. (LaPorte et al. 2020; Mills et al. 2016)
Anas discors	The Blue-winged Teal is a long-distance migrant, wintering in northern South America, with band recoveries as far south as Brazil and Peru. It is among the earliest North American ducks to migrate south in autumn and one of the last to return in spring. Some individuals cross the Gulf of Mexico, evidenced by sightings on oil platforms and large numbers passing through Florida. A small population breeds along the Gulf Coast, but their migratory behavior is uncertain. MD from satellite telemetry and banding across individuals and years. Omnivore. (Rohwer et al. 2020)
Aythya americana	The Redhead migrates from inland nesting marshes and molting lakes to coastal wintering areas, though a resident population exists in central Mexico. Small numbers occur year-round in parts of the U.S. and southern Canada, but their residency status is uncertain. Fall migration is well-documented through band recoveries, while spring migration remains poorly studied. Postbreeding molt migration results in large flightless concentrations on Canadian lakes rich in submerged vegetation. MD not found in the literature. Omnivore. (Woodin & Michot 2020)
Dendrocygna eytoni	The Plumed Whistling-Duck moves seasonally depending on water availability, dispersing inland during wet periods and concentrating along coasts and large lagoons in dry seasons. It has been recorded as a vagrant in Tasmania, New Guinea, Melanesia, and New Zealand, including the Chatham Islands. MD not found in the literature. Grazer. (Carboneras & Kirwan 2020)
Passerculus sandwichensis	The Savannah Sparrow is mostly migratory, except for resident populations along the California coast and in Mexico. Some birds move to lower elevations in winter. The large-billed rostratus subspecies has largely disappeared from historic breeding sites near the Colorado River due to habitat loss. Limited banding data show individuals traveling from breeding sites in Michigan, Vermont, and Wisconsin to wintering areas in Alabama, New York, and Florida. MD not found in the literature. Omnivore. (Wheelwright & Rising 2020)
Fulica armillata	The Red-gartered Coot is largely sedentary but exhibits local movements and temporary concentrations in response to habitat conditions. Present year-round in Rio Grande do Sul, with occasional records from Tristan da Cunha. MD not found in the literature. Grazer. (Taylor 2024)
Melanitta nigra	The Common Scoter is migratory, departing breeding areas in June, with males and immatures moving first. Migration routes pass through the White Sea, Gulf of Finland, and Baltic Sea, with birds molting in the Wadden Sea, France, Wales, and Denmark. Wintering extends to Morocco, peaking in the Baltic and North Sea from November to early December. Return migration occurs from February to May. Occasionally, individuals appear south of their normal range due to harsh weather. MD not found in the literature. Secondary Consumer. (Carboneras & Kirwan 2020)
Buteo platypterus	The Broad-winged Hawk is a complete migrant, with continental populations vacating breeding areas for winter. It migrates in large flocks or "kettles," sometimes numbering tens of thousands, particularly in Texas, Mexico, and Central America. Most migration occurs within a brief two-week window in both spring and autumn. Frequently associates with other raptors like Swainson's Hawks and Turkey Vultures, often soaring higher than larger species. MD from satellite telemetry across individuals from two populations over multiple years. Secondary Consumer. (Goodrich et al. 2020; McCabe et al. 2020)
Empidonax alnorum	The Alder Flycatcher is a long-distance migrant, breeding in Canada and the northern U.S. and wintering in northern South America. It arrives late in spring, similar to Willow and Yellow-bellied Flycatchers. Migration follows similar timeframes to the Willow Flycatcher but occurs slightly later. Nocturnal migration is suggested by tower kill data. MD not found in the literature. Secondary Consumer. (Lowther 2020)
Gypaetus barbatus	The Bearded Vulture is mostly sedentary, with juveniles dispersing widely before settling. Adults in South Africa have home ranges averaging 286 km², while juveniles and sub-adults range from 10,500 to 26,000 km². In the Pyrenees, natal dispersal distances average 47 km. Long-distance movements have been observed in satellite-tracked individuals reintroduced to the Alps and Spain. Occasional records in Sardinia suggest dispersal from Corsica. MD from GPS tracking across individuals and years. Tertiary Consumer (Scavenger / Carnivore). (Orta et al. 2020; Krüger & Amar 2017; Margalida et al. 2016; Krüger et al. 2014)
Nyctea scandiaca	The Snowy Owl exhibits variable migration patterns, with some individuals wintering near Arctic breeding grounds while others migrate south. Numbers and demographics fluctuate yearly, possibly due to changes in lemming

	populations. Large irruptions occur when prey is scarce, sometimes for two consecutive winters, with fewer birds in the second year. GPS telemetry across individuals and years. Secondary Consumer. (Holt et al. 2020; Brown et al. 2021)
Dendrocygna javanica	The Lesser Whistling-Duck is mostly sedentary, except for a small northern Chinese population that migrates south in winter. Similar patterns may occur in northwest Pakistan, where birds are mainly present from May to August. Winter influxes on Hainan Island suggest some seasonal movement. Vagrants have been recorded in Hong Kong, the Maldives, Oman, and Israel. In the Lesser Sundas, evidence suggests the species is resident, with breeding records and large flocks observed on Sumbawa and Flores. MD not found in the literature. Omnivore. (Carboneras & Kirwan 2020)
Dendrocygna arcuata	The Wandering Whistling-Duck is dispersive, moving according to water levels. It concentrates in permanent waters during dry seasons and disperses widely in wet periods. It is a non-breeding visitor to Kai Islands, an irruptive vagrant in Sumatra, and resident in East Timor, with large numbers on Roti. Its status on other Indonesian islands is unclear. The australis race has been recorded in New Caledonia and may occasionally reach and breed in southern Indonesia. MD not found in the literature. Omnivore. (Carboneras & Kirwan 2020)
Chenonetta jubata	The Australian Wood Duck is mostly sedentary but somewhat dispersive, concentrating in southwest and eastern Australia. It is absent from the continent's arid interior but can be found in suitable habitats elsewhere, including Tasmania. It has been recorded as a vagrant in New Zealand, Badu Island, and Papua New Guinea. GPS telemetry across individuals and years. Omnivore. (Carboneras & Kirwan 2020; McEvoy et al. 2019)
Anas sibilatrix	The Chiloe Wigeon migrates north from southernmost breeding areas, wintering as far as Uruguay and southern Brazil. It is sedentary in the Falklands/Malvinas but has been recorded as a vagrant on South Georgia, the South Shetland and South Orkney Islands, and off the coast of Tierra del Fuego. MD not found in the literature. Omnivore. (Carboneras et al. 2024)
Circus aeruginosus	The Western Marsh Harrier is mainly migratory in northern and eastern Europe and central Asia, but sedentary or dispersive in southern breeding areas. Northern birds winter from France and North Africa through the Mediterranean and Middle East to sub-Saharan Africa, while easternmost populations migrate to the Indian Subcontinent and Sri Lanka. Migrations involve powered flight rather than soaring. Satellite tracking reveals that most Swedish birds winter in West Africa, with adults showing fidelity to stopover and wintering sites. GPs telemetry across individuals and years. Tertiary Consumer. (Orta et al. 2020; Strandberg et al. 2008)
Aythya valisineria	The Canvasback is a short- to medium-distance migrant, with some wintering within breeding ranges in western North America and occasionally in the Great Lakes region. Small flocks (10–40 birds) migrate together, merging into larger groups at staging and wintering sites. Males and non-breeding birds undertake extensive molt migrations. GPS telemetry and observations across individuals and years. Omnivore. (Mowbray 2020; Cook et al. 2021)
Limosa haemastica	The Hudsonian Godwit migrates long distances between boreal breeding grounds and southern South America. It follows an elliptical migration route, with spring migration occurring farther west than fall migration. Birds pass through the Great Plains in spring and stage in Alaska, Saskatchewan, and James Bay in fall before making a non-stop flight over the western Atlantic to South America. Southbound migration appears to follow interior routes, while northbound birds travel along the coast. Some non-breeders remain in southern South America year-round. MD from banding and observations across populations, locations and years. Omnivore. (Walker et al. 2024; Senner 2012)
Recurvirostra avosetta	The Pied Avocet follows variable migration patterns. Northern birds migrate between August and October to warmer regions, staging in large numbers in the Netherlands. About one-third of Atlantic seaboard birds winter in sub-Saharan Africa, while over 10,000 winter in France, Iberia, and even Britain. Return migration occurs between March and May, with Banc d'Arguin in Mauritania serving as a key stopover. Asian wintering populations extend from the Persian Gulf and northwest India to southeast China. African birds are largely sedentary, with some intra-African migration. MD not found in the literature. Secondary Consumer. (Pierce et al. 2020)
Haematopus palliatus	The American Oystercatcher varies in migration by latitude. Birds from South Carolina to Florida are mostly non-migratory, though they form local wintering flocks. Some breeding populations from North Carolina to New Jersey migrate south. Birds from Massachusetts are fully migratory, though a few remain in winter. Northern birds use a "leapfrog" migration strategy, bypassing coastal sites to winter on Florida's northwest coast, which hosts up to 40% of the Northeast's breeding population. GPS telemetry and banding across individuals and years. Secondary Consumer. (Working Group et al. 2020; Clay et al. 2014)
Bucephala albeola	The Bufflehead is a complete migrant with distinct regional patterns. Birds breeding west of the Rockies migrate to the Pacific Coast, while those from the Northwest Territories, Saskatchewan, Manitoba, and Ontario move east or south to the Great Lakes and coastal states. Alberta birds migrate both east and west, with some wintering along the Gulf Coast and Southwest. Males, immatures, and unsuccessful breeders undertake separate molt migrations, sometimes forming groups on lakes near nesting sites. MD not found in the literature. Secondary Consumer. (Gauthier 2020)
Vanellus chilensis	The Southern Lapwing migrates to lower latitudes in winter, with migration details obtained from maps. MD not found in the literature. Secondary Consumer. (Santos 2020)
Vanellus vanellus	The Northern Lapwing is both migratory and resident. Post-breeding flocks form early, with summer movements mainly westward. British and southernmost breeders are partially sedentary, and many winter in Ireland. Migration occurs from September to November, often triggered by cold spells. Finnish breeders move south to Italy and North Africa, while others winter as far as Macaronesia and Southeast Asia. Spring migration peaks in early March, with males arriving first. Vagrants have been recorded as far as Alaska, East North America, Bermuda, and the Caribbean. MD not found in the literature. Secondary Consumer. (Wiersma et al. 2020; Donald et al. 2021; Potvin et al. 2016)
Platalea regia	The Royal Spoonbill is mostly sedentary in coastal Australia but makes irregular inland movements depending on water conditions. Birds frequently move between Australia and southern New Guinea. In New Zealand, post-breeding dispersal leads to estuarine and wetland concentrations. Occasional long-distance movements occur, with vagrants recorded on Norfolk and Lord Howe Islands. MD not found in the literature. Secondary Consumer. (Matheu et al. 2020)
Catharus ustulatus	The Swainson's Thrush is a complete long-distance migrant, breeding in western and northern North America and wintering from southern Mexico to northern Argentina. Eastern and western populations follow different migration routes, with some banded birds linking Panama and Colombia to breeding sites in Canada and the U.S. The species is a rare transient in the Greater Antilles, Cayman Islands, and northern Bahamas, and an uncommon migrant in Bermuda. MD not found in the literature. Secondary Consumer. (Mack and Yong 2020)
Anas bahamensis	The White-cheeked Pintail is mostly sedentary in the Galápagos and West Indies, though some Bahamian populations show winter absences. The nominate subspecies occasionally wanders north to Florida and Virginia, while the rubrirostrisrace is more dispersive, moving to lowlands north of its breeding range and sometimes south to southern Argentina. A record from Cocos Island (Costa Rica) suggests occasional long-distance vagrancy. MD not found in the literature. Omnivore. (Carboneras et al. 2024)
Threskiornis melanocephalus	The Black-headed Ibis is largely sedentary but moves in response to water levels and food availability. A remnant population in eastern China migrates to coastal wintering areas. It is a rare non-breeding visitor to Japan, the Philippines, Taiwan, Laos, and Borneo, with two records from Lake Baikal, Russia. Migratory flocks typically fly in single file or V formations. MD not found in the literature. Secondary Consumer. (Matheu et al. 2020)

Buteo jamaicensis	The Red-tailed Hawk is a partial short- to intermediate-distance migrant, with movements typically under 1,500 km. Some northern birds migrate as far as Central America and northern South America, with records in Colombia and Costa Rica. Migration timing varies annually based on snow cover, with northernmost populations leaving breeding grounds for 3–5 months. Many mid-latitude breeders winter near their breeding territories, while southern U.S. and Mexican populations are largely resident. MD from GPS telemetry and banding across individuals and years in north USA.Tertiary Consumer. (Preston and Beane 2020; Craighead et al. 2016)
Calidris canutus	The Red Knot is a long-distance migrant, breeding in the Arctic and wintering in coastal temperate and tropical regions. Migration involves long, non-stop flights of up to 8,000 km, stopping only at key sites. The species follows an elliptical migration route, taking advantage of food availability and minimising predation risks. Conservation concerns arise as large portions of populations rely on single staging areas. Some birds remain south of breeding grounds year-round. MD from banding and observations across populations and years in Europe. Secondary Consumer. (Baker et al. 2020; Davidson and Wilson 1992)
Fulica ardesiaca	The Andean Coot shows seasonal population movements, but its migration patterns are not well documented. MD not found in the literature. Omnivore. (Taylor 2024)
Threskiornis spinicollis	The Straw-necked Ibis is partially migratory, with some birds remaining sedentary while others make seasonal or irregular movements. Migration occurs between southeast and northern Australia, as well as coastal and inland wetlands. Birds also cross the Torres Strait between Australia and southern New Guinea. Non-breeding migrants arrive in Western Australia and depart in autumn. Vagrants have been recorded on Norfolk and Lord Howe Islands and in southern New Zealand. MD not found in the literature. Secondary Consumer. (Matheu et al. 2020)
Anastomus lamelligerus	The African Openbill breeds mainly in eastern and southern Africa, typically late in the wet season and early in the dry season. Some migrate north of the equator during the dry season (October–April), but southern African populations are mostly resident. Large-scale movements occur irregularly in response to local conditions. The species has reached Zanzibar, Pemba, and, exceptionally, Luxor, Egypt. MD not found in the literature. Secondary Consumer. (Elliott et al. 2020)
Aix sponsa	The Wood Duck is a partial migrant, with northern populations moving south in early autumn. Southern-breeding birds migrate shorter distances based on local conditions. About one-third of Wood Ducks in eastern North America are permanent residents, mainly from North Carolina to the Gulf of Mexico. In the Pacific Flyway, nearly 75% are nonmigratory, with permanent populations from Butte Sink, California, to Mexico. MD from banding and observations from multiple populations and over multiple years. Omnivore. (Hepp and Bellrose 2020; Hepp and Hines 1991)
Motacilla alba	The White Wagtail exhibits varied migration patterns. Some western and southern European populations are resident, while northern birds migrate southward. European birds winter in Iberia, North Africa, and South Asia, while Asian populations winter in Arabia, India, and Southeast Asia. North American populations migrate southwest to Asia. Birds from Japan, Sakhalin, and the Kuril Islands migrate south to winter in Japan and Southeast Asia. Vagrants have reached North America, particularly Alaska, and occasionally the U.S. East Coast. MD from multiple individuals across multiple years. Omnivore. (Badyaev et al. 2020; Dougall 1991)
Anas poecilorhyncha	The Spot-billed Duck is mainly sedentary but disperses in response to water availability. Some movements have been recorded in western Myanmar, though a record from Kazakhstan remains unconfirmed. MD from GPS telemetry across individuals and years. Omnivore. (Carboneras and Kirwan 2020; Kim et al. 2022)
Ardea cocoi	The Cocoi Heron is generally sedentary, but birds from the southernmost parts of their range migrate north during winter. Some dispersal occurs post-breeding, with records in Argentina, the Strait of Magellan, and Trinidad. Rare vagrants have been recorded in Ecuador, Brazil, the Falklands, and Gough Island. MD from banding and observations across individuals and years. Secondary Consumer. (Martínez-Vilalta et al. 2020; Hayes et al. 2023)
Podiceps major	The Great Grebe moves to coastal waters after breeding, returning to freshwater to breed. It occasionally strays far from shore, with records from 40 km offshore in Argentina and at least six records in the Falklands. Early 20th-century records from Spain are considered dubious. MD not found in the literature. Secondary Consumer. (Llimona et al. 2024)
Arenaria interpres	The Ruddy Turnstone is a long-distance migrant with no resident populations. It breeds in the Arctic and winters in temperate and tropical coastal areas worldwide. North American and Siberian populations migrate to Europe, Africa, Asia, Australia, and the Americas. Some populations make transoceanic migrations of thousands of kilometers. Most immatures remain at wintering sites during their first summer. MD from banding and observations across individuals and years. Secondary Consumer. (Nettleship 2020; Helseth et al. 2005)
Aythya australis	The Hardhead is present year-round in many areas but is dispersive and nomadic during the dry season. It may travel widely in response to drought or breeding success. The species has reached New Zealand, Java, Bali, Sulawesi, Timor-Leste, and New Guinea, with some sporadic breeding after irruptions. However, most populations outside Australia do not persist. MD not found in the literature. Omnivore. (Carboneras and Kirwan 2020)
Falco tinnunculus	The Common Kestrel is migratory in northern and eastern breeding ranges but is sedentary or dispersive elsewhere. Many migrate from Europe and Asia to Africa, India, and Indochina, with large numbers crossing to Africa. Juveniles are generally more dispersive. Exceptional vagrants have been recorded in the Caribbean and South America, including French Guiana and Brazil. MD not found in the literature. Secondary Consumer. (Orta et al. 2020)
Tadorna tadornoides	The Australian Shelduck is mostly sedentary but undergoes dispersal after breeding, traveling several hundred kilometers. Movements are linked to molting concentrations and water availability. It has reached northern Australia, New Zealand, and various islands, including the Chagos Islands, Norfolk, and the subantarctic Snares and Campbell Islands. MD not found in the literature. Omnivore. (Carboneras and Kirwan 2020)
Molothrus ater	The Brown-headed Cowbird is a short-distance migrant within North America, moving seasonally between breeding and wintering areas. Birds from the northeastern U.S. migrate approximately 800–850 km between summer and winter sites. MD from banding and observations across individuals, populations and years. Omnivore. (Lowther 2020)
Anas georgica	The yellow-billed pintail is partially migratory, with southern breeders moving north to winter in southeastern Brazil. Some migrate from the high Andes and central Chile, while others remain near their breeding areas. Populations in the Falklands may leave in winter, with occasional records from Antarctica. MD not found in the literature. Omnivore. (Carboneras et al. 2024)
Pluvialis fulva	The Pacific golden plover is a long-distance migrant, traveling from tundra breeding grounds to wintering areas in Oceania and Southeast Asia. It is known for extensive nonstop flights over open water. MD from geolocators across individuals and years. Omnivore. (Johnson et al. 2024; Johnson et al. 2011)
Nycticorax violaceus	The yellow-crowned night heron has some sedentary subspecies, while northern populations migrate south after breeding. Postbreeding dispersal is widespread, with young birds often moving north and west before beginning their southward migration in autumn. MD not found in the literature. Secondary Consumer. (Watts 2020)
Cacatua sanguinea	The little corella is a strong flier, moving long distances to find food and water. Large flocks can form at abundant food sources, such as grain fields, but break into smaller groups for breeding. MD from banding and observations across individuals and years for an introduced population. Omnivore. (Rowley and Boesman 2020; Blythman and Porter 2020)

