Integrating animal tracking and trait data to facilitate global ecological discoveries

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Abstract

Understanding animal movement is at the core of ecology, evolution, and conservation science. Big data approaches for animal tracking have facilitated impactful synthesis research on spatial biology and behavior in ecologically important and human-impacted regions. Similarly, databases of animal traits (e.g., body size, limb length, locomotion method, lifespan) have been used for a wide range of comparative questions, with emerging data being shared at the levels of individuals and populations. Here, we argue that the proliferation of both types of publicly available data creates exciting opportunities to unlock new avenues of research, such as spatial planning and ecological forecasting, across a diverse range of species. We assessed the feasibility of combining animal tracking and trait databases to develop and test hypotheses across geographic, temporal, and biological allometric scales. We identified multiple research questions addressing performance and distribution constraints that could be answered by integrating trait and tracking data. For example, how do physiological (*e.g*., metabolic rates) and biomechanical traits (*e.g.*, limb length, locomotion form) influence migration distances? How does habitat type influence movement metrics such as speed and energetic cost? We illustrate the potential of our framework with three case studies that effectively integrate trait and tracking data for comparative research. An important challenge ahead is the lack of taxonomic and spatial overlap in trait and tracking databases. We identify critical next steps for future integration of tracking and trait databases, with the most impactful being open and interlinked individual-level data. Coordinated efforts to combine trait and tracking databases will accelerate global ecological and evolutionary insights and inform conservation and management decisions in our changing world.

Keywords: Biologging, integration, macroecology, repository, tracking data, trait data.

1. Introduction

Understanding the feedback loops between animal attributes and their movements can catalyze the search for general laws in ecology, evolutionary, and conservation biology (*1*, *2*). For example, how does body size relate to maximum migration distances of species that walk, swim, or fly? How do size, sex, and reproductive strategies modulate movement patterns? Macroecology has relied on cross-species comparative analyses to address these questions at a global scale (*3*). More recently, advancements in biologging technologies (*i.e.,* instruments attached to animals to monitor their behavior and physiology) have separately provided unprecedented opportunities for research across biological scales, from individuals to ecosystems (*4*). Here, we propose that the integration of functional eco-physiology and movement ecology offers a powerful framework towards fundamental and applied research regarding the drivers and consequences of vertebrate movement across scales. We focus on mammals and birds, because most datasets currently available in open-access repositories are richest for these taxa (*5*, *6*).

2. Trait Databases

Organisms can be described by a suite of traits - *i.e.*, morphological, physiological, phenological, behavioral, and life history characteristics - that influence their performance and ecosystem effects (*7*, *8*) (Figure 1). Organismal traits are often measured on museum specimens or in field studies, and collections of these traits are published, either as manuscripts with supplemental tables (*e.g.*, (*9*–*11*)), stand-alone databases (e.g., (*12*–*14*)), or 'meta-databases' (*i.e.*, databases of databases, *e.g.*, (*15*–*17*)). For example, COMBINE (a COalesced Mammal dataBase of INtrinsic and Extrinsic traits, (*15*)) contains information on 54 traits for 6,234 extant and recently extinct mammal species, including information on morphology, reproduction, diet, life habit, phenology, behavior, and home range. Most of these databases contain data at the species level, typically presented as mean values derived from several individuals or studies, with limited information on intraspecific variation or sample sizes. However, databases such as iDigBio, VertNet, and FuTRES - which are collated exclusively from museum specimens - contain traits linked to individuals (*16*). Trait databases such as these are enabling researchers to address a vast array of questions at granular scales. For example, intraspecific studies have provided insight into macro-scale spatiotemporal patterns of variation in body size (*18*) and breeding phenology (*19*, *20*). Likewise, interspecific studies have discovered the drivers of litter size (*21*), lifespan (*22*), urban tolerance (*23*), and rates of contemporary change (*24*), and underscored the importance of continuous multivariate trait data at large scales (*25*).