Bucephala islandica	The Barrow's goldeneye is a medium-distance migrant, with seasonal movements between breeding, molting, and wintering areas. It is present year-round in parts of British Columbia and the Rocky Mountains, though it is uncertain whether breeding populations are resident or replaced in winter. Populations in different regions do not appear to mix. MD from banding and observations across individuals and years. Omnivore. (Eadie et al. 2020; Robert et al. 2002)
Pica pica	The Eurasian magpie is largely sedentary, though some northern populations move south in harsh winters. Scandinavian birds may attempt sea crossings to Denmark, but many turn back. Siberian populations shift south in severe weather, gathering near towns. Rare vagrants have been recorded in distant regions such as Singapore, Israel, and Lebanon. MD from banding and observations across populations and years in Eurasia. Secondary Consumer (Scavenger/Carnivore). (Madge et al. 2020)
Anhinga anhinga	The anhinga is a short-distance partial migrant, moving between summer nesting sites in the southeastern U.S. and wintering grounds in Florida, Louisiana, and Mexico. Much of the Florida population appears to be resident. Migration patterns in Central and South America are not well documented. MD not found in the literature. Secondary Consumer. (Frederick and Siegel-Causey 2020)
Melanitta fusca	The velvet scoter is migratory, wintering along European coasts, the Mediterranean, and the Black and Caspian Seas. Large numbers pass through the Baltic and Finland, with shifts in migration timing linked to climate change. Some vagrants reach distant locations such as Israel, Kuwait, and Greenland. MD not found in the literature. Secondary Consumer. (Carboneras et al. 2020)
Anas falcata	The falcated duck winters in East Asia, including China, Japan, Korea, and Southeast Asia. Occasionally, it appears further west in places such as Iraq and Turkey. Many records from Europe and North America likely involve escaped individuals. MD from banding and observations across individuals and years. Omnivore. (Carboneras and Kirwan 2020; Zhang et al. 2020)
Podilymbus podiceps	The pied-billed grebe is migratory in the northern part of its range, moving to lower latitudes in winter as lakes freeze. Southern populations remain resident year-round. MD not found in the literature. Secondary Consumer. (Muller and Storer 2020)
Limosa lapponica	The bar-tailed godwit is a long-distance migrant, moving from Arctic breeding grounds to wintering areas across temperate and tropical regions. European birds migrate as far as the west coast of Africa, while Siberian populations travel to Australia and New Zealand. Some individuals undertake nonstop transoceanic flights, among the longest of any bird, covering up to 25,000 km annually. MD from satellite telemetry and banding across populations and years. Secondary Consumer. (McCaffery and Gill 2020; Battley et al. 2012)
Pernis apivorus	The European honey buzzard migrates from breeding areas in Europe to wintering grounds in equatorial Africa. Most migrate through the Strait of Gibraltar or across the eastern Mediterranean, with some juveniles taking broader routes. Birds tracked from the Netherlands show faster return migrations in spring, avoiding adverse weather conditions. Some oversummer in West Africa rather than returning north. MD from satellite telemetry across locations and years. Secondary Consumer. (Orta et al. 2020; Hake et al. 2003)
Buteo rufinus	The long-legged buzzard shows varied migratory behaviour. North African populations are mostly resident, though some disperse. Eurasian birds are partially migratory, with those from northern breeding areas moving south to winter in the Middle East, South Asia, and sub-Saharan Africa. Migration patterns include seasonal movements related to drought conditions. MD not found in the literature. Tertiary Consumer. (Orta et al. 2020)
Aramus guarauna	The limpkin is generally sedentary, though some northern populations exhibit seasonal movements. In Florida, many females leave breeding territories in early summer, returning in winter. Seasonal dispersal occurs in response to water levels, particularly in Brazil and Costa Rica. Possible movements between Cuba and Florida are suggested by frequent records in the Florida Keys. MD not found in the literature. Secondary Consumer. (Bryan 2020)
Euphagus cyanocephalus	The brewer's blackbird is a medium-distance migrant. Birds from the Great Basin, Colorado Plateau, and Central Plains migrate south, with some travelling over 2,500 km to Mexico. Coastal populations in California and the Pacific Northwest are mostly resident, though some make short elevational migrations. Movements vary by region, with some birds shifting east in autumn. MD not found in the literature. Omnivore. (Martin 2020)
Falco peregrinus	The peregrine falcon is highly migratory in temperate and Arctic zones, with some individuals traveling over 14,000 km from breeding to wintering grounds. Tundra breeders migrate the furthest south, reaching Argentina and Chile, while some mid-latitude populations are resident. Birds wintering in Mexico and Central America often breed in the Arctic and Greenland. MD from satellite telemetry across two locations in Western hemisphere and North Russia. Tertiary Consumer. (White et al. 2020; Ganusevich et al. 2004; Fuller et al. 2002)
Otis tarda	The great bustard has complex migratory behaviour. Iberian populations are largely sedentary, though some individuals migrate seasonally. Males may travel up to 250 km to summering areas, often selecting habitats that provide shelter from heat. Eastern populations in Russia and Mongolia migrate up to 2,000 km to wintering grounds in Ukraine and China. MD from banding and observations across individuals and years. Omnivore. (Collar & Garcia 2020; Morales et al. 2000)
Aquila rapax	The tawny eagle is mostly resident but exhibits some seasonal movements. Some individuals shift into arid regions during the rainy season, particularly in West Africa. Rare vagrants have been recorded as far north as the Mediterranean and occasionally in Southeast Asia. It sometimes mixes with steppe eagle flocks during migration. MD from GPS telemetry across individuals in Central Asia over multiple years. Tertiary Consumer. (Kemp and Kirwan 2020; Ram et al. 2022)
Haliastur indus	The brahminy kite is generally sedentary, though some individuals migrate locally in response to seasonal rains. Some breeders in southern China move to Southeast Asia in winter. The species is largely resident in Australia and tropical Asia, congregating in areas with abundant food. Breeding pairs tend to remain in the same area year-round. MD not found in the literature. Secondary Consumer. (Debus et al. 2021)
Anas castanea	The chestnut teal is mostly sedentary, with small-scale inland and coastal dispersal in Australia. However, vagrants have been recorded in New Guinea, New Zealand, and Lord Howe Island, where breeding was documented in 1994. MD not found in the literature. Omnivore. (Carboneras et al. 2020a)
Anhinga rufa	The African darter is generally sedentary, though it moves sporadically in response to drought conditions. Some individuals have been recorded as vagrants in Morocco. MD not found in the literature. Secondary Consumer. (del Hoyo et al. 2020)
Theristicus melanopis	The black-faced ibis migrates from southern Chile and Argentina to the pampas of northern Argentina for the winter. It is a breeding summer visitor to Tierra del Fuego, with spring migration starting in late August and autumn migration occurring from late January to April. It migrates in large flocks, sometimes at great heights, and occasionally appears as a vagrant in the Falkland Islands. MD not found in the literature. Secondary Consumer. (Matheu et al. 2020a)
Podiceps auritus	The horned grebe is a complete medium-distance migrant, moving from inland freshwater breeding sites to coastal marine wintering areas. Migration occurs mostly at night, often in flocks, though some diurnal movements take place. Most individuals travel over 1,000 km between breeding and wintering locations. MD from banding and observations across individuals and years in Europe. Secondary Consumer. (Stedman 2020; Konter & Konter 2006)

Zoothera naevia	The varied thrush is a short-distance partial migrant. Birds breeding in interior regions migrate south for the winter, while the status of coastal breeders remains uncertain. A "leapfrog" migration pattern has been suggested, with northern breeders wintering further south than those from more southern breeding sites. Banding data indicate strong wintering site fidelity. MD not found in the literature. Omnivore. (George 2020)
Circaetus gallicus	The short-toed snake eagle is migratory in the Palearctic, wintering primarily in tropical North Africa and the Indian subcontinent. Migration occurs individually rather than in flocks, though concentrations are seen at key sea crossings such as the Strait of Gibraltar and the Bosporus. Most birds leave Europe from September to November, returning between late February and May. Some immatures remain in Africa during summer. MD from satellite telemetry across individuals and years in Europe. Tertiary Consumer. (Orta et al. 2020a; Meyburg et al. 1998; Pavón et al. 2010)
Theristicus caudatus	The buff-necked ibis is likely mostly sedentary, though some local movements occur. In Colombia, it occasionally wanders west of the Andes, and vagrants have been recorded in eastern Panama and Peru. MD not found in the literature. Secondary Consumer. (Matheu et al. 2020b)
Pernis ptilorhyncus	The crested honey buzzard is migratory in northern populations, while southern populations are mostly sedentary or locally dispersive. Breeders from Siberia and Japan migrate south from September to October, wintering across Southeast Asia, Indonesia, and the Philippines. Spring migration occurs from February to May, with some birds taking extended detours. Large movements have been recorded over Thailand, Malaysia, and Bali. MD based on satellite telemetry and banding across individuals and years in Asia. Secondary Consumer. (Orta et al. 2020b)
Eudocimus ruber	The scarlet ibis is primarily resident but undergoes local dispersal. Birds in Suriname move inland along rivers in dry seasons, and some depart from the Venezuelan llanos during droughts. They frequently travel long distances between nesting or roosting sites and feeding areas, often flying in V-formations. Stragglers have been recorded in Ecuador, Panama, Belize, and the West Indies, and vagrants occasionally reach the southeastern United States. MD not found in the literature. Secondary Consumer. (Matheu et al. 2020c)
Mimus polyglottos	The northern mockingbird is partially migratory, with some individuals in the northern part of its range moving south for winter. However, others remain year-round near breeding territories. Banding data suggest that some birds travel up to 800 km, though their movements are not well understood. MD not found in the literature. Omnivore. (Farnsworth et al. 2020)
Chloephaga poliocephala	The ashy-headed goose is partially migratory, moving north to winter in the pampas region of Argentina, where it mingles with ruddy-headed and upland geese. It is occasionally recorded in the Falkland Islands, typically from September to March, and has occasionally bred there, with some individuals possibly being resident on West Falkland. MD not found in the literature. Grazer. (Carboneras & Kirwan 2024)
Anas clypeata	The northern shoveler is highly migratory, flying south to winter at lower latitudes. In North America, migration is mostly north-south east of the Rocky Mountains, with few birds wintering on the Atlantic Coast. Large numbers cross the Rockies to winter in California and Mexico. Unlike other waterfowl, males do not undertake an extensive molt migration. MD not found in the literature. Omnivore. (Dubowy et al. 2020)
Lophodytes cucullatus	The hooded merganser is a short to intermediate-distance migrant, depending on breeding and wintering locations. Some birds remain in the southern portion of their range year-round, but many migrate north after breeding. Some winter as far north as ice conditions permit. Banding data show that birds from the northeastern U.S. migrate to the Atlantic Coast, while mid-continent populations migrate through the Mississippi Flyway. Birds breeding west of the Rockies migrate west and south towards the Pacific. MD not found in the literature. Secondary Consumer. (Dugger et al. 2020)
Ciconia boyciana	The oriental stork is migratory, traveling over mostly little-known areas of China. It leaves breeding grounds in Russia and China between September and October and returns between March and April. Some individuals begin migrating as early as July, traveling short distances daily and taking up to 116 days to reach wintering sites along the Yangtze River. Birds winter in China, primarily at Poyang Lake and East Dongting Lake. Migration routes are similar in autumn and spring, with movements occurring mainly during midday and afternoon. It is a rare vagrant in Tibet, the Philippines, and parts of Russia. MD based on satellite telemetry and GPS tracking across individuals and years for multiple migratory routes in China and Japan. Secondary Consumer. (Elliott et al. 2020; Shimazaki et al. 2004; Yang et al. 2023)
Anas undulata	The yellow-billed duck is mostly sedentary, with small-scale movements between wetlands. Some individuals disperse further, reaching Cameroon, Nigeria, Somalia, and Eritrea. In South Africa, occasional movements of up to 1,000 km have been recorded, with one individual traveling over 2,200 km. MD not found in the literature. Omnivore. (Carboneras & Kirwan 2020a)
Anas flavirostris	The yellow-billed teal migrates from its southernmost breeding areas to winter in temperate regions as far north as Uruguay, Paraguay, and southeastern Brazil. Andean and Falkland Islands populations are mostly sedentary, though Andean birds may descend to lower elevations in winter. Some have been recorded offshore from Patagonia. MD not found in the literature. Omnivore. (Carboneras & Kirwan 2020b)
Aix galericulata	The mandarin duck is mostly migratory in Asia, wintering in eastern, central, and southern China, Korea, Taiwan, and Japan. Migrants arrive in Russia and Sakhalin in March and April, while autumn migration occurs between September and November. However, Japanese and British feral populations are mostly sedentary. Radio-tracking in Taiwan has shown that young females exhibit stronger site fidelity than young males. The species occasionally appears in South Asia and has been recorded as a vagrant in Europe and North America. MD not found in the literature. Omnivore. (Carboneras & Kirwan 2020c)
Torgos tracheliotos	The lappet-faced vulture does not follow regular migration patterns, except in West Africa, where it shifts north during the rainy season and south during the dry season. Adults may forage over 200 km from the nest, while juveniles have been recorded dispersing at least 700 km. Tertiary Consumer. (Kemp et al. 2020a; Shobrak 2014)
Junco hyemalis	The dark-eyed junco exhibits great variation in migration patterns. Most populations migrate, though some remain in the same area year-round. Northern populations migrate south, with females and younger birds tending to move farther than males. In eastern North America, females are more common in the southern wintering range, while males dominate further north. Some montane populations are sedentary or undertake short-distance altitudinal migrations. Banding data indicate that displaced individuals can return to their breeding sites over long distances. MD not found in the literature. Omnivore. (Nolan et al. 2020)
Limosa limosa	The black-tailed godwit migrates in broad front movements with long-distance flights between staging sites and wintering areas. Southward migration occurs from June to October, with a return passage from February to April. Some one-year-olds remain in wintering areas throughout the summer. The Icelandic population migrates via Ireland to the coasts of Britain, France, Spain, Portugal, and Morocco. Most European populations winter in West Africa south of the Sahara, though numbers wintering in southwestern Spain have increased due to the expansion of rice fields and fish ponds. Birds breeding in central and eastern Europe winter in sub-Saharan Africa, while those from Kazakhstan migrate to India. Omnivore. (Van Gils et al. 2020a; Lourenço & Piersma 2015)
Numenius madagascariensis	The far eastern curlew is a long-distance migrant that follows coastal routes from the Kuril Islands, Sakhalin, and Russia down through Korea, Japan, the Philippines, Sumatra, and Borneo. It is less common in eastern China and

	Southeast Asia, where it appears mostly in transit. Large numbers reach northwestern and eastern Australia by August, with a gradual movement southward, peaking in November. Northbound migration occurs from February to April. Satellite tracking has shown that birds leave Queensland on a non-stop flight across the Pacific to China and Korea before continuing to breeding grounds in Russia. Some non-breeding individuals remain in Australia and China throughout the boreal summer. Vagrants have been recorded in Bangladesh, Diego Garcia, and as far as North America. MD from satellite telemetry across individuals following the East Asia flyway. Secondary Consumer. (Van Gils et al. 2020b; Driscoll & Ueta 2002)
Gyps coprotheres	The Cape Vulture moves around looking for food and has distinct breeding areas. Most individuals stay within 100 km of their nesting and roosting colonies, but some seasonal movements occur. Juveniles disperse widely, traveling up to 1,200 km into Angola, Zambia, and Mozambique. Foraging distances increase in winter, particularly in Namibia and South Africa. Some vultures use supplementary feeding stations, but their overall movement patterns remain extensive. MD from GPS telemetry across individuals in southern Africa over multiple years. Tertiary Consumer (Scavenger / Carnivore). (Kemp et al. 2020b; Martens et al. 2018)
Ardea goliath	The Goliath Heron is primarily sedentary but shows nomadic or dispersive movements in response to seasonal changes. In Ethiopia and Eritrea, fewer records exist between May and August, suggesting seasonal shifts. It is a non-breeding visitor in Cameroon and Lesotho, and vagrants have been recorded in Liberia, Madagascar, and parts of the Middle East. Most individuals remain within their preferred wetland habitats year-round. MD not found in the literature. Tertiary Consumer. (Martínez-Vilalta et al. 2020a)
Zonotrichia albicollis	The White-throated Sparrow is a short-distance nocturnal migrant influenced by weather. Although its breeding and winter ranges overlap, most populations migrate southward to areas with minimal snow cover in winter. Spring migration occurs when snow begins to melt, allowing access to the forest floor. This movement pattern ensures the species can forage efficiently throughout the year. MD not found in the literature. Omnivore. (Falls & Kopachena 2020)
Podiceps cristatus	The Great Crested Grebe is migratory and dispersive, especially in northern populations. Many individuals move from breeding lakes to larger water bodies to moult before continuing migration to coastal wintering areas. Large congregations form at sites such as the IJsselmeer in the Netherlands and the Turkish Black Sea coast. In Africa, movements are linked to rainfall patterns rather than true migration, while in New Zealand, post-breeding dispersal occurs. MD from banding and observations across individuals and years. Secondary Consumer. (Llimona et al. 2020; Konter & Konter 2006)
Zenaida auriculata	The Eared Dove is highly dispersive, forming large flocks in northeastern Brazil every two to three years. It is nomadic in Argentina, moving in search of food. After breeding, some individuals return to traditional roosting sites even after habitat destruction. The species has expanded its range to Caribbean islands such as St. Lucia, St. Vincent, and Barbados. It occasionally appears in the Falkland Islands and South Georgia. MD not found in the literature. Mixed Feeder (Grazer). (Baptista et al. 2024)
Anas cyanoptera	The Cinnamon Teal is mostly a short- to intermediate-distance migrant. Some populations in southern parts of the breeding range, such as in Mexico and California, are resident. South American populations tend to be sedentary or migrate only short distances. The species primarily moves to lower latitudes in winter, ensuring access to suitable wetland habitats throughout the year. MD from GPS telemetry and banding across individuals and years. Omnivore. (Gammonley 2020; Mackell et al. 2021)
Antigone antigone	The Sarus Crane is non-migratory in India, though some seasonal movements occur, particularly during droughts. In Southeast Asia, populations migrate from the upper Mekong to the delta in Vietnam. In Australia, most individuals breed around the Gulf of Carpentaria and move southward for winter. Non-breeders arrive at wintering sites as early as May, while some individuals remain into November. MD not found in the literature. Omnivore. (Archibald et al. 2020)
Anas rhynchotis	The Australasian Shoveler is mainly sedentary but shows dispersive and nomadic tendencies, especially in response to drought. In Australia, large numbers sometimes gather at specific wetlands, while in New Zealand, birds disperse widely after moulting. Some individuals travel long distances, with recoveries showing movements across both North and South Islands. The species occasionally wanders as far as New Caledonia. MD from banding and observations across individuals and years in New Zealand. Omnivore. (Carboneras & Kirwan 2020d; Rook 2002)
Aythya ferina	The Common Pochard is partially migratory, with some individuals traveling over 1,000 km in just a few days. Western European populations winter in Western Europe and North Africa, while those from eastern breeding grounds move to Southeast Asia. Males typically migrate earlier than females. Some birds remain in temperate regions year-round, making short-distance movements to avoid ice-covered water bodies. The species occasionally appears as a vagrant in the Americas and various islands. MD from banding and observations across individuals and years in Switzerland. Omnivore. (Carboneras et al. 2020b; Hofer et al. 2006)
Recurvirostra americana	The American Avocet is a medium-distance migrant ranging from Canada to Mexico. Migration patterns vary annually and are not well understood. In the western United States, movements occur both north-south and inland-coastal. Some birds remain at stopover sites for extended periods. Post-breeding movements are common, and long-distance flights of up to 200 km have been recorded before migration. On the East Coast, migration primarily takes place in the fall. MD not found in the literature. Omnivore. (Ackerman et al. 2020)
Egretta novaehollandiae	The White-faced Heron is mostly sedentary but undertakes widespread nomadic movements. In Australia, coastal birds move inland for the breeding season, while in New Zealand, individuals shift from exposed coastal areas to inland wetlands in winter. Post-breeding dispersal occurs towards Wallacea, particularly Lombok, Flores, and Sumbawa. The species occasionally reaches China, Taiwan, and the Solomons, expanding its known range. MD not found in the literature. Secondary Consumer. (Martínez-Vilalta et al. 2020b)
Nycticorax caledonicus	The Nankeen Night Heron is mostly sedentary, though post-breeding dispersal can be extensive, contributing to its colonization of the Sunda Islands and the Philippines. Some movements are tied to water availability, particularly in the Darling–Murray basin in Australia. Part of the population migrates north in winter, with Australian birds visiting New Guinea and Indonesian islands. Individuals have also been recorded as vagrants in Tasmania, Christmas Island, and Taiwan. MD not found in the literature. Secondary Consumer. (Martínez-Vilalta et al. 2021)
Egretta caerulea	The Little Blue Heron is a partial migrant, with northern breeding populations moving south to Central and South America by late autumn. Some individuals remain year-round in the southern United States and Mexico, while others migrate further south. Cold weather and prey scarcity drive migration. Post-breeding dispersal is unpredictable, with juveniles sometimes moving north before eventually heading south for the winter. MD not found in the literature. Secondary Consumer. (Rodgers & Smith 2020)
Fulica cristata	The Red-knobbed Coot is mainly sedentary but exhibits nomadic and opportunistic movements. In Africa, flocking behavior suggests seasonal movements influenced by water levels and food availability. Some individuals travel over 1,000 km outside the breeding season, while others remain on permanent water bodies. In South Africa, fluctuations in population numbers at certain wetlands are tied to rainfall patterns and water conditions. MD not found in the literature. Omnivore. (Taylor 2020a)

Asio flammeus	The Short-eared Owl is a partial migrant with complex movement patterns. Northern populations are highly migratory, but movements are often confused with nomadism and juvenile dispersal. In North America, migration is predominantly north-south, with some individuals traveling over 1,500 km. In Europe, birds breeding north of 50°N migrate, while those further south are mostly resident. The species also undertakes inter-island movements in the Galápagos. MD from banding and satellite telemetry across individuals and averaged across two studies in Europe and western North America. Secondary Consumer. (Wiggins et al. 2020; Call et al. 2012)
Gallinula tenebrosa	The Dusky Moorhen is sedentary, nomadic, or dispersive across Australia, sometimes showing seasonal fluctuations in numbers. It appears at temporary inland wetlands and disperses when water conditions change. Movements seem to be linked to rainfall, flooding, and food availability, but large-scale irruptions are rare. In New Guinea, it is considered locally nomadic, and vagrants occasionally reach New Zealand and Lord Howe Island. MD not found in the literature. Omnivore. (Taylor 2020b)
Catoptrophorus semipalmatus	The Willet has both resident and migratory populations. Birds from the West Indies remain year-round, while others migrate varying distances along the coasts of the Americas. Breeding populations from Canada undertake long-distance migrations, some traveling transoceanically. In the United States, fall migration begins early, with some individuals remaining on wintering grounds throughout the summer. MD from GPS telemetry and genetic analysis, across multiple individuals and years. Secondary Consumer. (Lowther et al. 2020; Huether et al. 2022)
Phoenicopterus jamesi	James's Flamingo performs altitudinal migrations, moving from high-altitude breeding lakes to lower elevations during the austral winter when freezing limits food availability. However, some birds remain at high-altitude lakes that are fed by hot springs. These seasonal movements ensure access to suitable feeding grounds in the Puna and surrounding valleys. MD not found in the literature. Primary Consumer. (Rivas et al. 2020)
Butorides striatus	The Striated Heron is primarily sedentary, but some northern populations migrate south in winter. In North America, birds from the United States winter as far south as the Caribbean and northern South America. In Asia, northern breeders migrate to southern China, Sumatra, and the Philippines. African populations are mostly resident but disperse in response to rainfall. Vagrants have been recorded as far as Europe, the Pacific, and the Indian Ocean islands. MD not found in the literature. Secondary Consumer. (Martínez-Vilalta et al. 2020c)
Loxia leucoptera	The White-winged Crossbill is highly nomadic, wandering boreal forests in search of conifer seeds. Movements vary depending on cone crop availability, sometimes resulting in large-scale irruptions. Birds may migrate long distances, occasionally forming flocks of up to 10,000 individuals. In some years, they remain within their breeding range, while in others, they travel significant distances in search of food. MD not found in the literature. Mixed Feeder (Grazer). (Benkman 2020)
Vanellus miles	The Masked Lapwing is a resident and dispersive species, responding to food availability in temporary wetlands. Young birds are more likely to disperse, and numbers increase in coastal areas when inland wetlands dry up. Some individuals undertake altitudinal migrations in regions like the Snowy Mountains of Australia. Vagrants have been recorded in New Guinea, Fiji, and other Pacific islands. MD not found in the literature. Secondary Consumer. (del Hoyo et al. 2020b)
Apus apus	The Common Swift is a long-distance migrant, arriving in Europe in spring and leaving by late summer. Most migration follows a southwestward path, with birds wintering in sub-Saharan Africa. Some individuals winter north of the Sahara, while others have been recorded as vagrants in various oceanic archipelagos. Swifts are known for their near-continuous flight, remaining airborne for most of the non-breeding season. MD from geolocators across multiple individuals, populations and years. Secondary Consumer. (Chantler et al. 2020; Åkesson et al. 2012)
Streptopelia orientalis	The Oriental Turtle Dove exhibits a mix of migratory and resident behavior. Northern populations from Siberia and Japan migrate south to winter in southern and eastern Asia. In the Himalayas and northern India, birds migrate further south during winter. The species' winter range remains poorly understood due to difficulties in subspecific identification. MD not found in the literature. Mixed Feeder (Grazer). (Baptista et al. 2020)
Seabirds	
Larus hyperboreus	Glaucous Gull migrates south ahead of ice in winter, with some overwintering in Nunavut, Labrador, and southwest Greenland. It mainly follows coastal routes, with immatures dispersing more widely at sea. Fall migration occurs along the Beaufort Sea coast into the Pacific and from the eastern Canadian Arctic along the Labrador coast into the Atlantic. Birds leave breeding areas from September to November, with young departing later. Spring migration follows similar paths, with early arrivals in April or May, often pausing at sea ice edges before reaching breeding sites. MD from telemetry to identify migratory movements. Omnivore. (Weiser & Gilchrist 2020; Baak et al. 2021)
Larus delawarensis	Ring-billed Gull is a partial migrant, wintering mainly in the southern US, especially along the Gulf Coast and Florida. Migration follows coasts, rivers, and inland routes, with some birds foraging far from water. Fall migration is slow, but spring migration is more direct, with birds returning to breeding grounds in the western US, including the Great Salt Lake and Montana. Some individuals follow the same migration routes yearly. MD from banding and observational data. Omnivore. (Pollet et al. 2020; Gabrey 1996)
Aptenodytes patagonicus	King Penguin undertakes extensive foraging migrations, traveling over 10,000 km in winter. Birds from Falkland Islands forage near the South American continental slope, while Crozet Island birds remain in Antarctic waters. Their primary prey, lanternfish, is found between the surface and 200 m depth. Post-breeding juveniles disperse widely, with some traveling over 1,000 km. Vagrants have been recorded in New Zealand, southern Australia, South Africa, and Brazil. MD from telemetry, light-level tracking and isotope analysis to identify feeding and breeding areas. Secondary Consumer. (Martínez et al. 2020a)
Sula dactylatra	Masked Booby does not have a regular migration pattern, but some birds leave colonies outside the breeding season. Adults from Ascension Island and Seychelles are resident year-round, while Pacific birds travel up to 2,000 km from breeding sites. Young and some adults have been observed foraging over 1,000 km from the nearest land. MD from observed occurrences. Secondary Consumer. (Grace et al. 2020)
Rissa tridactyla	Black-legged Kittiwake migrates south after breeding, with most birds wintering in ice-free waters. European birds join North American populations, and immatures often remain at sea year-round. Migration routes are unclear but likely follow continental shelves. Fall migration sees Arctic birds moving south from August to November. Spring migration is more direct, with adults returning to breeding areas by February in Newfoundland, while ice presence influences timing further north. MD from telemetry, geolocation (light-level) and banding data. Secondary Consumer. (Hatch et al. 2020a)
Catharacta antarctica	Brown Skua winters at sea, with some birds staying near New Zealand, Tristan da Cunha, and Gough Island year-round. Antarctic and subantarctic populations migrate north, with birds from South Georgia and the Falklands wintering in different regions. South Georgia birds spread widely in oceanic waters, while Falkland birds stay near the Patagonian shelf. Individuals consistently return to the same wintering areas each year. MD from telemetry, geolocation and isotope analysis. Secondary Consumer (Scavenger/Carnivore). (Furness et al. 2020a; Delord et al. 2018)
Sula sula	Red-footed Booby may migrate or disperse widely at sea, with adults rarely seen at colonies outside the breeding season. Long foraging trips obscure migration patterns, but birds can travel hundreds of kilometers from land. Juveniles disperse more widely than adults, sometimes traveling thousands of kilometers. Hawaiian birds mainly disperse

	eastward, with significant movement between islands. MD from telemetry, geolocation and banding. Secondary Consumer. (Schreiber et al. 2020a)
Pygoscelis papua	Gentoo Penguin is a partial migrant, with subantarctic populations remaining near colonies while Antarctic birds migrate north. In winter, birds reach as far as 43°S in Argentina, with vagrants recorded in Tasmania and New Zealand. Winter movements are limited, with most birds staying within 268 km of their breeding colony, reflecting their deep-diving foraging strategy. MD from GPS tracking multiple individuals. Secondary Consumer. (Wilson et al. 1998; Martínez et al. 2020b)
Onychoprion fuscatus	Sooty Tern breeds in tropical regions, with adults from Dry Tortugas, Florida, wintering at sea in the Gulf of Mexico and Caribbean. Fledglings migrate to West Africa, staying for 2–5 years before returning. Birds from Ascension Island also migrate to West Africa. Juveniles disperse widely, while adults return to breeding colonies 2–3 months before nesting. Migration timing varies, influenced by environmental conditions. MD not found in the literature. Secondary Consumer. (Schreiber et al. 2020a)
Morus bassanus	Northern Gannet migrates south in winter, with juveniles traveling farther than adults. Birds from North America move south along the Atlantic Coast, reaching Florida and the Gulf of Mexico by December. Some European birds reach West Africa. Spring migration begins in February, with adults returning to breeding sites before peak food availability. Juveniles lag behind, returning to northern waters by late May. MD not found in the literature. Secondary Consumer. (Mowbray 2020; Laurenson et al. 2021)
Larus argentatus	Herring Gulls show diverse migratory behaviors. Adults in the eastern US and Great Lakes are mostly sedentary, while those from Atlantic Canada migrate short distances south. Arctic and boreal populations travel further, with some from Nunavut reaching the Gulf of Mexico. Juveniles tend to disperse widely. Banding data from over 700,000 individuals provide key insights in MD. Omnivore. (Weseloh et al. 2020)
Phaethon rubricauda	Red-tailed Tropicbirds do not migrate regularly but disperse widely. Southernmost populations may follow warm currents across the equator. Peak distributions occur in three Pacific regions: near Hawaii, Polynesia, and Pitcairn Island. Seasonal movements peak in August–November and March. MD from banding and recovery data. Secondary Consumer. (Schreiber & Schreiber 2020a; Le Corre et al. 2003)
Larus glaucoides	Iceland Gulls migrate between Arctic breeding sites and polynyas. Many Canadian birds move south in winter, while Greenland populations mostly remain in southwestern Greenland. Some dispersal occurs along Greenland's coast, with occasional influxes into southern wintering areas. MD from banding data. Omnivore. (Snell et al. 2020)
Sula leucogaster	Brown Boobies have variable movement patterns. Juveniles can disperse hundreds of kilometers, while adults may forage over oceanic areas. In some locations, few return to colonies outside the breeding season, while others roost near colonies year-round. MD based on bandind data. Secondary Consumer. (Schreiber & Norton 2020)
Larus dominicanus	Kelp Gulls exhibit resident, migratory, and dispersive behaviors. Some remain year-round, while others travel long distances. South African populations disperse northward, reaching Mozambique and the Gulf of Guinea. South American birds winter as far north as Ecuador, Brazil, and occasionally North America. MD based on banding an resighting. Secondary Consumer. (Burger et al. 2020a; Whittington et al. 2009)
Spheniscus magellanicus	Magellanic Penguins migrate north after molting, reaching northern Argentina and southern Brazil in the Atlantic and up to 30º S in the Pacific. Satellite tracking shows most Beagle Channel individuals move into the Atlantic, staying within 50 km of the coast. Md based on satellity tracking. Secondary Consumer. (Martínez et al. 2020b)
Diomedea melanophris	Black-browed Albatrosses migrate based on breeding location. Falkland birds winter off South America's east coast, while South Georgia birds head to South Africa's Benguela Current. Juveniles follow distinct routes, with many from South Georgia wintering in South African waters. MD from satellite tracking. Secondary Consumer. (del Hoyo et al. 2020a)
Larus marinus	Great Black-backed Gulls are partial migrants. Northernmost populations leave breeding areas in winter, while southern birds show variable dispersal. Nova Scotia and Massachusetts populations remain year-round, but those from Maine and Newfoundland winter further south. Icelandic juveniles sometimes reach Britain. MD from banding data. Secondary Consumer. (Good 2020)
Sula granti	Nazca Boobies mostly remain near breeding colonies year-round. Young birds disperse after the breeding season, sometimes traveling long distances. MD from bading and resighting. Secondary Consumer. (Cuccaro Diaz et al. 2020; Huyvaert & Anderson 2004)
Pygoscelis adeliae	Adélie Penguins migrate to feeding grounds after breeding. Juveniles stay near breeding areas before dispersing. Unlike most penguins, adults molt on ice floes rather than at colonies. They move north after breeding to krill-rich waters. Immature birds remain in pack ice zones for 2–5 years before returning to colonies. MD from satellite tracking. Secondary Consumer. (Martínez et al. 2020c)
Uria aalge	Common Murres migrate to escape winter ice, with high-latitude populations moving south while others are partially migratory or sedentary. North Atlantic and Gulf of Alaska movements remain complex. Some Bering Sea birds winter among the Aleutian Islands, while eastern Pacific populations show varying dispersal. East Atlantic birds move south from breeding sites in fall and return north in spring. MD from observed population movements across seasons. Secondary Consumer. (Ainley et al. 2021)
Anous stolidus	Brown Noddies shift between breeding colonies and oceanic feeding areas. Their non-breeding range remains largely unknown, but some individuals make long-distance movements. MD from tracking data. Secondary Consumer. (Chardine et al. 2020; Lebarbenchon et al. 2023)
Larus glaucescens	Glaucous-winged Gulls vary in migration, with some wintering in breeding areas while others move south. Juveniles often disperse farther than adults but generally remain within 200 km of their natal sites. A few individuals have traveled over 2,000 km. MD from banding studies. Omnivore. (Hayward & Verbeek 2020)
Larus fuscus	Lesser Black-backed Gulls migrate south for winter but are increasingly overwintering near breeding areas, especially in Western Europe. Northernmost populations travel furthest, sometimes reaching equatorial Africa. Many birds winter in the Iberian Peninsula, Mediterranean, and West Africa, with some crossing the Sahara. MD from GPS tracking data. Omnivore. (Burger et al. 2020b; Shamoun-Baranes et al. 2017)
Stercorarius maccormicki	South Polar Skuas migrate from Antarctica to northern waters. They leave breeding sites in March and return in October–November. Their migrations form large oceanic loops, with birds reaching as far north as Japan, British Columbia, and Greenland. MD from geolocator data. Secondary Consumer. (Furness et al. 2020b; Kopp et al. 2011)
Fregata magnificens	Magnificent Frigatebirds disperse widely outside the breeding season. Some remain near breeding sites due to their long breeding cycle, while nonbreeders and juveniles travel long distances. Band recoveries show movements of up to 5,000 km. MD from GPS tracking device data. Secondary Consumer. (Diamond & Schreiber 2020; Giambalvo et al. 2022)
Fregata minor	Great Frigatebirds are mostly sedentary due to extended breeding, but some disperse widely. Birds from Kure Atoll have been recorded in the Marshall Islands and the Philippines before returning to breed. Juveniles are highly nomadic, appearing across tropical seas. MD from satellite transmitter data. Secondary Consumer. (Gauger Metz & Schreiber 2020; Weimerskirch et al. 2017)

Larus michahellis	Yellow-legged Gulls show diverse movement patterns. Some populations are resident, while others migrate north in summer and return south in winter. Western Mediterranean birds are largely sedentary, but some move to the Bay of Biscay. Eastern populations disperse northward post-breeding, reaching Northern and Central Europe before returning south in autumn. MD from banding resighting methods. Omnivore. (Arizaga et al. 2010; del Hoyo et al. 2020c)
Pygoscelis antarctica	Chinstrap Penguins migrate between breeding sites in the South Shetlands and feeding areas near the South Orkneys and South Sandwich Islands. They winter in pack ice zones, with some individuals traveling over 3,500 km. Some birds reach Australia, the Crozet Islands, and the Falklands. MD from satellite telemetry data. Secondary Consumer. (Martínez et al. 2020d; Hinke et al. 2019)
Stercorarius pomarinus	Pomarine Skuas migrate long distances from Arctic breeding grounds to wintering areas in tropical and subtropical oceans. Most remain north of the equator, but some travel further south. Large numbers winter near marine upwellings off West Africa. They mostly migrate offshore but are sometimes seen inland. MD from satellite telemetry. Secondary Consumer (Scavenger/Carnivore). (Haven Wiley & Lee 2020; Harrison et al. 2022)
Phalacrocorax carbo	Great Cormorants are mostly sedentary, but northern populations migrate south in winter. Some individuals move short distances to ice-free waters, while others, especially juveniles, travel long distances along coasts. MD from ring and resighting data. Secondary Consumer. (Hatch et al. 2020; Bregnballe et al. 2006)
Larus canus	Common Gulls migrate short to medium distances from breeding areas in northern Asia and Europe to winter in warmer regions. Some populations move only short distances, while others travel as far as the Mediterranean, Middle East, and southern Asia. Migration timing varies, with adults generally leaving earlier than juveniles. MD from ringing recovery data. Omnivore. (Moskoff et al. 2021; Pedersen et al. 2000)
Ardenna grisea	Sooty Shearwaters breed in New Zealand and the Southern Ocean before migrating to the northern hemisphere. They travel vast distances, often completing figure-eight loops across the Pacific, moving through the Peru and California currents before returning south. Others reach the North Atlantic, crossing to Europe before migrating southward again. MD from geolocator data. Secondary Consumer. (Carboneras et al. 2020; Hedd et al. 2012)
Fregata ariel	Lesser Frigatebirds are mostly sedentary, but immatures and non-breeders disperse widely across tropical seas. Many follow winds westward to the Coral Sea, then move north through New Guinea toward the Philippines, with some reaching Japan and Russia. MD from bading recovery data. Secondary Consumer. (Orta et al. 2020; Sibley & Clapp 1967)
Larus pipixcan	Franklin's Gulls are the only North American gull species, besides Sabine's Gull, that migrates south of the equator. They leave breeding grounds in mid-to-late July, initially wandering before forming flocks and heading directly south. They winter along coastal Peru and southern Chile. MD from banding recovery data. Secondary Consumer. (Burger & Gochfeld 2020)
Macronectes giganteus	Southern Giant Petrels disperse widely outside the breeding season. While some adults remain at breeding sites in winter, juveniles and non-breeding adults migrate northward, often traveling over 10,000 km, particularly to Australian and New Zealand waters. MD from banding recovery, satellite telemetry and geolocators.Tertiary Consumer (Scavenger / Carnivore). (Carboneras et al. 2020; CMS no date)
Uria lomvia	Thick-billed Murres migrate south in response to sea ice. Some populations undertake migrations over 2,000 km, with juveniles leaving Arctic breeding sites earlier than adults. They winter near ice margins, sometimes making large irruptions into more southerly waters. MD from miniature electronic tracking devices across individuals. Secondary Consumer. (Gaston & Hipfner 2020; Frederiksen et al. 2016)
Diomedea cauta	Shy Albatrosses forage widely but remain relatively close to breeding colonies in Tasmania. Breeders from different colonies use distinct feeding areas. Juveniles disperse further, with some reaching South Africa and Namibia. MD from GPS tracking devices. Secondary Consumer. (del Hoyo et al. 2020; Mason et al. 2023)
Diomedea immutabilis	Laysan Albatrosses leave breeding sites between July and October. Some post-breeding birds migrate from Hawaii to the North Pacific, foraging near the Aleutian Islands before returning. MD from GPS tracking devices. Secondary Consumer. (Awkerman et al. 2020; Hernández Montoya et al. 2019)
Anous minutus	Black Noddies are mostly sedentary but some breeding colonies are abandoned during the non-breeding season. Dispersing individuals travel long distances, sometimes over 4,000 km. While some return to their natal sites, the full extent of their migration remains unclear. MD from observations and banding data across multiple populations in different areas. Secondary Consumer. (Gauger 2020; Tarburton 1987)
Sula nebouxii	Blue-footed Booby does not undertake long migrations but forages within 30 km of shore. Juveniles may disperse, but adults generally remain near breeding areas. MD from direction recorders used to detect movement patterns. Secondary Consumer. (Hernández Díaz & Salazar Gómez 2020; Zavalaga et al. 2008)
Fulmarus glacialis	Northern Fulmar exhibits pelagic dispersal rather than strict migration. High-Arctic populations migrate in response to sea ice changes, while some Alaskan breeders move seasonally to the California Current. European and Greenlandic birds display transoceanic movements, and immatures may remain at sea for up to three years before visiting breeding sites. MD from satellite transmitter across multiple individuals over two years. Secondary Consumer. (Mallory et al. 2020; Hatch et al. 2010)
Phaethon aethereus	Red-billed Tropicbird does not migrate regularly, though juveniles disperse widely. Some individuals remain near breeding colonies, while others travel over 1,500 km. Observations have been recorded as far as Hawaii, England, Angola, and Australia. MD from GPS tracking data informing trip distance and duration. Secondary Consumer. (Orta et al. 2020; Madden et al. 2022)
Sterna caspia	Caspian Tern is a partial migrant. North American and European birds disperse post-breeding before migrating south. Some remain year-round along coasts, while immatures stay on wintering grounds. Band recoveries indicate migrations of up to 5,000 km. Fall migration is slower and meandering, while spring migration is faster and direct. MD from banding-recovery on an expanding population. Secondary Consumer. (Cuthbert & Wires 2020; Ludwig 1942; Gill & Mewaldt 1983)
Larus ridibundus	Black-headed Gull migrates south in winter from northern breeding grounds, while lower-latitude populations are more sedentary. Swiss breeders winter in the western Mediterranean, Scandinavian birds migrate to Britain and West Africa, and those in Spain originate from France and Belgium. MD from GPS tracking and banding-recovery data from individuals in the same declining colony. Secondary Consumer. (Burger et al. 2020; Fijn et al. 2022)
Larus atricilla	Laughing Gull is partially migratory. Northern populations migrate south in autumn to Central and South America, while others remain in Florida, Cuba, and the Gulf Coast. Migration distances range from 2,100 to 3,000 km. MD from banding orientation experiments across multiple individuals. Omnivore. (Burger 2020; Southern 1980)
Sterna bergii	Greater Crested Tern has largely unknown movement patterns. Some populations are resident, while Australian birds disperse a few hundred kilometers. Middle Eastern populations migrate south to winter along the East African coast. MD from GPS/GSM transmitters across individuals over multiple years. Secondary Consumer. (Gochfeld et al. 2020; Yu et al. 2022)
Eudyptes chrysocome	Southern Rockhopper Penguin migrates post-molt, spending around six months at sea. Falklands populations move to coastal Argentina, reaching up to 35°S. Satellite tracking shows wintering areas near Tierra del Fuego and Burdwood