3. Tracking Databases

A key trait of animals is their mobility, which drastically extends and shapes their interactions with the abiotic and biotic environment (*26*, *27*). Biologging and biotelemetry techniques—the use of animal-borne sensors to monitor location, behavior, and performance over time and space (*28*–*30*) are central to the field of movement ecology (*1*). Summaries of tracking data are often published in supplemental tables (*31*) and, increasingly, raw data are made available in data papers (*32*) or databases (*33*). For example, Movebank (*34*) is a global data platform for animal tracking that (as of March 2024) contains 6.3 billion location records, including 8,242 studies and 1,400 taxa. All data in Movebank are harmonized to a shared data model and vocabulary (http://vocab.nerc.ac.uk/collection/MVB/current/). This vocabulary stores individual location and sensor measurement records, including a timestamp and associated animal and device identifiers, which can be used to calculate many key movement metrics (Figure 1). These data expand our knowledge beyond geographic distribution (range/occurrence) by including temporally explicit movement information that describes different types of movements (*i.e.,* natal dispersal, seasonal migrations, daily movements). Further, Movebank supports storage of trait measurements commonly taken at the time of device attachment or retrieval. Tracking databases have allowed for a suite of impactful research papers across disciplines and levels of biological organization (*35*–*38*).

4. Interoperability between trait and tracking databases

Although trait and tracking bases have both matured rapidly in recent years, they are rarely combined for macroecology research. The harmonization of tracking and trait databases could be part of a much broader shift towards the full interoperability of databases in ecology (*39*). Recent efforts in this direction have resulted in the examination of the influence of body size on maximum migration distance and displacement from human disturbance (*40*–*42*). Other work has suggested that trophic guild likely mediates global reductions in mammal movements in high human density areas (*43*). Bird banding data have also been used to link natal dispersal with wing shape, including wing aspect ratio (*44*) and hand-wing index (*25*), and the hand-wing index has been used to address questions regarding the ecological processes linked to dispersal ability variation at a global scale (*45*). Although banding data contain valuable individual-level movement data, often paired with measured traits, here we focus instead on tracking data because they provide valuable information on emigration and mortality events that are not captured in banding data.

Integration of tracking data with trait data could enhance the generality of research in ecology and evolution in mammals and birds (Figure 1). However, this vision will require overcoming some key challenges associated with long-term, individual-level ecological datasets, including harmonization of datasets, their own biases, and the expertise of researchers who develop and curate them (*46*). Here, we detail these challenges and ways to address them.

4.1. Disparities in data sharing norms

Trait data repositories commonly adopt open science principles (*39*), whereas sharing in tracking data repositories has historically been more limited (*47*, *48*). Making trait data publicly available is becoming the norm (*39*), possibly because trait-based analyses rely so much on synthesis and communal resources like museum collections (where reporting catalog numbers alongside derivative data is a norm in publication and often a precondition of loaning collections) or databases generated using decades of public investment (*e.g.,* long-term banding operations). As a result, researchers who publish trait measurements often provide full access to the data. We are not aware of an assessment of the proportion of collected trait data that are published or contributed to open trait databases. In contrast, while there is no available estimate of the number of animals equipped with tracking devices globally (*49*), only a portion of tracking data are publicly discoverable or available to date (*50*). Support for non-public tracking data is a prerequisite for databases and collaborative projects to enhance use of data on endangered species, real-time and legally restricted data, government data that require agency sharing agreements for use, and data collection for ongoing studies that have not yet been published.

To better understand disparities in data sharing norms, we accessed trait databases that contain data from only birds (AVONET(*10*)), only mammals (PHYLACINE (*13*), PanTHERIA (*14*)), and both birds and mammals (AnAge (*51*, *52*), EltonTraits (*53*)) along with tracking data from both birds and mammals (Movebank (*34*)). Specifically, we extracted genus, species, and adult body size information from all databases. These trait databases are designed to provide open access to collected data, whereas Movebank, like most tracking databases, offers a suite of services including open and controlled data sharing. In Movebank (*34*), likely the largest tracking database, as of March 2024 13% (744 out of 5,659) of studies were available for open access download, of which 11% (616 species) corresponded to mammals and birds (with license types CC_BY = 178, CC_BY_NC = 96, CC_0 = 245, CUSTOM = 93) (Table S1). These 616 studies contained data from 28,105 individual tracking data deployments.

Many biologging repositories are designed for collaborative data collection (Ocean Tracking Network (*54*)) or research syntheses (EuroMammals (*55*)), often with flexible sharing requirements to promote participation. However, the lack of mandates on data publication also presents challenges for data persistence and replicability. We argue that there are two possible reasons for this difference in current data sharing norms between trait and tracking data: the inevitable costs of collecting tracking data, and conservation concerns associated with publicly available tracking data. First, there are the financial costs and time investments to individual researchers who collect and curate animal tracking data. Tracking data costs are substantially higher (hundreds to thousands of dollars per animal in instruments) relative to the cost of measuring animal traits from specimens that have already been collected and curated (tens to hundreds of dollars per animal in equipment). Moreover, the costs of tracking data are proportionally higher relative to resource availability in nations with limited research funding. Another set of reasons for the lower accessibility of tracking data relative to trait data is the conservation concerns related to high resolution tracking data of endangered species, especially those with high site fidelity. One solution to the limited access to tracking data is for funding agencies and journals to continue mandating open access to data, as has been done with the specimens and other samples (*56*), but such mandates should carefully consider equity and conservation concerns (*56*), including specific attribute fields (*57*, *58*). A potential alternative is for these entities to mandate discoverability of studies so data owners could be contacted to discuss potential use. In addition, clear ownership and license agreements can maximize the likelihood that proper credit is given when the data are used. For example, Movebank offers a public data repository that supports dataset curation, citations licenses, and persistent identifiers (DOIs) (*34*), and government agencies have designed similar archiving efforts using Movebank's data format (e.g., (*59*)). Likewise, tracking databases could develop a community-endorsed set of data standards to adopt, like those common in trait databases (*60*).

4.2. Disconnections in taxonomic keys

Another consideration for merging trait and tracking data is finding matching taxonomic keys (*e.g.*, common name, Latin name) across databases (*61*). Users can take advantage of the existing wide functionality (*e.g.*, the R package *taxize* (*62*)) to search over various taxonomic data sources such as the Integrated Taxonomic Information System (ITIS) for scientific and common species names, along with upstream taxonomic classifications (*e.g.*, family, order). Taxonomy crosswalks, or tables that show equivalent fields in multiple database schema, can also be used to connect the data across different datasets (*e.g.*, phylogeny and range maps (*10*), or in our case, trait and tracking data). All databases that we examined had genus and species formatted in a consistent manner, which allowed them to be used as the merging key. It will also be important to establish norms in reporting which version of taxonomies have been used to label trait and tracking data, so that taxonomic changes can be accounted for over time.

4.3. Disconnections among levels of organization

Data format and complexity differ substantially between trait and tracking databases. In their simplest form, trait databases associate trait values with an individual (*e.g.*, (*16*)), population (*e.g.,* (*63*–*65*)) or species (*e.g,* (*53*)). Moreover, trait databases often exist in a more readily usable form than spatiotemporal data from biologging sensors in tracking databases that must be processed to obtain the metric of interest (*e.g.*, migration distance). Another major challenge of integrating trait and tracking databases is that most trait databases still hold data at the species level (often without calculation methods, variance measures, or sample sizes), whereas tracking databases hold data at the individual level. One possible solution for synthesis would be to aggregate tracking data down to the species level and include associated sample size and uncertainty. However, trait-based datasets should also consider reporting information at the individual level, as substantial intraspecific variation exists in species traits (*66*). A key benefit of aggregation is being able to match tracking data with trait data for the many species that are only available at the species level. However, aggregation of tracking data can obscure important intraspecific variation. An alternative to aggregation that may become more tenable soon is using tracking data at the individual-level and pairing it with the more limited, but growing, individual-level trait databases. This approach would make it possible to calculate covariation between traits and tracking. Doing so substantially reduces available data in which tracking data are accompanied by individual-level trait data (*e.g.*, age, sex, body size); for example, only 24% of tracking datasets were associated with individual trait data in our data download. Additionally, it is often difficult to measure many individual-level traits while instrumenting living animals (*i.e.,* during physical or chemical restraint) in the same way non-living animals can be measured. While advanced methods are facilitating increased intra-specific trait sampling from museum specimens (*e.g.*, (*67*)), overlapping tracking and trait data are still elusive because the specimens are unlikely to have historical tracking data, and resources to link representations of individuals across data platforms are still in early stages (*68*). Therefore, for the foreseeable future, the most likely path forward may be to generate and deposit individual-level data trait data. We also expect that the emerging application of expert-trained artificial intelligence to biological images such as camera trap photos will become more useful in generating estimates of trait values.