	Bank, with some individuals traveling over 2,000 km. MD from satellite transmitters across individuals. Secondary Consumer. (Martínez et al. 2020; Pütz et al. 2002; Pütz et al. 2006)
Gygis alba	White Tern does not undertake regular migrations but disperses from breeding sites to sea. Most individuals leave nesting islands for several months between breeding seasons, though some remain year-round. MD from global location sensors across individuals. Secondary Consumer. (Niethammer & Patrick 2020; Carlile & O'Dwyer 2022)
Ardenna tenuirostris	Short-tailed Shearwater is a transequatorial migrant. After breeding, it migrates eastward, then northwest to the Sea of Okhotsk and Aleutian Islands, reaching Arctic waters beyond the Bering Strait. Return migration begins in August, primarily via the central Pacific, with some birds taking alternative routes through the Indian Ocean or along North America's west coast. Rare vagrants have been recorded in the Atlantic. MD from banding and geolocator data across individuals. Secondary Consumer. (Carboneras et al. 2020; Boyle et al. no date)
Phalacrocorax atriceps	Imperial Shag does not undertake significant migrations, remaining near breeding colonies while foraging for food. Md from accelerometer data. Secondary Consumer. (Gómez Laich 2021; Quintana et al. 2011; Harris et al. 2012, 2014)
Aptenodytes forsteri	Emperor Penguin is likely dispersive, with little known about its movements. Adults rarely travel north of 60°S, while young birds disperse widely beyond the pack ice, reaching as far north as 54°S to 56°S. MD from satellite telemetry. Secondary Consumer. (Martínez et al. 2020; Wienecke & Robertson 1997)
Larus schistisagus	Slaty-backed Gull is mostly non-migratory, dispersing into the Bering Sea and Sea of Japan. Some migrate south to China and Taiwan, with occasional records as far as the Philippines and Indonesia. Non-breeders and wintering birds reach Alaska and occur along the North American Pacific coast, with vagrants recorded as far as Europe and the Atlantic. MD data not found in the literature. Omnivore. (Burger et al. 2020)
Sula variegata	Peruvian Booby is largely sedentary, but El Niño events trigger mass desertions and large-scale vagrancy north to Colombia and south to Chile. Some individuals are present year-round off southern Ecuador. MD from GPS data across individuals on their foraging trips. Secondary Consumer. (Carboneras et al. 2020; Ludynia et al. 2010)
Sterna paradisaea	Arctic Tern makes the longest regular migration of any bird, breeding in the Arctic and wintering in Antarctic waters. It travels between productive feeding areas, often in a series of long flights. MD from geolocators across individuals. Secondary Consumer. (Hatch et al. 2020; Fijn et al. 2013)
Larus cachinnans	Caspian Gull is largely migratory, moving west and south after breeding. Its main wintering areas are in the Black and Caspian Seas, with some individuals reaching the Middle East, Persian Gulf, and North Africa. Some migrate northwest into Central and Western Europe, with records as far as Scandinavia, Poland, and Israel. MD from banding and resighting. Omnivore. (Burger et al. 2020; Dubinina 2015)
Alle alle	Dovekie migrates south from Arctic breeding grounds to winter in the North Atlantic, primarily around Newfoundland, Grand Banks, and the Gulf of St. Lawrence. Molting individuals become temporarily flightless and rely on ocean currents for southward movement. MD based on geolocators across individuals. Secondary Consumer. (Montevecchi & Stenhouse 2020; Dufour et al. 2022)
Diomedea epomophora	Southern Royal Albatross disperses widely across the Southern Ocean post-breeding, wintering primarily off Patagonia, the Falklands, and southern South America. Some individuals are observed off southern Africa, Tasmania, and New Zealand waters year-round. MD from satellite transmitters across individuals. Secondary Consumer. (del Hoyo et al. 2023; Wienecke & Robertson 1997)
Larus californicus	California Gull migrates seasonally between inland breeding grounds and the Pacific Coast. Most individuals leave breeding sites in late summer to winter along the coast, with subadults often remaining in wintering areas year-round. MD not found in the literature. Omnivore. (Winkler 2020)
Macronectes halli	Northern Giant Petrel is a long-ranging forager, dispersing widely over the Southern Ocean after breeding, with movements influenced by food availability. MD based on observations and assessment of historical and current distribution. Tertiary Consumer (Scavenger / Carnivore). (Carboneras et al. 2020; Quintana et al. 2011)
Sea turtles	
Lepidochelys olivacea	Olive Ridley Turtles nest in large synchronous events called arribadas, primarily in the eastern Pacific and other scattered locations. After laying eggs, females remain near the shore before resuming broader movements. MD from satelite telemetry and tagging and recapture data. Secondary Consumer. (Cáceres-Farias et al. 2022; Honarvar 2008; Hays & Scott 2013.)
Dermochelys coriacea	Leatherback Turtles undertake long-distance migrations across thousands of kilometers. Eastern Pacific populations follow a persistent southbound corridor toward the Galápagos Islands, while other populations show varied post-nesting routes. MD from satelite telemetry and tagging and recapture data. Secondary Consumer. (CMS IOSEA; Wallace et al. 2010; Shillinger et al. 2008.)
Chelonia mydas	Green Turtles migrate between widely dispersed foraging areas and localised nesting sites. Migrations span hundreds of kilometers and occur every few years, with both males and females participating. MD from satelite telemetry, tagging and recapture data and genetic analysis. Omnivore. (Read et al. 2014; Hays & Scott 2013.)
Caretta caretta	Loggerhead Turtles migrate from nesting sites in the Caribbean, Mediterranean, and other global locations to offshore foraging grounds. Some individuals undertake seasonal movements to avoid unfavorable temperatures. MD from satelite telemetry, tagging and recapture data and stable isotope analysis. Secondary Consumer. (European Tracking Network; Evans et al. 2019; Hays & Scott 2013.)
Natator depressus	Flatback Turtles remain largely within the northern Australian continental shelf, preferring shallow, turbid coastal waters. Unlike other sea turtles, they do not undertake extensive oceanic migrations. MD from satelite telemetry, tagging and recapture data and environmental modelling. Omnivore. (Limpus & Miller 2000; Thums et al. 2017.)
Eretmochelys imbricata	Hawksbill Turtles are circumtropical and migrate between nesting beaches and foraging areas, primarily coral reefs. Juveniles transition from pelagic to coastal habitats, where they remain for most of their lives. MD from satelite telemetry and stable isotope analysis. Secondary Consumer. (CMS IOSEA Connectivity; CMS Species Profile; Hays & Scott 2013.)
Lepidochelys kempii	Kemp's Ridley Turtles have a unique regionalised distribution, with nearly all individuals nesting on a single beach in Mexico. They undertake synchronised mass nesting events and migrate through the Gulf of Mexico and the Atlantic coast. MD from satelite telemetry and tagging and recapture data. Secondary Consumer. (Bonka 2020; Hughes & Landry 2016.)
Marine invertebrates	
Pandalus borealis	Northern Prawn migrates inshore during the reproductive season, with egg-bearing females moving from deeper offshore waters to nearshore estuaries for spawning. MD from tagging surveys, fisheries surveys and environmental and fisheries data analysis. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Haynes & Wigley 1969; Koeller et al. 2007.)

Chionoecetes opilio	Snow Crab undergoes ontogenetic migrations, with juveniles moving to deeper waters as they mature. Seasonal migrations between shallow and deep habitats also occur. MD from fisheries surveys and tagging-recapture data. Secondary Consumer (Scavenger/Carnivore). (Divine et al. 2017; Mullowney et al. 2018; Biron et al. 2008.)
Loligo pealeii	Longfin Inshore Squid migrates seasonally, moving inshore in spring and offshore in winter. It undertakes long migrations along the Atlantic coast to remain within favorable temperature ranges. MD from fisheries surveys to assess species distribution and environmental correlation analysis. Secondary Consumer. (NOAA Fisheries; Summers 1969.)
Chionoecetes bairdi	Tanner Crab molts in mass aggregations, moving into shallow waters for the process before returning to deeper habitats. MD information not found in the literature. Secondary Consumer. (Palomares & Pauly 2024; Stone 1999.)
Callinectes sapidus	Blue Crab migrates between estuarine and coastal environments, with females moving seaward to spawn. Offshore larval development helps avoid low salinity and estuarine predators. MD from telemetry, tagging-recapture data and current and tidal modelling to infer movement pathways. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Carr et al. 2004; Hines et al. 1995; Aguilar et al. 2005.)
Paralithodes camtschaticus	Red King Crab migrates seasonally, moving to shallow waters in late winter for mating and molting before returning to deeper waters to feed. Juveniles remain in shallow coastal areas, while adults migrate to depths of up to 300m. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Jørgensen et al. 2005.)
Jasus edwardsii	Southern Rock Lobster follows seasonal movements linked to reproduction, molting, and feeding. Males migrate offshore after mating, while females move to deeper waters before larval release. Most individuals exhibit strong site fidelity, though some travel long distances. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Booth 1997; Linnane et al. 2005; Atkinson & Branch 2003.)
Jasus lalandii	West Coast Rock Lobster does not undergo large-scale directed migrations but moves from inshore nursery areas to deeper waters. Seasonal inshore-offshore migrations, mainly for molting and reproduction, involve dispersal of females offshore in spring. MD based on fisheries data and tagging-recapture data to infer movement patterns and identify long-movement events. Secondary Consumer (Scavenger/Carnivore). (Booth 1997; Atkinson & Branch 2003)
Parapenaeus longirostris	Deep-Water Pink Shrimp exhibits ontogenetic migration, with juveniles moving inshore and offshore into nursery grounds. Older individuals shift to deeper areas, rarely reaching three years of age. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Tom et al. 1988; Ardizzone et al. 1990.)
Paralithodes platypus	Blue King Crab undertakes seasonal migrations, moving to shallow waters in summer for feeding and spawning, then retreating to deeper areas in winter. Some populations remain in deeper waters year-round. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Artemenkov et al. 2022.)
Octopus vulgaris	Common Octopus migrates inshore for feeding and growth before mature females spawn in shallow waters. After reproduction, adults return to deeper waters, with seasonal inshore migrations peaking in spring. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Smale & Buchan 1981; Fuentes & Iglesias 2010; Oosthuizen & Smale 2003.)
Loligo vulgaris	European Squid follows a seasonal migration pattern, moving inshore for reproduction. Juveniles hatch near the coast and gradually migrate toward deeper waters as they mature. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Cabanellas-Reboredo et al. 2012.)
Illex illecebrosus	Northern Shortfin Squid has a one-year lifespan and migrates extensively between the southern U.S. and eastern Canada. It undergoes a northward feeding migration and a southward spawning migration, with some populations remaining in low-latitude waters year-round. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Coelho et al. 1994.)
Farfantepenaeus aztecus	Brown Shrimp follows an ontogenetic migration pattern. After offshore spawning, larvae move inshore into estuaries during winter, spend their juvenile stage there, and migrate offshore as subadults to complete their life cycle. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Riera et al. 2000.)
Litopenaeus setiferus	White Shrimp moves from estuarine nursery grounds to offshore waters in seasonal pulses. Spawning occurs offshore, with larvae later migrating back inshore. Two waves of offshore migration occur each year. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Lindner & Anderson 1956.)
Pandalus montagui	Pink Shrimp migrate from Florida estuaries to offshore waters near the Tortugas. Juveniles spend months in estuaries before migrating offshore to complete their life cycle. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Warren & Sheldon 1967.)
Panulirus argus	Montagu's Shrimp follows tidal migration patterns, feeding at low slack water during daylight. They move into feeding areas with flood tides and return to deeper waters with ebb tides. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Bertelsen 2013.)
Farfantepenaeus duorarum	Caribbean Spiny Lobster migrates offshore for reproduction. Females move to deeper waters for spawning, making multiple reproductive migrations within a single season. MD information not found in the literature. Secondary Consumer (Scavenger/Carnivore). (Palomares & Pauly 2024; Costello et al. 1986.)
Extinct species	
Schistocerca gregaria	Desert Locust performs episodic migrations, drastically increasing abundance at irregular intervals. Roughly, it continues to occur at 20 yr intervals. MD information not found in the literature. Mixed Feeder (Grazer). (Verlinden et al. 2020.)
Acipenser dabryanus	Yangtze Sturgeon breeds up and down the Yangtze River following complex movements, but never reaching the estuary. MD from telemetry and recapture. Secondary Consumer. (Sykes Jr. et al. 2020.)
Atelopus chiriquiensis	Chiriqui Harlequin Toad breeds along streams in the upper mountains of Costa Rica. MD information not found in the literature. Secondary Consumer. (Pratt 2020.)
Camptorhynchus labradorius	Labrador Duck (Wintering – breeding). Spend Winter along the coast of New Jersey, and summers in Newfoundland's coast MD information not found in the literature. Omnivore. (Snyder & Russell 2020.)
Coregonus oxyrinchus	Kaua‘i ‘Ō‘ō move to feed up and down mountains and areas looking for food. MD information not found in the literature. Primary Consumer. (Fishbase; Borcherding et al. 2008.)
Corvus hawaiiensis	‘Ākepa Feeding move up and down mountains and areas looking for food. MD information not found in the literature. Omnivore. (Banko et al. 2020.)
Cyanopsitta spixii	Carolina Parakeet wintering unclear and diffuse small latitudinal movements - possibly not migrant. MD information not found in the literature. Mixed Feeder (Grazer). (Sharpe et al. 2022.)
Ectopistes migratorius	Passenger Pigeon Display general north to south movement in winter. Wandering in response to food supply and weather. Movements around East North America. MD information not found in the literature. Mixed Feeder (Grazer). (Blockstein 2020.)

Hippotragus leucophaeus	Blue Antelope breeds west in winter rainfall zone (along the west south coast of South Africa) and migrated east due to summer drought in pursuit of better pastures. MD information not found in the literature. Grazer. (Tyler Faith & Thompson 2013.)
Hydrodamalis gigas	Steller's Sea Cow disperses by drifting with the current. MD information not found in the literature. Grazer. (Sharko et al. 2022.)
Melanoplus spretus	Rocky Mountain Locust breeds in East Rocky Mountains, but can invade areas almost reaching the entire mid and west USA when invading. MD information not found in the literature. Mixed Feeder (Grazer). (Lockwood 2010; Skinner 2000.)
Oryx dammah	Scimitar-horned Oryx feeds in South of Sahel at the end of May, and as the rains start at the end of May, they move further south into sub-Sahelian wooded steppes. At the end of July, they do massive quick migrations towards the north of their distribution where rains have started. In October-November, large herds disperse for the cold season. They return in March towards the summer quarters. Nomadising varies depending on rain availability. MD information not found in the literature. Grazer. (Devillers & Devillers-Terschuren 2006).
Pinguinus impennis	Great Auk breeds and overwinters when migrating north in late summer and south in fall-early winter, some auks moved in and out of the Gulf of St. Lawrence through the Strait of Belle Isle between Labrador and Newfoundland near Port au Choix. MD from assessing historical accounts and comparing seasonal behaviour to other similar species. Secondary Consumer. (Montevecchi & Kirk 2020)
Psephurus gladius	Chinese Paddlefish breeds in China, endemic to the Yangtze River and its tributaries. This species is considered diadromous as it spends at least part of its life in the sea and migrates upriver to reproduce. MD information not found in the literature. Secondary Consumer. (Lee et al. 2022.)

3. Description of taxonomic groups

Species were systematically classified into taxonomic groups based on their superclass, phylum, class, order, family, and genus. Mammals (*Mammalia*) were divided into marine mammals, including species from the orders *Cetacea* (whales, dolphins, porpoises) and *Sirenia* (manatees, dugongs), as well as the families *Odobenidae* (walruses), *Otariidae* (sea lions, fur seals), *Phocidae* (true seals), and *Ursus maritimus* (polar bears), while all remaining mammals were classified as terrestrial mammals. Otters were not considered since we did not find any biomass data and/or migratory information for this group. Birds (*Aves*) were categorised into seabirds, encompassing orders *Sphenisciformes* (penguins), *Procellariiformes* (petrels, shearwaters, albatrosses), *Suliformes* (excluding *Anhinga*), and families *Phaethontidae* (tropicbirds), *Laridae* (gulls, terns), *Stercorariidae* (skuas), and *Alcidae* (auks, puffins), while all other birds were classified as terrestrial birds. Fish species were separated into marine and diadromous, depending on the information available on their migrations. Using information available on GROMS and FishBase, we classified each species as oceanodromous (marine fish) or diadromous (diadromous fish). Since we did not find any biomass data on potadromous fish, we did not consider freshwater fish. Other taxa were separated into marine invertebrates, comprising species from *Decapoda* (crabs, lobsters), *Euphausiacea* (krill), *Stomatopoda* (mantis shrimps), *Isopoda* (isopods), *Amphipoda* (amphipods), *Leptostraca*, as well as mollusks from subclasses *Pteriomorphia*, *Heterodonta*, *Anomalodesmata*, *Palaeoheterodonta*, *Protobranchia*, and *Cephalopoda* (squids, octopuses, cuttlefish), while all other arthropods and invertebrates were classified as terrestrial invertebrates. Lastly, marine reptiles (*Chelonioidea*, sea turtles) were separated from terrestrial reptiles, which included all remaining species within *Reptilia*.

Table S5. Summary of criteria used to define the different taxonomic groups.

Taxonomic group	Criteria
Marine mammals	Species included within *Cetacea, Sirenia, Odobenidae, Otariidae, Phocidae*. Given its close association with the marine environment, *Ursus maritimus* was also included, although it was not classified as migratory.
Terrestrial mammals	All the other mammal species. This includes bat species.
Seabirds	This group included *Sphenisciformes, Procellariiformes, Suliformes, Phaethontidae, Laridae, Stercorariidae* and *Alcidae*. Other aquatic groups and shorebirds were not included here. Most notably, pelicans were not included as they were considered waterbirds.
Terrestrial birds	All other bird species, including pelicans, shorebirds and waterbirds.
Marine fish	Taxonomy based on migratory information: Marine fish species included all fish species performing oceanodromous migrations.
Diadromous fish	Taxonomy based on migratory information: Diadromous fish species included all fish migrating in between marine and freshwater ecosystems.
Marine invertebrates	Species within *Decapoda, Euphausiacea, Stomatopoda, Isopoda, Amphipoda, Leptostraca, Pteriomorphia, Heterodonta, Anomalodesmata, Palaeoheterodonta, Protobranchia* and *Cephalopoda*.
Terrestrial invertebrates	Arthropod species not belonging to marine invertebrates.
Sea turtles	Species within *Chelonioidea*.
Other reptiles	Reptiles not considered sea turtles.
Amphibia	Species within *Amphibia*.

4. Mass migrations and biomass data

Contribution of mass migrations to the overall migratory biomass

For each taxonomic group, we assessed the cumulative biomass patterns. We were able to identify a group of species in each group amounting to more than 90% of the total current biomass (Figure S1). That, in some cases, consisted in less than ten species (e.g., marine and diadromous fish), while in some others this consisted of many species (seabirds and terrestrial birds). Overall, this allowed to identify a small group of species (<10% of all migratory species) that accounted for more than 90% biomass and which we termed 'mass migrations.' This migratory biomass accounted for a considerable fraction of biomass for most taxonomic groups, reaching >50% biomass and, in some cases, the majority of all the biomass (Figure S2). Lastly, when accounting for mass migrations over the last centuries, we accounted for a conservative biomass threshold (>10^{11} grams) that ensured that all species considered in the assessment would have contributed at least 0.01% to the overall migratory biomass.

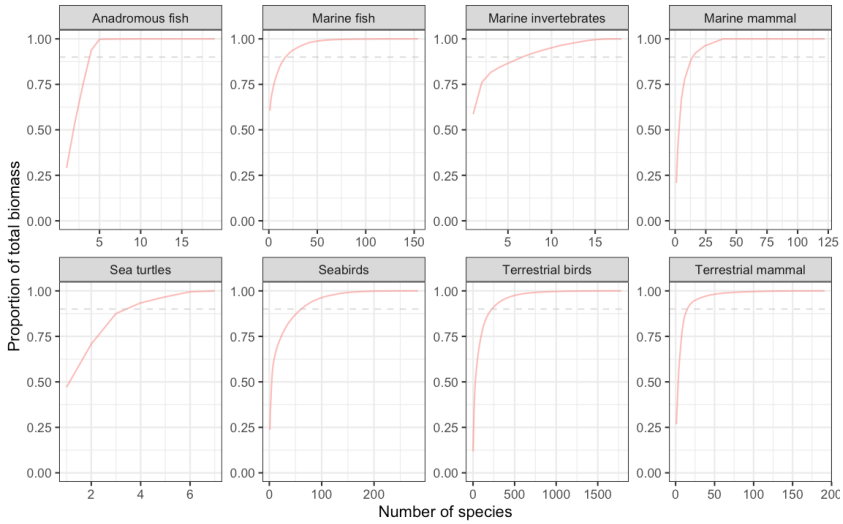

Figure S1 – Accumulation curves indicating the number of species needed to obtain >90% biomass per taxonomic group. Horizontal grey dashed lines indicate the 90% threshold for proportion of total biomass.

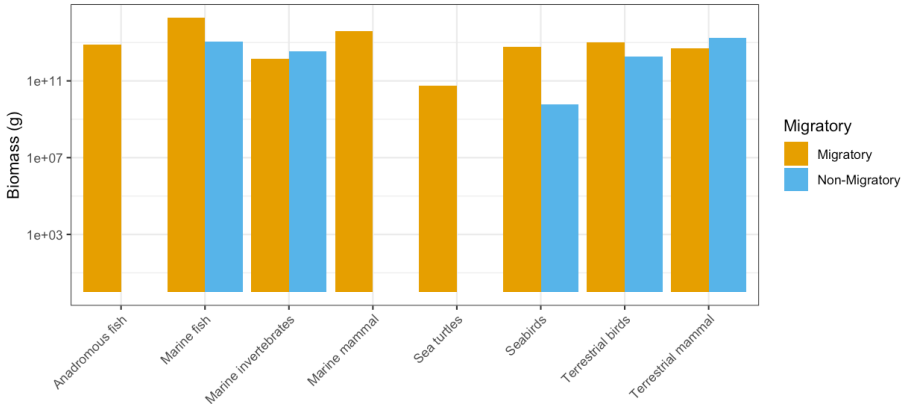

Figure S2 – Comparison between migratory and non-migratory biomass, based on information from biomass datasets obtained for this study.