4.4. Disparities across the Tree of Life

There are data for many more species in trait databases than in tracking databases. Trait databases contain data for thousands of species (AVONET = 11,009 bird species, Amniote =

14,183, AnAge = 593, COMBINE = 6,033, EltonTraits = 15,393, PHYLACINE = 5,831, PanTHERIA = 3,542) whereas tracking databases include fewer species (e.g. Movebank = 1,400 species). Across all trait databases, data are available for 19,662 species of which only 1.8% (362 species) also have publicly available tracking data. This low overlap means that trait-tracking integration efforts are currently possible for a remarkably low percentage of the Tree of Life, thus greatly hindering our current potential for generality in macroecology. These 362 species (265 bird species and 96 mammal species) are from 240 genera and 35 orders (Figure 2, Figure S1, Figure S2). Clearly, the integration of trait and tracking databases will inevitably be constrained by the number of species with movement data available in tracking databases. However, trait databases do not have dense representation for all the species that are most abundant in tracking databases, such as the largest mammals, and tracking data sometimes come from a biased subset of populations. Asymmetric availability of trait data (*69*), tracking data (*70*), and demographic data (*5*) is well-established. Given the limitations in the size of tracking instruments and the important ethical considerations associated with tracking instrument size relative to animal size (*71*), taxa in tracking databases are generally larger bodied than those represented in trait databases (Figure 3). However, there is substantial overlap in both size and species representation, which makes integration of trait and tracking databases possible, and new methods for automated monitoring of smaller animals in the field might further close this gap (*72*).

4.5. Disparities across geography and time

Trait and tracking data collection are often limited to a small portion of species ranges. As a result, species-specific trait data are often pieced together from several geographically distant sources (*e.g.*, adult body mass from one continent, limb length, brain size or age at maturity from another continent, *etc.*) or from several sources that lack georeferenced data. This approach obscures potentially important geographical variation and trade-offs. Moreover, a substantial fraction of long-term animal ecology datasets represent areas of the planet with low biodiversity (*73*) or with limited vulnerability to climate change (*46*, *74*). Therefore, piecing together traits and tracking data from geographically or taxonomically biased sources can lead to incomplete or even erroneous conclusions (*75*). Likewise, information about when the trait measurements or specimens were collected is increasingly important for studies about biotic responses to environmental change. Climate change is dramatically shaping traits and movement patterns in animals. For example, some birds are becoming smaller (*76*), some migrations are being threatened (*77*), and some geographic distributions are shifting (*78*). Thus, it may be problematic to integrate historic trait measurements with contemporary tracking data (*e.g.*, those from AVONET collected in the 1970s, when few animals were instrumented with biologgers due to technological limitations (*79*)). When integrating trait and tracking databases, researchers should note when and where measurements were made. To quantitatively assess geographic distributions of trait and tracking measurements, we created a map of meta-data from the three databases that contained geographic location data (Centroid Lat/Lon for AVONET, Mid-Range Lat/Lon for PanTHERIA, and Deployment Lat/Lon for Movebank) (Figure 4). We found that available tracking data deployment locations are predominantly from the United States and Europe, whereas trait data are much more widely available overall, and reflect the much higher species diversity in Central and South America, Africa, and Asia. Similar to the data sharing disparities (section 4.1), the disparities in geographic distribution of tracking databases may be due to the large cost associated with tracking studies. However, note that tracking data locations have a broader geographic distribution than deployment locations (*80*).

4.6. Disconnections across disciplines.

Why are tracking and trait data not integrated more often? We argue that this disconnect is the result of disciplinary silos including publication venues rather than a reflection of its potential. Trait databases are often used to address evolutionary or community ecology questions, whereas tracking data are often used to address questions related to behavioral ecology or applied wildlife management and conservation. To test this hypothesis, we searched for papers citing the foundational publication of four trait databases and one movement database in Web of Science. We used the *refsplitr* package in R (*81*) to parse the references by journal name, and tallied the number of times each database publication was referenced in each journal (Figure S3). We also examined a measure of impact in each of the journals, the h5-index value from Google Scholar, which represents the h-index for articles published in the last 5 complete years (*i.e.*, the largest number h such that h articles published in 2018-2022 have at least h citations each). We found that the foundational Movebank publication (*33*) tends to be cited in different journals (e.g. *Ecology and Evolution, Ecography, Journal of Animal Ecology*) which have lower impact factors (Google Scholar h5-index range 61-67) as compared to the foundational trait database publications (PHYLACINE (*13*), PanTHERIA (*14*), COMBINE (*15*), AVONET (*10*), AnAge (*52*)) which tend to be cited in interdisciplinary journals such as *Proceedings of the Royal Society B* and *PLOS ONE* with higher impact factors (h5-index range=83-212). This is not an insurmountable problem, but requires proactive efforts to break down disciplinary silos.

5. Case studies

Overlap in data availability suggests that integrating trait and tracking databases is possible. Here, we provide three ideas for case studies to demonstrate the potential utility of integration.

5.1. Metabolics case study

In birds, computer simulations suggest that the relationship between behavior, environment, and life history is fundamentally mediated by metabolism (*82*). However, disconnections between biomechanics, bioenergetics, and ecology have resulted in major unanswered questions about how the energetic costs of locomotion scale up to entire migrations. A major question in ecology is: how much does movement explain deviations between field metabolic rate and body mass? Theory has shown that the costs of migration are extensive, but nuanced energetic and demographic trade-offs exist (*83*). Trait databases (*9*, *84*) contain an enormous amount of field metabolic rate and body mass data at the species level (Figure 5a). Variation around the relationship between field metabolic rate and body mass may be explained with many metrics derived from tracking data. For example, longer migration distances or increased daily movement distance could contribute to both heightened basal and field metabolic costs. Theory could be used as a starting point to determine which tracking and trait metrics are ripe for integration.

5.2. Size-specific longevity case study

Ungulates vary in body mass from the approximately 1.5 kg Java mouse deer (*Tragulus javanicus*) to the approximately 1500 kg hippopotamus (*Hippopotamus amphibius*). Nearly half of all extant ungulate species migrate (*85*) and some larger bodied ungulates undertake extremely long migrations. For example, Caribou (*Rangifer tarandus*) have one of the longest migrations of any terrestrial mammal (*31*). The evolution of longer migrations facilitated larger body size (*85*); however, support for whether or not large body size facilitates longer migrations is inconsistent (*31*, *86*). In contrast, larger body size is suggested to increase longevity because of the “live slow, die old” life history strategy that typifies most large species (*87*, *88*). Although large body size increases migration distance and longevity, trade-offs exist between migration distance and longevity as migrations can increase survivorship by allowing individuals to exploit productive foraging grounds but can also reduce survival due to factors such as energetic constraints of travel and risk of predation or disturbances (*89*–*91*). Thus, understanding the interactions between body size, migration distance, and longevity will help disentangle some of the driving forces behind macroecological patterns and elucidate trade-offs between migration distance and longevity. Integration of existing species-level tracking and trait data could be used to ask: Can migration distance help explain some of the variance in the longevity~body size relationship, and can body size influence the migration distance~longevity relationship? Potential hypotheses include: H_0 migration distance is unrelated to longevity, and H_1 animals that migrate further have shorter longevity when controlling for body size. Researchers could analyze individual-level tracking data (*e.g.,* from (*31*) or Movebank or Euromammals) along with species-level size and longevity data from other databases (*e.g.,* from AnAge (*52*)) to identify macroecological patterns across herbivores (Figure 5b) and other mammals. Currently, body size (*92*), longevity (*17*, *52*), and migration distance (*31*) data exist for 11 ungulate species; however, expansion of this dataset will increase statistical power and allow for more robust conclusions to be made. The analysis could also be applied to birds, which experience most of their mortality during migrations (*93*) but seem to have higher annual adult survival with increased migration distance (*94*).

5.3. Sexual niche divergence case study

Sexual size dimorphism and sexual niche partitioning are widespread phenomena amongst vertebrates (*11*), and are thoroughly studied in ungulates (*95*). Hypothesized proximate and ultimate causes of sexual niche partitioning include differential predation risk, foraging strategies, and activity budgets. These hypotheses can be mechanistically tested by combining biologging to quantify space use, movement behavior, and activity patterns, with trait measurements such as sex, size, and metabolic rates at the individual level. Biologgers have been attached to males and females in many species separately (*96*), but large comparative analyses have yet to be done. For these questions, individual-based tracking data and trait measurements are needed because they capture intraspecific variation, especially in metrics such as migration distance and home range stability that often vary according to "movement syndromes" (such as residents, migrants, and nomads) that exist within and between species (*97*). The combination of tracking and trait data should allow for broader syntheses to elucidate the causes and consequences of sexual segregation.