Exploring potential contributions of missing biomass data to overall migratory biomass

To assess the biomass of migratory species lacking empirical estimates, we developed a predictive framework adapted from Greenspoon et al. (2023). Species-level trait data were compiled from multiple sources: range maps from the IUCN Red List (used to calculate range area via Mollweide equal-area projections); fish traits from FishBase and SeaLifeBase (rfishbase); marine traits from the MarineSpeciesTraits database; mammalian body masses from PanTHERIA; and avian traits from AVONET. We also incorporated IUCN status and taxonomic Order as categorical predictors.

We applied quantile regression forests (QRF; randomForestSRC) to predict biomass density (kg km^{-2}) for species lacking empirical estimates. The model was trained on observed biomass densities (biomass / range area) using six predictors: taxonomic group, body mass, range size, IUCN status, trophic level, and order. QRFs generated median (0.5 quantile) predictions and 95% prediction intervals (2.5% and 97.5%), which we then scaled by range size to estimate total biomass.

To propagate uncertainty through the entire modeling workflow, we generated 1,000 bootstrap replicates per species and repeated the QRF modeling process 1,000 times, producing 10^6 total biomass estimates per species. For species lacking reported confidence intervals, fixed biomass densities were retained across replicates. For each species, the resulting distributions were summarized to obtain the mean and 95% confidence interval (CI) of total biomass. This hierarchical bootstrapping–modeling design propagated uncertainty from empirical data through model training and prediction to the final biomass estimates, ensuring that reported CIs reflect both observation and model variance

Model validation was conducted through repeated 80/20 train–test partitions across 1,000 replicate datasets, each derived by bootstrapping observed biomass densities within their empirical uncertainty bounds. For each replicate, model performance was evaluated using the root mean square log error (RMSLE) and the empirical coverage rate of the 95% prediction intervals (i.e., the proportion of test observations whose observed densities fell within predicted bounds). Median RMSLE values across replicates were used to assess predictive accuracy, while coverage rates near 0.95 confirmed appropriate uncertainty calibration. Variable importance scores were extracted from the QRF models to ensure consistency of predictor influence across runs.

Unlike Greenspoon et al. (2023), who employed support vector machines (SVMs), we chose QRFs due to their robustness to irregular data distributions and ability to generate distributional predictions. While SVMs often achieve high accuracy, their performance can be degraded in patchy, heterogeneous global datasets. Because our aim was exploratory—illustrating the potential contribution of poorly documented taxa rather than producing precise global totals—we considered QRFs a more suitable framework.

Model performance across taxonomic groups was evaluated separately using group-specific QRF models, each trained and validated independently to assess generalisability across taxonomic groups more thoroughly. Cross-group comparisons revealed similar RMSLE distributions (median 0.42–0.58) and near-nominal coverage (0.92–0.96), suggesting consistent predictive performance across taxa and predictor sets.

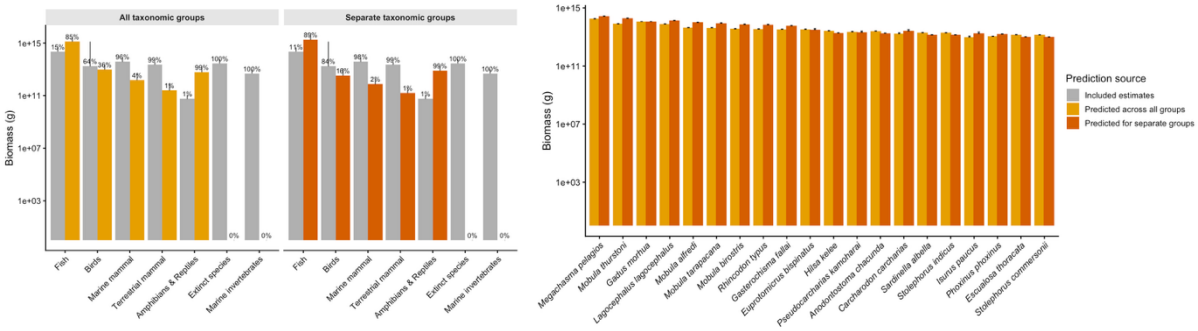

Figure S3. Biomass predictions from QRF models (mean ± 95% CI). Left: comparisons between included and predicted (missing) biomass per taxonomic group. Right: top 20 contributing (fish) species. Prediction sources include predictions made with one single model across all taxonomic groups (light orange) and predictions made with one model per taxonomic group (dark orange).

QRF modelling allowed to include biomass for 1353 additional species in the dataset, accounting now for 70% of all migratory species idenfied in this study (i.e., with 44% species included previously). QRF predictions revealed that mass migratory events accounted for most biomass across taxonomic groups (Fig. S3). A notable exception was fish: predictions for missing species suggested ~15 additional migratory fish with individual biomass exceeding 10^{13} g. These correspond to missing fish biomass estimates between three and nine times higher than total observed fish biomass (though with overlapping confidence intervals), implying that undocumented pelagic species could substantially increase global migratory biomass. Resulting new migratory biomass estimates would be an order of magnitude higher, reaching $1.31\ 10^{15} \pm 1.37\ 10^{15}$ g (mean ± C.I.) when aggregating all taxonomic groups within the same QRF model, and $1.8\ 10^{15} \pm 1.95\ 10^{15}$ g when modelling taxonomic groups in separate QRF models. These results highlight the need to expand assessments beyond well-documented groups such as birds and cetaceans (UNEP-WCMC, 2024b) to include migratory fishes.

However, caution is warranted. Migratory behaviour is complex, and extrapolations based on non-migratory traits may introduce bias. For example, *Gadus morhua* exhibited the highest biomass in our dataset, yet its close relative *Gadus macrocephalus* showed estimates three orders of magnitude lower. Additionally, fish biomass is heavily influenced by fisheries dynamics, complicating extrapolations to non-commercial species (Szuwalski & Thorson, 2017). Other factors must also be considered, such as the effect of different migratory strategies in the species fitness, the presence of species interactions, or the uneven effect of human impacts and climate change across species. Nonetheless, our results demonstrate that poorly documented migratory species could meaningfully reshape global biomass estimates.

Although the inclusion of additional fish species would increase total migratory biomass, ~90% of migratory fish biomass remained concentrated in fewer than 30 species—still consistent with the "mass migration" pattern dominated by a few taxa. Data gaps among amphibians, reptiles, and invertebrates (both marine and terrestrial) suggest that the true migratory biomass may be considerably larger than QRF models predict. Future work should (a) refine biomass predictions by incorporating migratory performance traits (e.g., distance, timing, or metabolic scope), environmental context (including species interactions) and human impacts. Research should also (b) expand taxonomic coverage, particularly for invertebrates, to achieve a more comprehensive global synthesis.

Of the remaining 30% of migratory species that we could not include in this analysis, 51% and 36% corresponded to fish and invertebrates, respectively (Figure S4A). Among these, most fish were marine migrants while most invertebrates corresponded to various groups including butterflies and months, flies and aphids, and other invertebrates likes bees (Figure S4B). However, for most of these species, little migratory information was available (Figure S4C), which reinforces the idea that more research is needed in less known geographies and taxa. In addition, please note that diel vertical migration (DVM) refers to species exclusively engaging in DVM and thus does not exclude other species that may partake in DVM but also perform other types of migration. Given that DVM was not part of the main focus of assessment here, we resolved to exclude its usage in combination with other types of migrations to avoid any confusion.

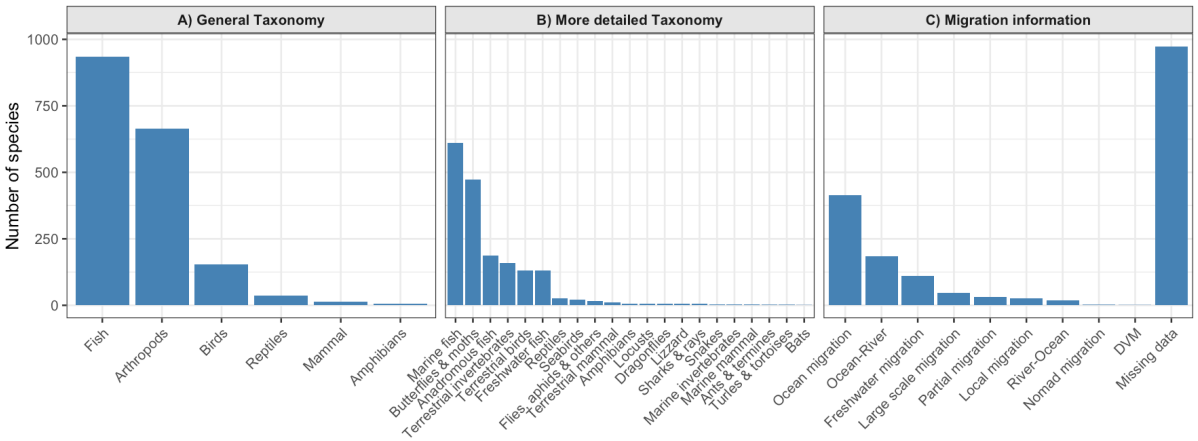

Figure S4. Description of migratory species not included in the main and exploratory analyses. Summary of species not included to previous analyses due to missing biomas (main analyses) and missing trait data (exploratory analyses in this section). General taxonomy refers to main groups, while more detailed taxonomy is provided to give further insight into the ecology of the missing species. Migration information is provided, as given in the databases from which species lists were obtained (e.g. GROMS).

Finally, a global estimate of absolute migratory biomass remains unavailable. This limitation stems from a) the incomplete ecological and behavioral classification of migratory status for many species, b) the complex migratory ecology and large disparities among taxonomically similar species (e.g., *Gadus morhua* vs. *Gadus macrocephalus*) and c) the possibility that other ecologically relevant migratory species have not yet been described (due to the difficulty in describing migratory behaviours). Consequently, current migratory biomass estimates must be viewed as conservative. In addition, the objective of this study was not to produce a comprehensive census of global migratory biomass, but to evaluate how migratory biomass has changed through time and to examine the ecological and functional implications of such losses for the biosphere.

5. Calculations for global biomass estimates

Comparisons with global standing animal biomass

Using the information in Bar-On et al., (2018), we estimated the total vertebrate biomass in the biosphere by converting carbon mass to total biomass using established carbon-to-biomass ratios. The total vertebrate carbon mass was estimated to be between 0.4 and 20 Gt C (gigatons of carbon; lower and upper bound of 95% confidence intervals), equivalent to 0.4-20×10^{15} g C. Vertebrate biomass varies in carbon composition, with estimates ranging between 15% and 30% of dry biomass. Using these two estimates, we computed total biomass (B) as:

$$\mathrm{B} = \frac{M_C}{f_C} \tag{11}$$

where M_C is the total carbon mass in grams, and f_C is the carbon fraction of biomass, taken as 0.15 (lower bound) and 0.30 (upper bound). Substituting the values, we obtained:

$$B_{low} = \frac{0.4\ 10^{15}\ g\ C}{0.3} = 1.33\ 10^{15}\ g\ biomass \tag{12}$$

$$B_{high} = \frac{20\ 10^{15}\ g\ C}{0.15} = 1.33\ 10^{17}\ g\ biomass \tag{13}$$

To assess the proportion of migratory vertebrates in the biosphere, we compared these values with our estimates of migratory biomass. The percentage of migratory biomass (P_{mig}) relative to total vertebrate biomass was calculated as:

$$P_{mig} = \left(\frac{M_{mig}}{B}\right) X\ 100 \tag{14}$$

Where M_{mig} represents the migratory biomass, where $M_{mig,low}$ accounts for the 95% CI lower boundary and $M_{mig,high}$ indicates the 95% CI upper boundary. This yielded a range of:

$$P_{low} = \left(\frac{1.11\ 10^{14}}{1.33\ 10^{17}}\right) X\ 100 = 0.08\% \tag{15}$$

$$P_{high} = \left(\frac{1.64\ 10^{14}}{1.33\ 10^{15}}\right) X\ 100 = 12.31\% \tag{16}$$

Thus, our estimates suggested that migratory biomass constituted approximately 0.08% to 12.31% of the total biosphere vertebrate biomass.

Calculations for zooplankton Diel Vertical Migration contributions and biomass change

Using global synthesis datasets and model-based literature values, we estimated the present-day global biomass of zooplankton performing diel vertical migration (DVM) and its projected change under climate-driven decline. A Monte Carlo framework (10,000 iterations) was implemented to propagate uncertainty in each parameter based on published ranges.

The total global zooplankton carbon stock (C_x) was derived from (Hernández-León et al., 2020), who reported a single value of 1.4 Pg C (1 Pg = 10^{15} g).

To express biomass in total wet mass, we applied a carbon-to-wet-weight conversion factor ($k_{(}CW_{)}$) following (McConville et al., 2016). These studies report that carbon comprises roughly 0.01–19.03% of wet mass. This was modeled with the mean and sd from this range:

$$k_{CW} \sim log\mathcal{N}(0.95, 0.48)$$

To reconstruct historical trends, we incorporated an additional decline parameter based on long-term ecosystem model outputs from 1960 to 2060 (Laufkötter et al., 2013). These indicate a 5% global zooplankton biomass decrease since 1960.

Future climate-driven reductions in zooplankton biomass were parameterized from long-term projections from 1980 to 2100 (Heneghan et al., 2023). For the worst SSP scenarios, these studies suggest global zooplankton declines of 16+/-4% by 2100. We represented the fractional decline ($\Delta_{(}DVM_{)}$) as:

$$\Delta_{DVM} \sim \mathcal{N}(0.16, 0.04)$$

As a result, it was estimated that DVM contributes up to 1.08 10^{17} g. This represented a 5% decline since 1960, when marine zooplnakton was 1.13 10^{17} g, and in 2100 further declines will result in around 9.25 10^{16} g. However, this is a conservative estimate since carbon content in marine zooplankton was estimated conservatively at 9.52% of their mean wet biomass. These estimates can be up to 3 orders of magnitude larger, as C content varies a lot among zooplankton with e.g. gelatinous zooplankton containing only 0.01% carbon compared to their wet biomass (McConville et al., 2016).

Calculations for human movement and biomass contributions

We estimated the human biomass mobilised through different forms of movement—domestic travel, international travel, and nomadic mobility—using the most recent data available for the period 1995–2019. The analysis integrates large-scale tourism and demographic datasets and converts the number of individuals traveling or moving each year into an equivalent human biomass using region-specific mean body weights. These estimates represent the biomass associated with human movement, not the total biomass of the human population, as the same individuals may undertake multiple trips or roundtrips within a year. Consequently, the dataset likely includes widespread double counting of travelers and therefore reflects the magnitude of human mass in motion rather than the mass of distinct individuals.

Data on domestic travel were obtained from two complementary global sources. The first source was the (Organisation for Economic Co-operation and Development (OECD), 2019), which reports the annual number of total domestic trips by country. Records were filtered to include only variables describing total national trips, and country names were standardized for consistency (for example, from “China (People’s Republic of)” to “China”).

The second source was the (UN World Tourism Organization (UNWTO), 2024), which provides annual totals of domestic trips for the period 1995–2022. Values were converted from string to numeric form, scaled from thousands to total trip counts, and reshaped into long format.

The two datasets were merged, with UNWTO data prioritized for countries with overlapping coverage, and OECD data included only for countries missing from UNWTO records. The resulting dataset represents the total number of domestic trips per country and year (N_{dom}).

Data on international travel were derived from the UNWTO Outbound Tourism by Mode of Transport dataset (UNWTO, 2024; same source as above). We selected records labeled *“Total departures”*, representing the total number of international trips made annually by residents of each country between 1995 and 2022. Data were cleaned, standardized by country name, converted from thousands to total trip counts (Value $\times$ 1000), and harmonized to form a global dataset of outbound international mobility (N_{int}).

Populations engaged in continuous or semi-nomadic mobility were incorporated through manually compiled estimates of nomadic populations by country. These data were derived from demographic and ethnographic sources, and region-specific studies on pastoral and nomadic communities. Values were reported in millions of individuals and converted to total counts (Value $\times$ 10^6), with all estimates referenced to 2019.

All datasets were merged into a unified table describing human movement by country**,** year**,** and movement type (domestic, international, or nomadic). Continental assignments were generated using standard geographic classifications, with manual adjustments for small island states and Central American countries to ensure consistent regional groupings. Each record was assigned a mean adult body mass **(**BW**)** characteristic of its

continent, based on global anthropometric averages compiled from regional studies of adult height and weight distributions (Walpole et al., 2012).

To convert movement counts into biomass, the total mass associated with human movement (B) was computed as:

$$B = N \times BW \times 1000$$

where N is the number of individuals or trips, BW is the mean adult body weight (kg), and the factor of 1000 converts tonnes to kilograms. This formulation yields the total instantaneous human mass in motion for each country, year, and movement type.

Total biomass per movement type was obtained by summing across all countries:

$$B_{\text{type}} = \sum_{i} N_i \times BW_i \times 1000$$

We found a total of 1.36 10^{16} g participating in human movement worldwide, including national (89.2%), international (10.6%) and nomadic (0.02%) movements. This estimate is systematically different from recent estimations (Rosenberg et al., 2025), as it does not account for total distance travelled. It also quantifies the biomass involved in each human movement, and multiplies the biomass of a given individual for as many trips as they have performed within a year. Calculations are available in the Supplementary Code.

6. Data pre-processing before modelling

Metric selection for the Living Planet and RAML databases

The Living Planet Database includes time series of vertebrate populations that meet specific data standards to ensure consistency, traceability, and scientific validity (Living Planet Index, 2016). Each record in the database represents a population time series, defined as data for a single species monitored at a specific location over time. Eligible time series must: (a) involve a vertebrate species (mammals, birds, fish, reptiles, or amphibians); (b) span at least two years, not necessarily consecutively; (c) use accepted abundance metrics such as full counts, estimates, densities, indices, biomass, proxies (e.g. breeding pairs or catch-per-unit effort), samples, or occupancy; (d) be based on data collected using consistent methods and spatial coverage, with any changes in method or area requiring separate entries; and (e) originate from referenced and traceable sources, including peer-reviewed publications, government reports, grey literature, or curated databases. Data from experimental studies, survival rates, recruitment alone, uncorrected changes in methodology or area, or catch/hunting data without effort standardisation are excluded.

The RAML database compiles time series data across 74 distinct fisheries-related metrics (RAM Legacy Stock Assessment Database, 2018; Table S6). However, not all these metrics are suitable for tracking temporal changes in wild population size. Several variables were excluded based on three main criteria: (a) lack of ecological relevance to population size; (b) dependence on external factors such as fishing effort, management decisions, or reporting biases; and (c) lack of statistical independence due to being derived from other variables already present for the time series (e.g. ratios involving total biomass or abundance). To address these limitations, we applied a filtering process whereby: (a) metrics not representative of wild population size (e.g. aquaculture biomass, mortality, recruitment loss) were excluded; (b) metrics driven primarily by management objectives or external pressures (e.g. reference points or target values) were removed; and (c) ratio-based metrics or other derived values that could introduce collinearity were discarded. Following this selection, we prioritised core abundance measures for each time series, specifically retaining the most informative and least redundant metrics. The final dataset included three primary metrics: total biomass (TB), total abundance (TN), and spawning stock biomass (SSB), which best reflect temporal trends in wild fish populations. To harmonise with LP criteria (and reports using this dataset; UNEP-WCMC, 2024), we also included catch-per-unit-effort (CPUE), despite this metric being influenced by external technological advancements over time (Ye & Dennis, 2009). We also included additional metrics that were closely aligned with TB, TN, SSB and CPUE (e.g., SSB for males, TBbest) but exclude them if any of the main metrics was already quantified for the time series. We also excluded CPUE if any of the other main metrics were being used.

Table S6. Summary of all variables included in the timeseries dataset in the RAML database

Metric	Description	Reasons for inclusion/exclusion
AQ (Aquaculture)	Biomass of fish produced in aquaculture systems. Units: Biomass	Excluded. Not representative of population size.
BdivBmgtpref (Biomass divided by management-preferred biomass)	Indicates status relative to management target. Units: Biomass ratio	Excluded. It is a ratio metric and depends on external factors (management).
BdivBmgttouse (Biomass divided by biomass used in management)	Shows biomass relative to an actionable management target. Units: Biomass ratio	Excluded. It is a ratio metric and depends on external factors (management).
BdivBmsypref (Biomass divided by preferred MSY biomass)	Used to compare biomass to MSY-based preference. Units: Biomass ratio	Excluded. It is a ratio metric and depends on external factors (management).
BdivBmsytouse (Biomass divided by MSY biomass used in management)	Key metric for MSY-based management decisions. Units: Biomass ratio	Excluded. It is a ratio metric and depends on external factors (management).
Cadvised (Catch advised by management)	Advisory for sustainable fishing levels. Units: Catch (tonnes or other units)	Excluded. It is a ratio metric and depends on external factors (management).
CdivMEANC (Catch divided by mean catch)	Measures current catch relative to the historical average. Units: Ratio	Excluded. It is a ratio metric.
CdivMSY (Catch divided by Maximum Sustainable Yield)	Reflects sustainability in relation to MSY. Units: Ratio	Excluded. It is a ratio metric.
Cpair (Catch per paired gear unit)	Specific to paired fishing techniques. Units: CPUE metric	Excluded. It is a ratio metric and depends on external factors (management).
CPUE (Catch per Unit Effort)	Common measure of fishing yield. Units: Catch/effort	**Included to harmonise with LP data.** Depends on external factors (technology biasing effort).
CPUEraw (Raw Catch per Unit Effort)	Unstandardised, may reflect immediate catch rates. Units: Raw catch/effort	Excluded. Depends on external factors (technology biasing effort).
CPUEsmooth (Smoothed Catch per Unit Effort)	CPUE that accounts for variability over time. Units: Smoothed catch/effort	Excluded. Depends on external factors (technology biasing effort).
CPUEstand (Standardised Catch per Unit Effort)	CPUE that corrects for factors like effort, gear type. Units: Adjusted CPUE	Excluded. Depends on external factors (technology biasing effort).
CUSTC (Custom or user-defined catch metric)	Variable, dataset-specific. Units: Not specified	Excluded. Not standardised across timeseries for a given species.
DIS (Discard rate or discards of catch)	Indicates waste or unutilised catch. Units: Discards in weight/percentage	Excluded. Not representative of population size.
DiscC (Discarded catch)	Reflects unutilised portion of the catch. Units: Discards (tonnes or other units)	Excluded. Not representative of population size.

EB (Exploitable biomass)	Biomass available for fishing. Units: Biomass	Excluded. Depends on external factors (management decisions).
EFFORT (Fishing effort)	Measures intensity of fishing. Units: Number of fishing units or time spent	Excluded. Depends on external factors (technology biasing effort and management decisions).
ER (Exploitation rate)	Indicator of fishing pressure. Units: Proportion of stock harvested	Excluded. Not representative of population size.
ERbest (Best estimate of exploitation rate)	Most reliable measure of fishing intensity. Units: Proportion	Excluded. Not representative of population size.
ERdivERmgt (Exploitation rate divided by management target rate)	Measures how close exploitation is to target rate. Units: Ratio	Excluded. Not representative of population size and depends on external factors (technology biasing effort and management decisions).
ERdivERmsy (Exploitation rate divided by MSY-based rate)	Reflects fishing pressure relative to MSY. Units: Ratio	Excluded. Ratio metric, not representative of population size and depends on external factors (technology biasing effort and management decisions).
F (Fishing mortality)	Direct measure of fishing impact. Units: Mortality rate (per year or other)	Excluded. Not representative of population size.
F/Z (Ratio of fishing mortality to total mortality)	Shows the proportion of mortality due to fishing. Units: Mortality ratio	Excluded. Ratio metric. Not representative of population size.
FdivFmgt (Fishing mortality divided by management target)	Indicates status relative to management targets. Units: Mortality ratio	Excluded. Ratio metric. Not representative of population size. Depends on external factors (management decisions).
FdivFmsy (Fishing mortality divided by MSY-based mortality)	Key indicator for overfishing. Units: Mortality ratio	Excluded. Ratio metric. Not representative of population size. Depends on external factors (management decisions).
gillnetCPUE (Catch per Unit Effort using gillnets)	Reflects catch success with specific gear. Units: Catch/effort (gillnets)	Excluded. Depends on external factors (technology biasing effort).
ILLC (Illegal, Unreported, and Unregulated (IUU) Landed Catch)	Shows unregulated or unreported fishing levels. Units: Catch (tonnes or other units)	Excluded. Not representative of population size.
longlineCPUE (Catch per Unit Effort using longlines)	Reflects longline-specific catch rates. Units: Catch/effort (longlines)	Excluded. Depends on external factors (technology biasing effort).
PR (Proportion of recruits)	Measures new individuals entering the fishery. Units: Recruitment ratio	Excluded. Not representative of population size.
R (Recruitment)	Indicates population replenishment. Units: Number of new individuals	Excluded. Following Living Planet stardanrds, recruitment data is not considered.
RB (Reproductive biomass)	Biomass capable of reproducing. Units: Biomass	Included. Proxy for population size. Considered low-quality.
RBdivRBmsy (Reproductive biomass divided by MSY-based biomass)	Compares reproductive biomass to MSY levels. Units: Biomass ratio	Excluded. Ratio metrics.
RBdivRBref (Reproductive biomass divided by reference biomass)	Measures biomass relative to reference points. Units: Biomass ratio	Excluded. Ratio metrics.
RecC (Recruited catch)	Reflects catch from newly recruited individuals. Units: Catch (tonnes or other units)	Excluded. Following Living Planet stardanrds, recruitment data is not considered.
RH (Relative harvest)	Indicates proportion of stock harvested. Units: Harvest ratio	Excluded. Ratio metric.
RL (Recruitment loss)	Measures loss in recruitment. Units: Recruitment rate loss	Excluded. Not linked to population size.
SPR (Spawning Potential Ratio)	Measures reproductive capacity relative to unfished stock. Units: Ratio	Excluded. Not linked to population size.
SSB (Spawning Stock Biomass)	Biomass of spawning individuals. Units: Biomass	**Included.** Mid-quality, only bested by direct measures of biomass or abundance.
SSBdivSSBmgt (Spawning Stock Biomass divided by management target)	Compares SSB to management target. Units: Biomass ratio	Excluded. Ratio metric.
SSBdivSSBmsy (Spawning Stock Biomass divided by MSY-based biomass)	Reflects stock sustainability relative to MSY. Units: Biomass ratio	Excluded. Ratio metric.
SSBf (Female Spawning Stock Biomass)	Biomass of females contributing to reproduction. Units: Biomass	**Included.** Low-quality and redundant with SSB.
SSBm (Male Spawning Stock Biomass)	Biomass of males contributing to reproduction. Units: Biomass	**Included.** Low-quality and redundant with SSB.
SSF (Sustainable Spawning Fraction)	Spawning biomass without fishing and natural mortality. Units: Fraction	Excluded. Ratio metric.
STB (Survey total biomass)	Total biomass as estimated from surveys. Units: Biomass (survey-derived)	Excluded. Surveys not frequently not for the whole stock.
STB1+ (Survey total biomass of 1+ year fish)	Indicates biomass of fish over 1 year. Units: Biomass (1+ year fish)	Excluded. Not linked to population size.
STB2+ (Survey total biomass of 2+ year fish)	Indicates biomass of fish over 2 years. Units: Biomass (2+ year fish)	Excluded. Not linked to population size.
survB (Survey biomass)	Biomass estimate from surveys. Units: Biomass (survey-derived)	Excluded. Surveys not frequently not for the whole stock.
survB_absolute (Absolute survey biomass)	Direct survey biomass measurement. Units: Biomass (absolute value)	Excluded. Surveys not frequently not for the whole stock.
survB_index (Survey biomass index)	Relative biomass index from surveys. Units: Index value	Excluded. Ratio metric.
survBdivsurvBmgt (Survey biomass divided by management target biomass)	Compares survey biomass to management target. Units: Biomass ratio	Excluded. Ratio metric. Depends on external factors (management).
survRB (Survey reproductive biomass)	Biomass estimate from surveys of reproductive fish. Units: Biomass (survey-derived)	Excluded. Ratio metric.
TAC (Total Allowable Catch)	Sets upper limit for sustainable catch. Units: Catch limit (tonnes or other units)	Excluded. Depends on external factors (management).
TB (Total Biomass)	Total biomass of the fish population. Units: Biomass	**Included.** High-quality metric.
TBbest (Best estimate of total biomass)	Most reliable estimate of total biomass. Units: Biomass	**Included.** High-quality metric, but redundant with Total Biomass.
TBdivTBmgt (Total biomass divided by management target)	Reflects biomass status relative to management goals. Units: Biomass ratio	Excluded. Ratio metric.
TBdivTBmsy (Total biomass divided by MSY-based biomass)	Reflects sustainability relative to MSY. Units: Biomass ratio	Excluded. Ratio metric.

TC (Total Catch)	Total amount of fish caught. Units: Catch (tonnes or other units)	Excluded. Depends on external factors (management).
TCbest (Best estimate of total catch)	Most reliable measure of total catch. Units: Catch (tonnes or other units)	Excluded. Depends on external factors (management).
tERmsy (Target exploitation rate based on MSY)	Target fishing pressure for MSY. Units: Exploitation rate	Excluded. Ratio metric.
tFmsy (Target fishing mortality based on MSY)	Target mortality rate for MSY. Units: Mortality rate	Excluded. Ratio metric.
TL (Total landings of fish from the fishery)	Total fish brought to land from fishing operations. Units: Landings (tonnes or other units)	Excluded. Depends on external factors (management).
TN (Total number of fish in stock)	Total population size. Units: Number of individuals	**Included.** High-quality metric.
TNdivTNmsy (Total number of fish divided by MSY-based number)	Reflects population size relative to MSY. Units: Ratio	Excluded. Ratio metric.
towCPUE (Catch per Unit Effort in tow fishing)	Reflects tow-specific fishing success. Units: Catch/effort (tow fishing)	Excluded. Depends on external factors (management).
tSSBmsy (Target spawning stock biomass based on MSY)	MSY-based target for spawning biomass. Units: Biomass	Excluded. Depends on external factors (management).
UdivUmgtpref (Exploitation rate divided by management-preferred rate)	Indicates exploitation status relative to management preference. Units: Ratio	Excluded. Ratio metric.
UdivUmgttouse (Exploitation rate divided by rate used in management)	Measures exploitation relative to actual management use. Units: Ratio	Excluded. Ratio metric.
UdivUmsypref (Exploitation rate divided by MSY-preferred rate)	Reflects sustainability relative to MSY preference. Units: Ratio	Excluded. Ratio metric.
UdivUmsytouse (Exploitation rate divided by MSY rate used in management)	Reflects exploitation relative to MSY used by management. Units: Ratio	Excluded. Ratio metric.
Yield (Yield of fish harvested)	Total output of fish harvested. Units: Yield (tonnes or other units)	Excluded. Depends on external factors (management).
Z (Total mortality rate)	Overall rate of fish deaths, natural and fishing. Units: Mortality rate	Excluded. Not linked to population size.

Sensitivity tests to assess the effect of metric selection on model outputs

To evaluate the robustness of our results to data filtering, we compared posterior estimates from the full dataset against those from the filtered version used in the main analyses.

Marine fish models showed notable divergence between the two datasets. Posterior means were only weakly correlated (r = 0.016), and absolute parameter differences were substantial (up to Δmean = 3.6). Relative differences—defined as the proportional change in filtered-data model coefficients relative to those from the full dataset—sometimes exceeded 100%, with several species-level effects changing both sign and magnitude. For instance, coefficients for individual species and some site-level random intercepts differed by more than an order of magnitude. Random-effect variability for metric in the filtered-data model decreased from 0.62 to 0.14 (ΔSD = –0.48), indicating reduced between-group variance under the filtered dataset (Fig. S5A–B).

Despite these shifts, fixed-effect parameters preserved their qualitative interpretation and sign consistency, suggesting that filtering influenced the magnitude and precision of certain species-level estimates more than the direction or overall inference. Thus, removing unfit metrics increased precision in species-level estimates and reduced potential biases, yielding more ecologically meaningful results.

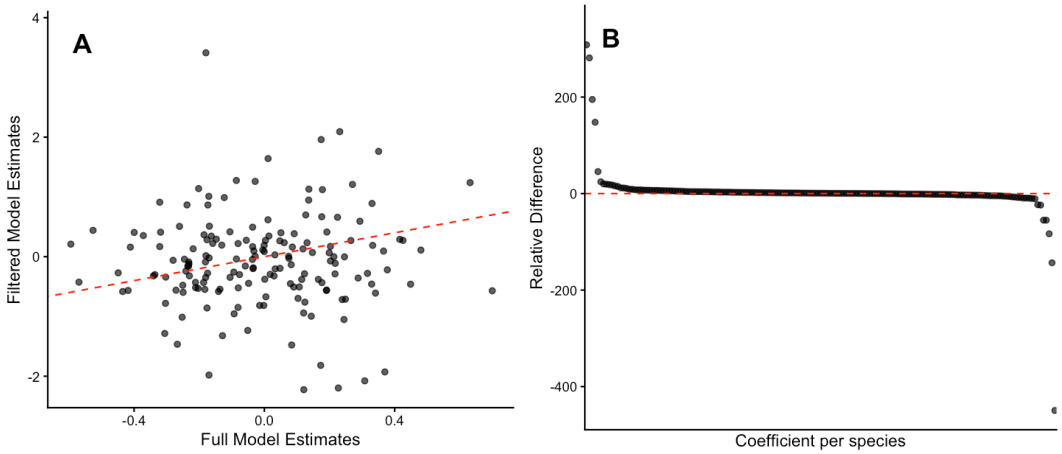

Figure S5. Sensitivity analysis comparing results from the full and filtered datasets. (A) Fixed-effect parameter species-level estimates. (B) Relative differences in coefficients per species. Dashed lines indicate the 1:1 expectation.

For diadromous fish, all metrics met the inclusion criteria, resulting in identical model structures and parameter estimates between the full and filtered datasets, and thus results are not presented here. Sensitivity analyses for

marine invertebrates were not performed due to their much lower relevance in this study and to simplify results for this section.

Assessing effects of missing data and choosing a modelling strategy

Following the guidelines in Bowler et al., (2025), we also assessed the effects of missing data on each dataset to be modelled. For each model, we ran a linear model *lm* and checked generalised variance inflation factors (GVIF) across both numerical and categorical variables per model (across taxonomic group and a general model). GVIF allowed for comparisons across variables with different degrees of freedom and showed that latitude and longitude were moderately colinear potentially due to the clustering of locations. To remove this collinearity, we centred both Latitude and Longitude (without scaling with standard deviation) across all groups.

We observed a general trend of increased missing data post-1950, which then decreased over time, and marine taxa and shorter time series exhibited higher missing data percentages (Table S7; Figure S6-S13). Across groups, % missing data increased in shorter time series for terrestrial birds, seabirds, terrestrial and marine mammals. Over time, % missing data decreased over time for terrestrial and marine mammals, marine fish and seabirds. Spatially, we saw clustering of data points in terrestrial and marine mammals, terrestrial birds, seabirds and marine fish. Lastly, all groups presented differences in % missing data across the metrics used to measure population size.

Table S7. Summary of missing data patterns across various taxonomic groups. The table presents an overview of missing data distribution, missing data percentages based on the number of data points, trends over time, spatial distribution, and by unit class. The final column highlights observable links between missing data patterns and time series duration, historical periods, geographic regions, and unit class. Missing taxonomic groups (i.e., freshwater mammals, freshwater fish and marine invertebrates) presented too few data to be indicative of any patterns. Cells for covariates presenting a potential linked with % missing data for a given taxonomic group are underscored.

Taxonomic Group	Distribution of Missing Data	Missing Data by Duration of Time Series	Missing Data Over Time	Spatial Distribution of Missing Data	Missing Data by Metrics used
Terrestrial Mammals	Low percentages, most below 25%	Sparse missing data	Decrease over time	Sparse, less data and more % missing points in the southern hemisphere	Higher for biomass
Marine Mammals	Increasing percentages post-1950	Sparse missing data	Slight decrease over time	Very sparse, more missing data in North America	Much lower for unknown metrics
Terrestrial Birds	Moderate levels, peak in early 20th century	More missing data for datasets <40 years	Two peaks, one around 1960 and another around 2005	Clustered in Europe, North America and Australia. More missing data in Asia and Australia	Low to moderate across units
Seabirds	Consistent moderate levels	More missing data for datasets <35 years	Decrease over time	Mostly around Europe and North America. More missing data in the southern hemisphere	Moderate missing data
Marine Fish	Large range, many low but some high percentages	More missing data for datasets with <50 data points (Living Planet data?)	Spike after 1950, and then decrease over time	No apparent patterns	Higher for units used in the RAM dataset, and for survey Biomass
Diadromous Fish	Relatively low, most below 25%	Mostly sparse	Spike after 1960, and then decrease over time	Clustered in North America and Europe	A few metrics show more % missing points
Sea Turtles	Concentration in series with fewer data points	Sparse	No apparent patterns	No apparent patterns	No apparent patterns

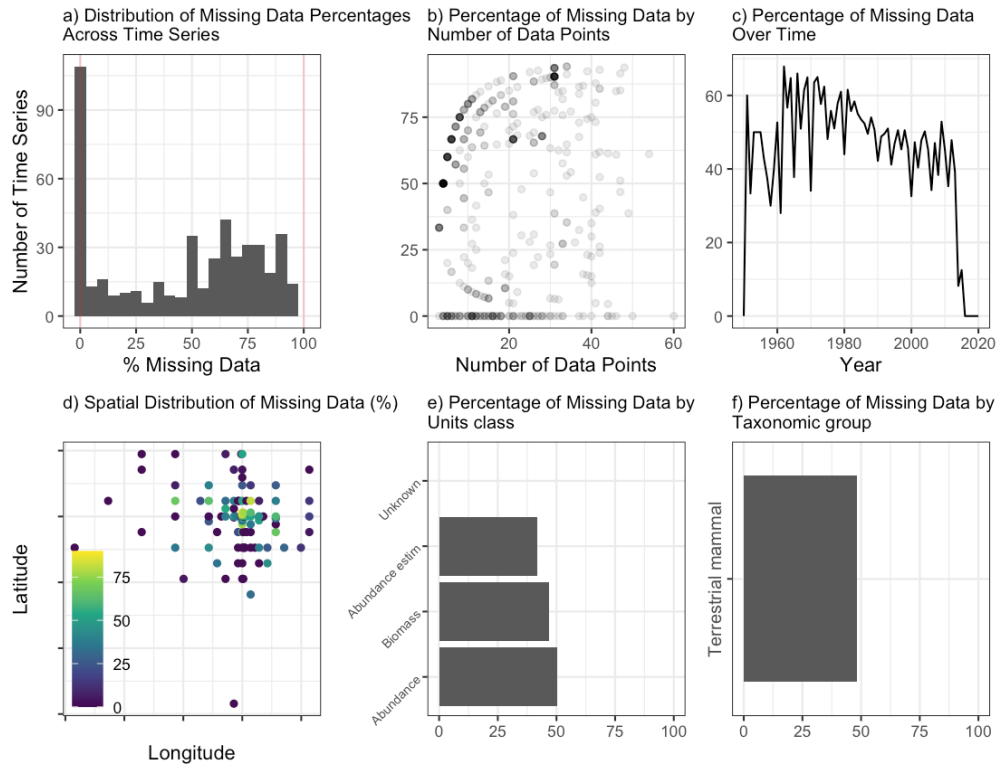

Figure S6. Overview of missing data patterns for terrestrial mammals. Panels show (a) a histogram displaying the distribution of missing data percentages across time series, (b) a plot showing the percentage of missing data by the number of data points per time series, (c) a line plot showing the percentage of missing data over time, (d) a scatter plot mapping the spatial distribution of missing data with color representing the percentage at each location, (e) a bar chart illustrating missing data percentages by units class, and (f) a bar chart showing missing data percentages by taxonomic group.

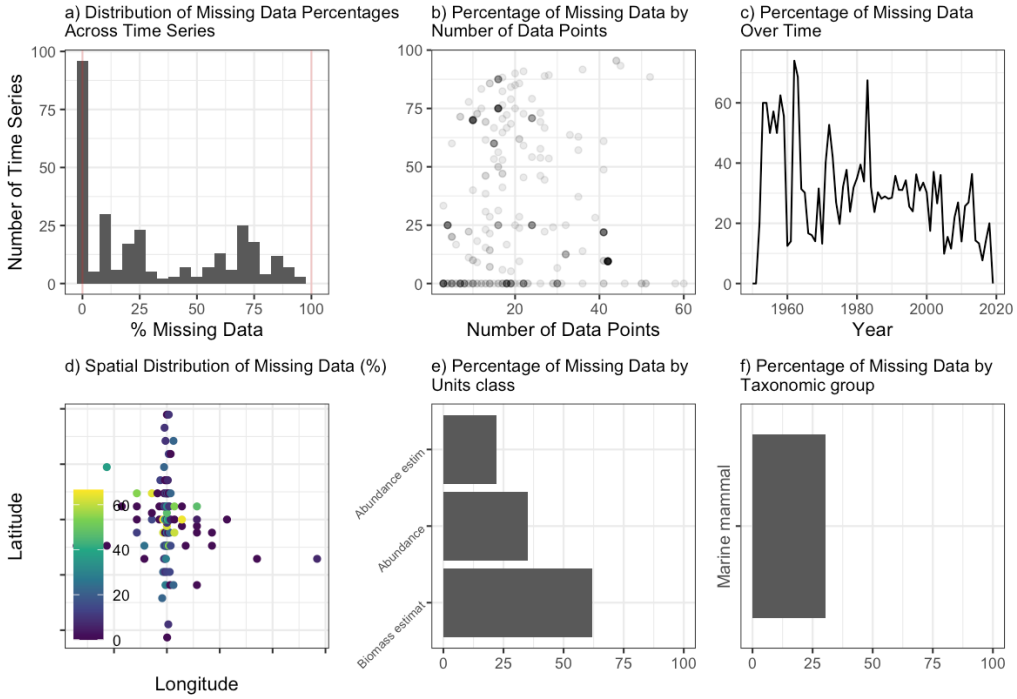

Figure S7. Overview of missing data patterns for marine mammals. Panels show (a) a histogram displaying the distribution of missing data percentages across time series, (b) a plot showing the percentage of missing data by the number of data points per time series, (c) a line plot showing the percentage of missing data over time, (d) a scatter plot mapping the spatial distribution of missing data with color representing the percentage at each

location, (e) a bar chart illustrating missing data percentages by units class, and (f) a bar chart showing missing data percentages by taxonomic group.

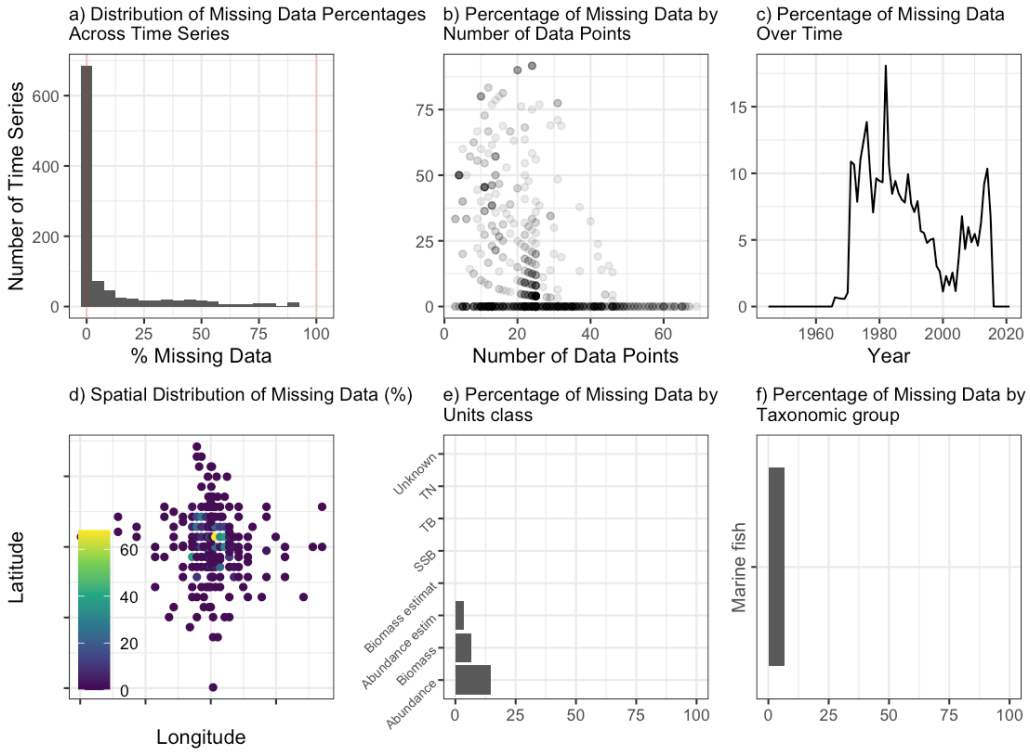

Figure S8. Overview of missing data patterns for marine fish. Panels show (a) a histogram displaying the distribution of missing data percentages across time series, (b) a plot showing the percentage of missing data by the number of data points per time series, (c) a line plot showing the percentage of missing data over time, (d) a scatter plot mapping the spatial distribution of missing data with color representing the percentage at each location, (e) a bar chart illustrating missing data percentages by units class, and (f) a bar chart showing missing data percentages by taxonomic group.

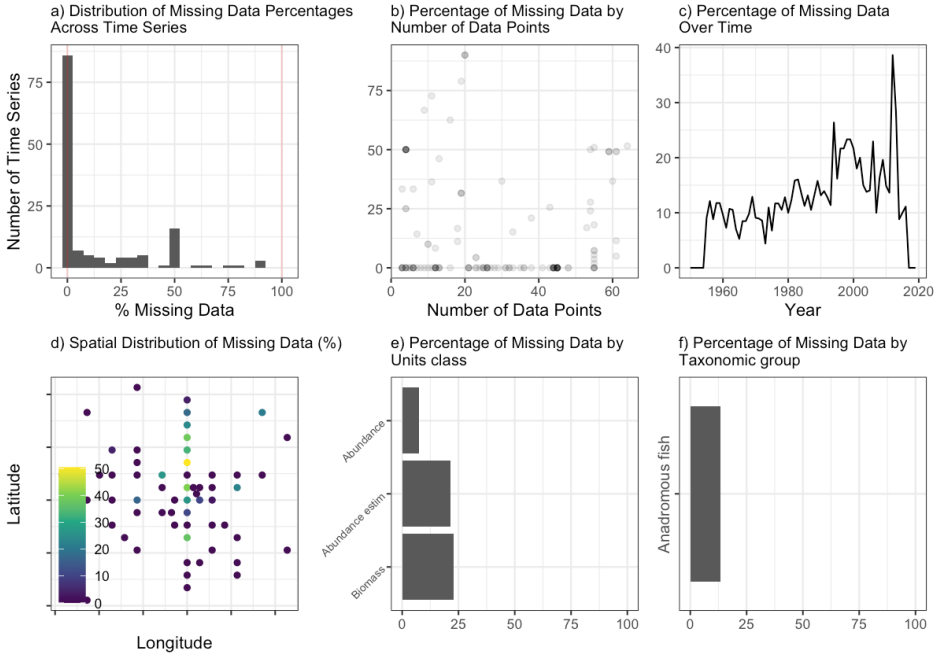

Figure S9. Overview of missing data patterns for diadromous fish. Panels show (a) a histogram displaying the distribution of missing data percentages across time series, (b) a plot showing the percentage of missing data by the number of data points per time series, (c) a line plot showing the percentage of missing data over time, (d) a scatter plot mapping the spatial distribution of missing data with color representing the percentage at each

location, (e) a bar chart illustrating missing data percentages by units class, and (f) a bar chart showing missing data percentages by taxonomic group.

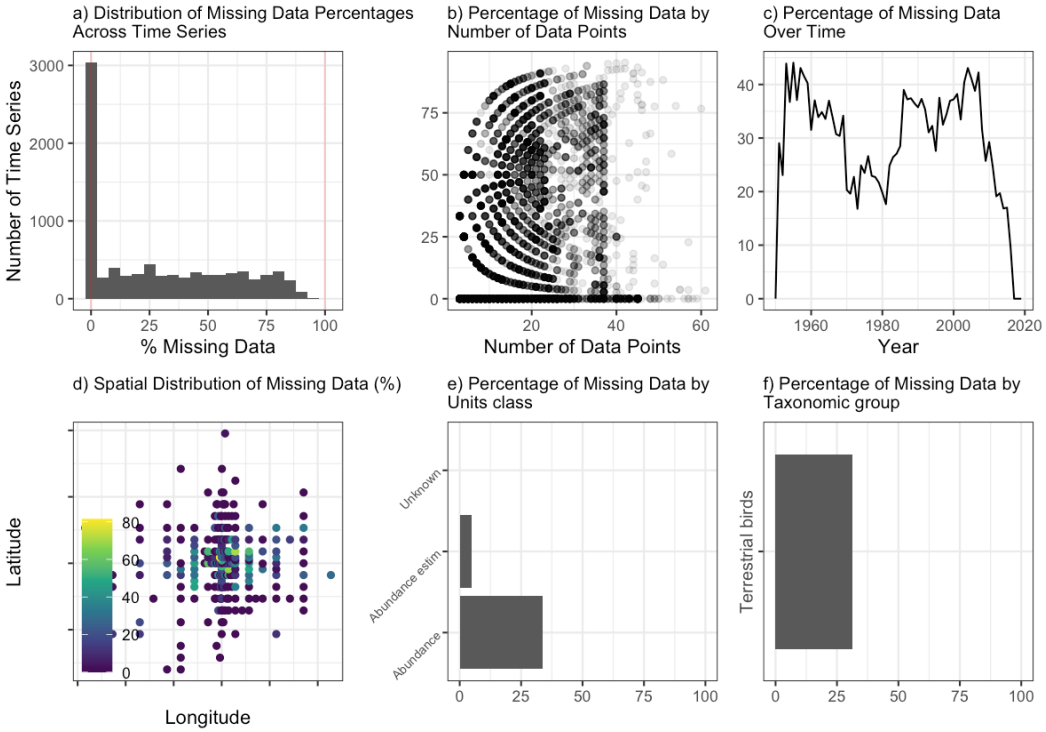

Figure S10. Overview of missing data patterns for terrestrial birds. Panels show (a) a histogram displaying the distribution of missing data percentages across time series, (b) a plot showing the percentage of missing data by the number of data points per time series, (c) a line plot showing the percentage of missing data over time, (d) a scatter plot mapping the spatial distribution of missing data with color representing the percentage at each location, (e) a bar chart illustrating missing data percentages by units class, and (f) a bar chart showing missing data percentages by taxonomic group.

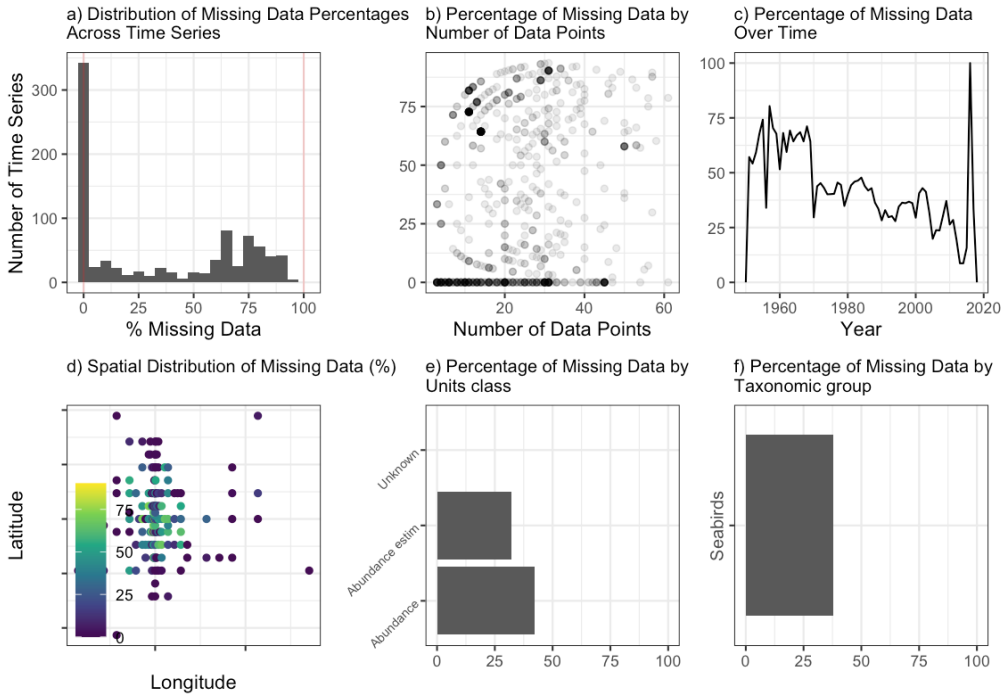

Figure S11. Overview of missing data patterns for seabirds. Panels show (a) a histogram displaying the distribution of missing data percentages across time series, (b) a plot showing the percentage of missing data by the number of data points per time series, (c) a line plot showing the percentage of missing data over time, (d) a scatter plot mapping the spatial distribution of missing data with color representing the percentage at each

location, (e) a bar chart illustrating missing data percentages by units class, and (f) a bar chart showing missing data percentages by taxonomic group.

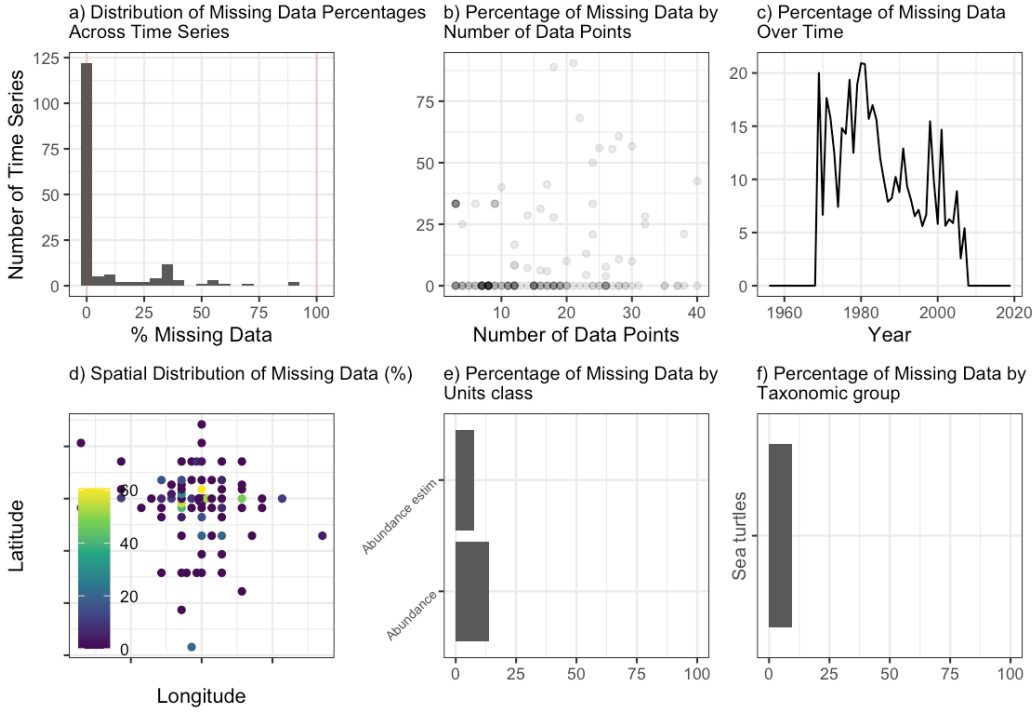

Figure S12. Overview of missing data patterns for sea turtles. Panels show (a) a histogram displaying the distribution of missing data percentages across time series, (b) a plot showing the percentage of missing data by the number of data points per time series, (c) a line plot showing the percentage of missing data over time, (d) a scatter plot mapping the spatial distribution of missing data with color representing the percentage at each location, (e) a bar chart illustrating missing data percentages by units class, and (f) a bar chart showing missing data percentages by taxonomic group.

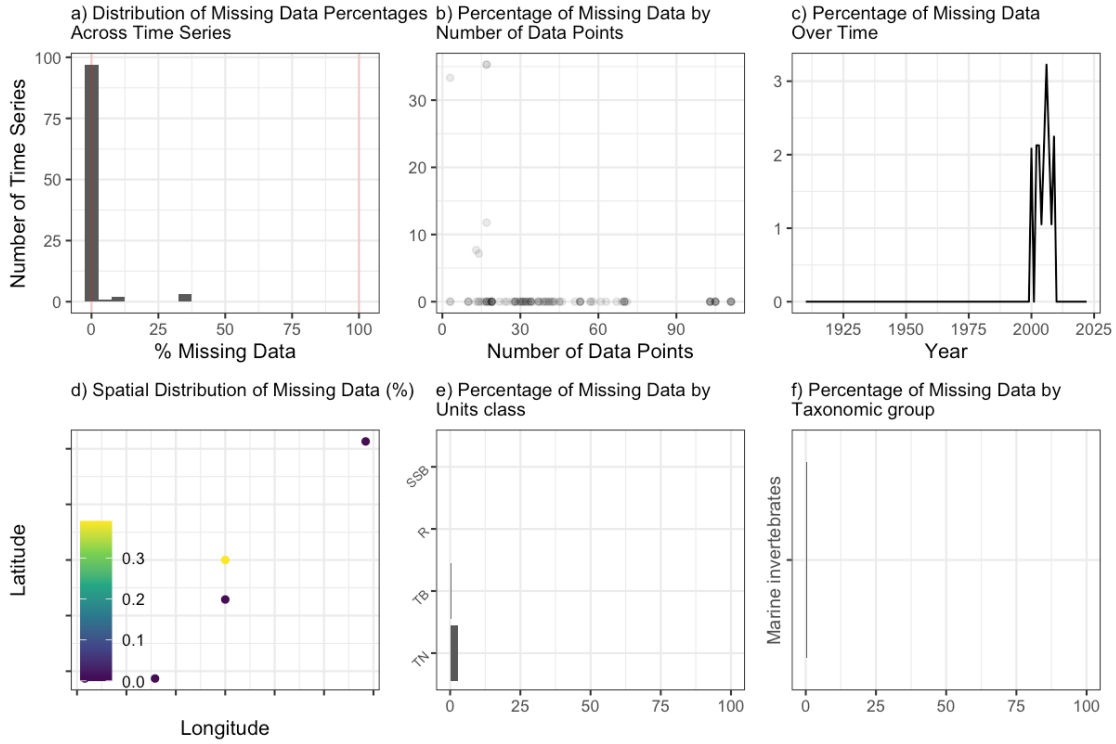

Figure S13. Overview of missing data patterns for marine invertebrates. Panels show (a) a histogram displaying the distribution of missing data percentages across time series, (b) a plot showing the percentage of missing data by the number of data points per time series, (c) a line plot showing the percentage of missing data

over time, (d) a scatter plot mapping the spatial distribution of missing data with color representing the percentage at each location, (e) a bar chart illustrating missing data percentages by units class, and (f) a bar chart showing missing data percentages by taxonomic group.

Bowler et al., (2025) emphasised that missing data in biodiversity monitoring can introduce biases in ecological modelling, particularly when the factors driving missingness overlap with those influencing species trends. In our dataset, most taxonomic groups exhibited some correlation between missing data and the observed variables (Table S8). In sea turtles, missing values were entirely random, meaning that ignoring them would not introduce bias but might reduce statistical power. Handling correlated missing data requires approaches that avoid unnecessary data removal, as excluding the affected time series can distort population estimates and reinforce other existing biases. Instead, we applied Bayesian multilevel models that have shown to improve biodiversity predictions (Johnson et al. 2024). By integrating these methods, we mitigated the risks associated with missing data while preserving the integrity of population trend analyses.

Table S8. Summary of missing data patterns and types across taxonomic groups in the dataset. The table categorises (Bowler et al., 2025) the type of missing data as MAR (Missing at Random) or MCAR (Missing Completely at Random), providing a brief description of the patterns observed in each group. These patterns include temporal trends, geographic clustering, and associations with specific traits or metrics. For some groups, potential regional biases are noted, while others exhibit more random distributions of missing data.

Taxonomic Group	Type of Missing Data (Bowler et al. 2024)	Description of Missing Data in Dataset
Terrestrial Mammals	MCAR (Missing Completely at Random), Potential MAR (regional bias)	Sparse missing data, decrease over time, more missing data in the southern hemisphere, higher for biomass.
Marine Mammals	MAR (Missing at Random)	Increasing percentages post-1950, slightly decreases over time, more missing data in North America, lower for unknown metrics.
Terrestrial Birds	MAR (Missing at Random), MCAR (No clear link to time series duration)	Moderate levels of missing data, peaks in 1960 and 2005, clustered in Europe and North America, more missing data in Asia and Australia.
Seabirds	MAR (Missing at Random)	Consistent moderate levels, more missing data in datasets <35 years, mostly around Europe and North America, more missing data in the southern hemisphere.
Marine Fish	MAR (Missing at Random)	Large range of missing data, spike after 1950, no apparent spatial patterns, higher for RAM dataset and survey biomass.
Diadromous Fish	MCAR (Missing Completely at Random), Potential MAR (regional bias)	Mostly sparse missing data, spike after 1960, clustered in North America and Europe, some metrics show more missing points.
Sea Turtles	MCAR (Missing Completely at Random)	Concentration in shorter series, no apparent patterns over time or space, no apparent patterns in metrics used.

7. Description of model variables and model specification

Biomass model – variables included in the model

To model biomass across mass migratory species, we included the following variables

- Scientific (binomial) species name.
- Estimated total biomass for the species (from compiled databases).
- Standard error (uncertainty) associated with the biomass estimate.
- Categorical code representing the major taxonomic group (e.g., terrestrial birds, seabirds, terrestrial mammals, marine mammals, marine fish, diadromous fish, marine invertebrates, sea turtles).
- Taxonomic order of the species.
- Total geographic range area (in square meters).
- Mean adult body mass (in grams).
- Trophic or functional group classification (e.g., herbivore, omnivore, consumer, decomposer).
- IUCN Red List conservation status category (e.g., Least Concern, Endangered).
- Type of migration (e.g., to-and-fro, nomadic, unknown).
- Type of migration system (e.g., latitudinal, altitudinal, coastal–offshore, depth-related).
- Source of the biomass record (e.g., RAM, Greenspoon, Callagher, literature).

Biomass model – model specification

We fitted a generalised additive mixed-effects model (GAMM) to estimate species-level biomass as a function of species traits and ecological characteristics. The model was implemented in a fully Bayesian framework using the brms package (v2.21.0) with the cmdstanr backend. The response variable was the log-transformed biomass, modelled as a smooth function of log body mass and log geographic range size using thin-plate regression splines. We used a tensor product smooth to capture potential interactions between these two continuous predictors while allowing for flexible, non-linear relationships.

To account for group-specific variation in these relationships, we included factor-smooth interactions for major taxonomic groups, trophic levels, and IUCN Red List categories. This allowed the slopes and shapes of the body mass–biomass and range size–biomass relationships to differ across ecological and taxonomic contexts, rather than imposing a single global trend across all species. Categorical predictors (taxonomic group, trophic level, and IUCN status) were also included as fixed effects, alongside two binary indicators for missing body mass and range size data, to retain all species in the model and control for potential bias introduced by data imputation.

To model hierarchical structure and residual non-independence, we included random intercepts and slopes across multiple ecological and taxonomic levels. Specifically, random slopes for log body mass and log range size were nested within taxonomic group, trophic level, and IUCN category. In addition, random intercepts were included for movement type, migration system, data source, taxonomic order, and species identity, thereby accounting for unmeasured heterogeneity across ecological and phylogenetic scales. We also modelled heteroscedasticity in the residual variance structure by fitting a separate model for the residual standard deviation (σ) as a linear function of the log-transformed standard error of biomass estimates.

Priors were weakly informative and followed the default settings in brms: a Student-t prior with 3 degrees of freedom, mean = 0, and scale = 3 for the intercept; Student-t(3, 0, 5) for regression coefficients; and exponential(0.6) and exponential(0.3) for random effect and smooth standard deviations, respectively. These priors provide regularisation while allowing broad parameter space exploration.

The resulting model was,

$$y_{it} \sim Normal(\mu_{it}, \sigma_{it})$$

$$\mu_i = \alpha + f_{\text{tensor}}(\log\ M_i, \log\ R_i) + f_{\text{group}}(\log\ M_i, \text{taxon}_i) + f_{\text{group}}(\log\ R_i, \text{taxon}_i) + f_{\text{group}}(\log\ M_i, \text{trophic}_i)$$

$$+ f_{\text{group}}(\log\ R_i, \text{trophic}_i) + f_{\text{group}}(\log\ M_i, \text{IUCN}_i) + f_{\text{group}}(\log\ R_i, \text{IUCN}_i) + \text{Taxon}_i$$

$$+ \text{Trophic}_i + \text{IUCN}_i + \text{BodyMassMiss}_i + \text{RangeMiss}_i + u_{movement[i]} + u_{migration[i]}$$

$$+ u_{database[i]} + u_{order[i]} + u_{species[i]}$$

$$\log(\sigma_i) = 1 + \log(\text{SE})_{\text{biomass}_i}$$

where y_i is the observed log-transformed biomass for species *i*; α is the global intercept; f_{tensor} represents the tensor smooth for the interaction between body mass and range size; f_{group} denotes group-specific smooths for taxonomic, trophic, and conservation groups; and u terms represent random intercepts for hierarchical groupings (movement type, migration system, data source, taxonomic order, and species).

Population models (Living Planet and RAML data) - variables included in the model

To model population changes across species, we adopted a parsimonious approach in which we included the minimum number of variables per model to avoid overfitting issues. These variables included

- Natural log-response ratio variables used to standardise population changes across time series, using population size at the first year of the time series as denominator. Here, the response variable to assess population change over time.
- Year of observation within each time series.
- Species name (scientific name).
- Unique identifier for each time series. Any given species can present multiple time series, or only one.
- Metric category (e.g., measurement units, data sources), which are divided into: biomass, abundance, biomass estimate, abundance estimate, and unknown.
- Latitude and Longitude – coordinates centred around 0.

Population models (Living Planet and RAML data) - model specification

Similar to above, we used a GAMM fitted in a Bayesian framework (brms) and the cmdstanr backend. The response variable was the log response ratio of abundance, modelled as a smooth function of year and species identity. To estimate non-linear population trajectories, we included a cubic regression spline for year with six knots, and a factor-smooth interaction between year and species (Binomial) with four knots. This structure allowed species to share an overall mean temporal trend while permitting species-specific deviations, capturing both global and individual patterns in abundance change. A random intercept for metric category accounted for residual hierarchical variance among measurement groups.

Because temporal autocorrelation within population time series violates independence assumptions, we explicitly modelled temporal dependence using a first-order autoregressive process at the time-series level. This structure assumes that observations adjacent in time are more similar than distant ones, reducing bias in slope estimates and improving precision. The autocorrelation coefficient (ρ) was constrained between –1 and 1.

To capture spatial non-independence among sites, we constructed a custom spatial covariance matrix based on pairwise Haversine distances (in km) between all sites with known coordinates. Distances were normalised between 0 and 1, with values closer to 1 representing nearby sites. A small constant (10^{-6}) was added to the diagonal to ensure positive definiteness. This spatial matrix was treated as an external covariance structure for spatial random effects.

Priors were weakly informative. We used an exponential(1) prior for standard deviations of random effects, a normal(0, 0.5) prior for the autoregressive parameter, and a Student-t(3, 0, 0.4) prior for smooth term standard deviations. These priors were centred near zero, with broad variance allowing flexibility while providing mild regularisation to stabilise estimation.

The resulting model was,

$$y_{it} \sim Normal(\mu_{it}, \sigma_{it})$$

$$\mu_i = a + f_{\text{smooth}}(\text{Year}_t) + f_{\text{species}}(\text{Year}_t, \text{Binomial}_i) + u^{metrics[i]} + \varepsilon_{it} + \sigma_{it}$$

$$u = MVN\left(0, \sum spatial\right)$$

$$\varepsilon_{it} = \rho\, \varepsilon^{i(t-1)} + \eta_{it}$$

$$u = (u_1, u_2, \ldots, u_n)^T \sim MVN\left(0, \sum spatial\right)$$

, where y_{it} represents the observed log-transformed population size for time series *i* at time *t*. The term *a* refers to the model intercept. The term $u^{metrics\ [i]}$ is a random intercept for measurement unit associated with time series *i*, and $\Sigma_{spatial}$ is the spatial covariance matrix based on normalised geographic distances between sites. The symbol ρ represents the temporal autocorrelation coefficient.

8. Model diagnostics

Model diagnostics evaluated model fit by checking assumptions and identifying potential issues. Standardised residual histograms assessed normality, with good fits showing symmetrical, bell-shaped distributions centred at zero—while skewness or long tails suggested misspecification. Residuals vs. predicted plots tested for heteroscedasticity and bias, with random scatter indicating homoscedasticity, and patterns suggesting missing predictors or nonlinearity. Posterior predictive checks compared observed data to simulated predictions; deviations, especially in the tails, indicated that models underestimated variability or failed to capture extreme values.

Overall, models met assumptions of normality and homoscedasticity, though some underpredicted variability (Figure S14–S21). Residual histograms were generally centred around zero, but the model for terrestrial birds showed peaked distributions, suggesting restricted variance estimates. Residual plots showed minimal heteroscedasticity, with a very faint curvature in some (e.g., diadromous fish, marine fish, terrestrial mammals) pointed to potential nonlinearity driven by few data points. Posterior predictive checks confirmed good central trend capture, but the model for terrestrial birds struggled with extreme values.

Bayesian R^2 and leave-one-out cross-validation (LOO) provided complementary insights into model fit and predictive performance across taxa. Model fit was generally strong, with high explained variance ($R^2 > 0.70$) for marine invertebrates ($R^2 = 0.773$), marine mammals ($R^2 = 0.741$), marine fish ($R^2 = 0.710$), and terrestrial mammals ($R^2 = 0.791$), indicating robust capture of population trends and strong predictive accuracy. Seabirds also showed good performance ($R^2 = 0.730$), while sea turtles ($R^2 = 0.517$) and diadromous fish ($R^2 = 0.457$) displayed moderate fits, consistent with their smaller sample sizes and greater temporal variability. Terrestrial birds exhibited a comparable R^2 of 0.507, reflecting broad temporal and taxonomic diversity within that group. LOO cross-validation scores further supported these patterns, with effective number of parameters (p_{loo}) values ranging from ~9 (sea turtles) to ~202 (seabirds), suggesting appropriate model complexity relative to data richness. A few models (notably for marine mammals and terrestrial mammals) had higher p_{loo} values, reflecting more flexible temporal structures rather than overfitting.

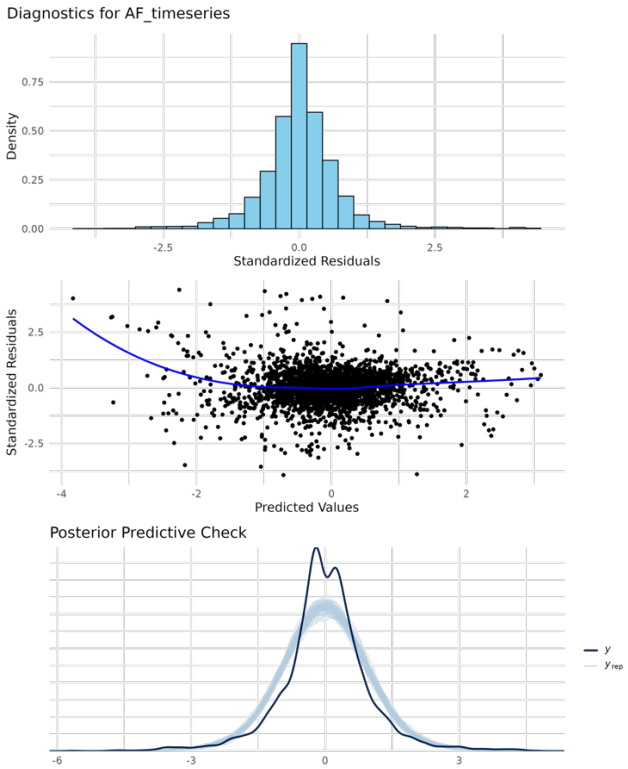

Figure S14. Model diagnostic plots assessing assumptions for the diadromous fish model. (Top) Histogram of standardised residuals, evaluating the distribution of model errors. (Middle) Standardised residuals plotted against predicted values, assessing patterns of heteroscedasticity and potential bias. (Bottom) Posterior predictive check, comparing observed data (black line) with model-simulated predictions (blue distributions) to evaluate the model's ability to replicate observed variability.

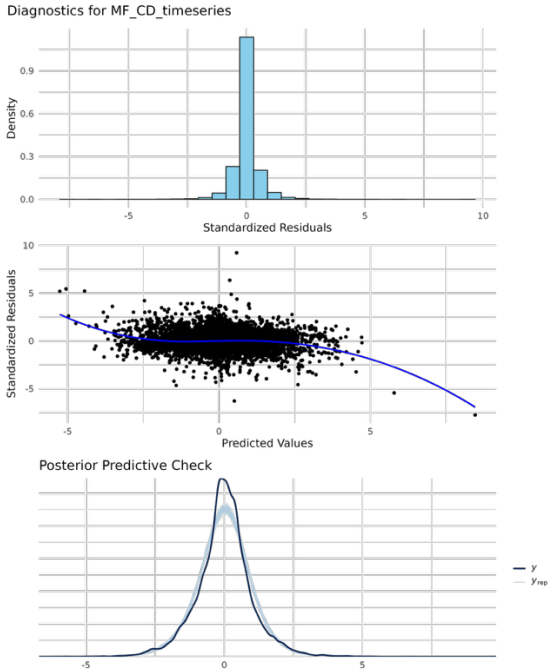

Figure S15. Model diagnostic plots assessing assumptions for the marine fish model. (Top) Histogram of standardised residuals, evaluating the distribution of model errors. (Middle) Standardised residuals plotted against predicted values, assessing patterns of heteroscedasticity and potential bias. (Bottom) Posterior predictive check, comparing observed data (black line) with model-simulated predictions (blue distributions) to evaluate the model's ability to replicate observed variability.

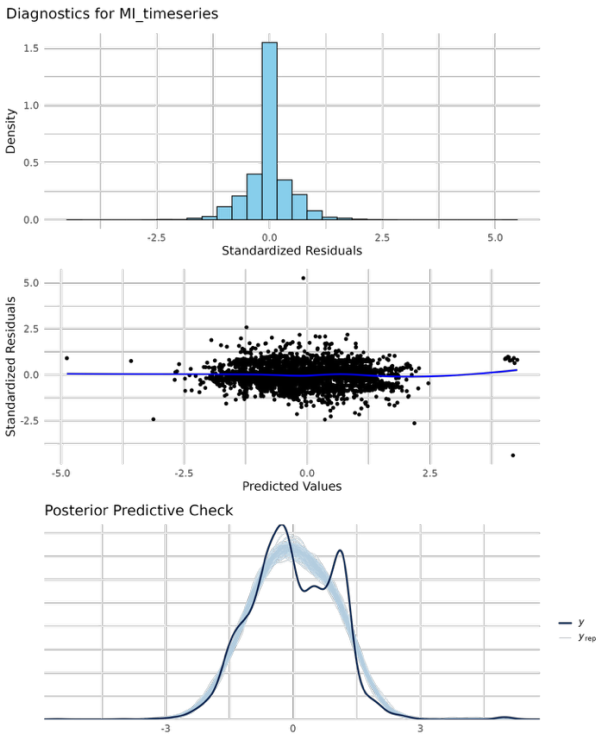

Figure S16. Model diagnostic plots assessing assumptions for the marine invertebrate's model. (Top) Histogram of standardised residuals, evaluating the distribution of model errors. (Middle) Standardised residuals plotted against predicted values, assessing patterns of heteroscedasticity and potential bias. (Bottom) Posterior predictive check, comparing observed data (black line) with model-simulated predictions (blue distributions) to evaluate the model's ability to replicate observed variability.

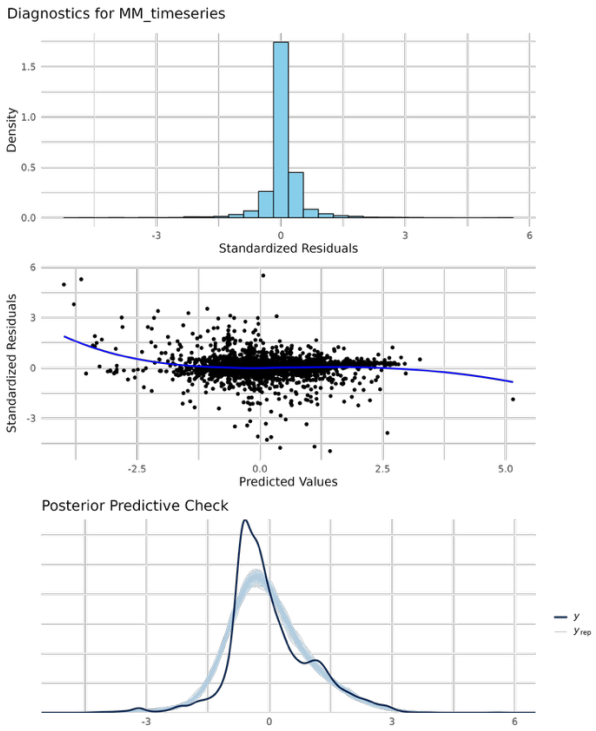

Figure S17. Model diagnostic plots assessing assumptions for the marine mammal's model. (Top) Histogram of standardised residuals, evaluating the distribution of model errors. (Middle) Standardised residuals plotted against predicted values, assessing patterns of heteroscedasticity and potential bias. (Bottom) Posterior predictive check, comparing observed data (black line) with model-simulated predictions (blue distributions) to evaluate the model's ability to replicate observed variability.

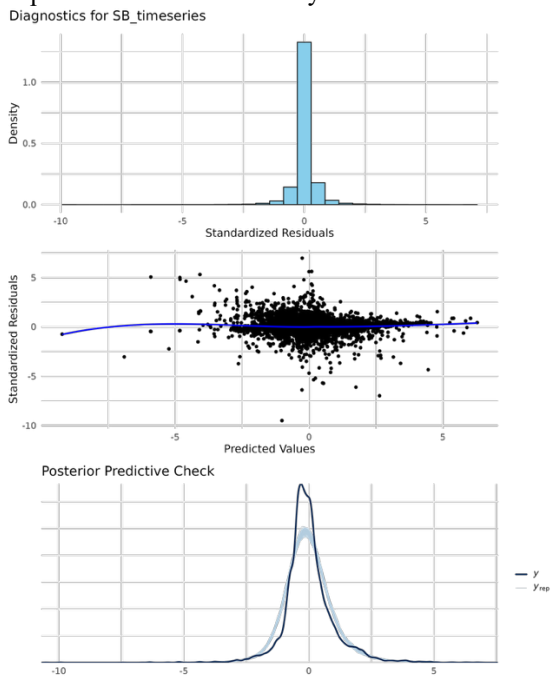

Figure S18. Model diagnostic plots assessing assumptions for the seabird's model. (Top) Histogram of standardised residuals, evaluating the distribution of model errors. (Middle) Standardised residuals plotted against predicted values, assessing patterns of heteroscedasticity and potential bias. (Bottom) Posterior predictive check, comparing observed data (black line) with model-simulated predictions (blue distributions) to evaluate the model's ability to replicate observed variability.

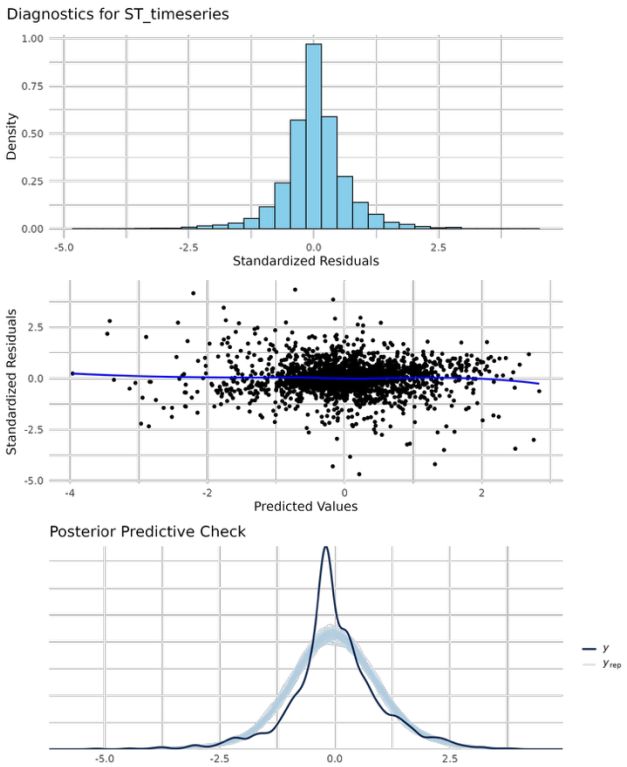

Figure S19. Model diagnostic plots assessing assumptions for the sea turtle's model. (Top) Histogram of standardised residuals, evaluating the distribution of model errors. (Middle) Standardised residuals plotted against predicted values, assessing patterns of heteroscedasticity and potential bias. (Bottom) Posterior predictive check, comparing observed data (black line) with model-simulated predictions (blue distributions) to evaluate the model's ability to replicate observed variability.

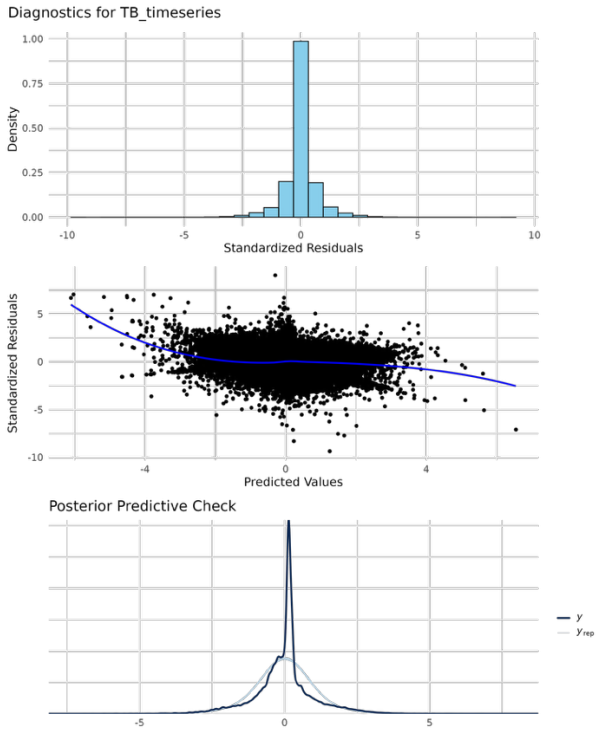

Figure S20. Model diagnostic plots assessing assumptions for the terrestrial bird's model. (Top) Histogram of standardised residuals, evaluating the distribution of model errors. (Middle) Standardised residuals plotted against predicted values, assessing patterns of heteroscedasticity and potential bias. (Bottom) Posterior predictive check, comparing observed data (black line) with model-simulated predictions (blue distributions) to evaluate the model's ability to replicate observed variability.

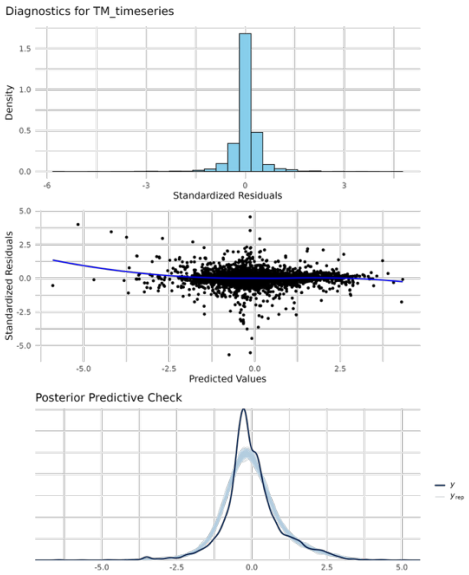

Figure S21. Model diagnostic plots assessing assumptions for the terrestrial mammal's model. (Top) Histogram of standardised residuals, evaluating the distribution of model errors. (Middle) Standardised residuals plotted against predicted values, assessing patterns of heteroscedasticity and potential bias. (Bottom) Posterior predictive check, comparing observed data (black line) with model-simulated predictions (blue distributions) to evaluate the model's ability to replicate observed variabilit

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