As a proof of concept, we downloaded a multi-species tracking dataset from Movebank (*97*), retaining tracks from species where both adult males and females were instrumented. Unfortunately, this yielded only six species: one bird (*Gyps africanus*), three mammals (*Antidorcas* marsupials, *Canis mesomelas*, and *Loxodonta africana*), and two reptiles (*Chelonoidis hoodensis* and *C. porteri*). The sexual size dimorphism of these six species range from the monomorphic *Gyps africanus* to the 2:1 male:female size ratio of *Chelonoidis*. We tested whether sexual size dimorphism was associated with space use using a simple approach: 1) estimating space use by each individual as the area of the convex hull containing their track (minimum 90 days), and 2) calculating the log fold change of the mean convex hull area between males and females (Figure 5c). We could increase analytical power with larger sample sizes and more sophisticated estimates of home range size. However, major challenges for this approach are data access limitations and heterogeneity in data characteristics and structure (e.g., sampling rates, location accuracy), which demand substantial effort to synthesize tracking studies for comparison to trait databases.

Together, these three case studies show that integrating trait and tracking databases is possible and shows great promise.

6. Integration into the future

We are entering a new and data-rich era of possibilities for comparative work (*46*). The transition of scientific journals from print to online publication has revolutionized the use of supplemental data and living databases (*98*), and accelerated momentum toward open science (*99*). It is now increasingly possible to combine trait and tracking databases to discover broad patterns and make predictions, even about species whose traits or movement patterns cannot yet be measured at scale. Future integration efforts can be accelerated in four ways. First, higher discoverability and <u>more open access to tracking data</u> will be critical for expanding the number and types of taxa in comparative studies. Rapid technological innovations including Motus and ICARUS are making it possible to instrument progressively smaller animals, which will increase the promise of trait-tracking integration in the future, but only if the data are openly accessible and taxonomically and spatiotemporally indexed. Second, future research, especially synthesis efforts, will benefit from <u>measurements of more and different individual-level traits</u>. For example, bioenergetics and biomechanics traits are nearly absent from trait databases (*e.g.*, muscle fiber anatomy, reaction speed, maneuverability, fuel carrying capacity, stride length, cost of transport, body temperature ranges, fat stores). Measuring multiple traits per individual (*e.g.*, from museum specimens and biologged individuals) can fill in gaps for living individuals where few traits are measured. Coordinated networks across scales of biological organization could be used to measure linked traits (*100*). Third, researchers across both domains need to make <u>individual-level trait data available</u>. As noted above, the majority of trait databases have historically reported data at the species level, despite the importance of intraspecific variation

(*101*). The impact of within-species variability (*102*) on ecological and evolutionary processes can be important even if means are the same (*21*). Finally, future comparative efforts will benefit from integration with other types of databases not discussed here, including population models (*e.g.,* matrix population models through COMADRE (*64*) , PADRINO (*63*), and MOSAIC (*103*)), other movement data (*e.g.,* camera trap and ringing/banding/tagging data), environmental data (*e.g.,* remote sensing), and genomic data.

7. Conclusion

Data on animal traits and movement patterns have independently provided invaluable insights because they each represent a critical link between phenotypic and behavioral characteristics of organisms and their roles in populations, communities, and ecosystems (*104*). We believe that harmonization of trait and tracking databases would facilitate major exploration and discovery, including quantifying and predicting animal responses to climate change and landscape fragmentation, explaining performance limits, and understanding demographic drivers. Integration of trait and tracking data with other types of databases would also allow us to reflect on sources of bias in our understanding of the natural world (e.g., how representative are population model databases or tracking databases in terms of biomes, foraging strata, and nocturnality *vs.* diurnality). This integration will require our research communities to continue collection and deposition efforts strategically and openly.

Major remaining opportunities exist to improve geographic, taxonomic, and disciplinary overlap between trait datasets and tracking datasets, especially at the individual level. A key challenge is the inevitable trade-off between nuance and generalization in grouping data; species have been used as sampling units for macroecological research (*10*) because variance in trait values among species usually outweighs within-species variance (*105*) (but see (*101*)). Numerous opportunities also exist to leverage artificial intelligence to bridge the traits-tracking gap, including by training artificial intelligence to estimate traits of tracked individuals, either from images such as camera trap photos or from regression-based approaches trained from other datasets. As the pace of climate change accelerates, data-driven conservation efforts using species traits and tracking patterns are needed (*106*, *107*). We argue that the expansion of publicly available animal tracking and trait databases make now an ideal time to combine the two into a rich quantitative framework for developing and testing hypotheses in vertebrate animals across geographic, temporal, and biological allometric scales.

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Data availability statement

Reproducible, fully commented scripts and data are available on Dryad (https://doi.org/10.5061/dryad.s4mw6m9dz), including DOIs for all databases.

Competing interests

The authors declare no competing or financial interests.

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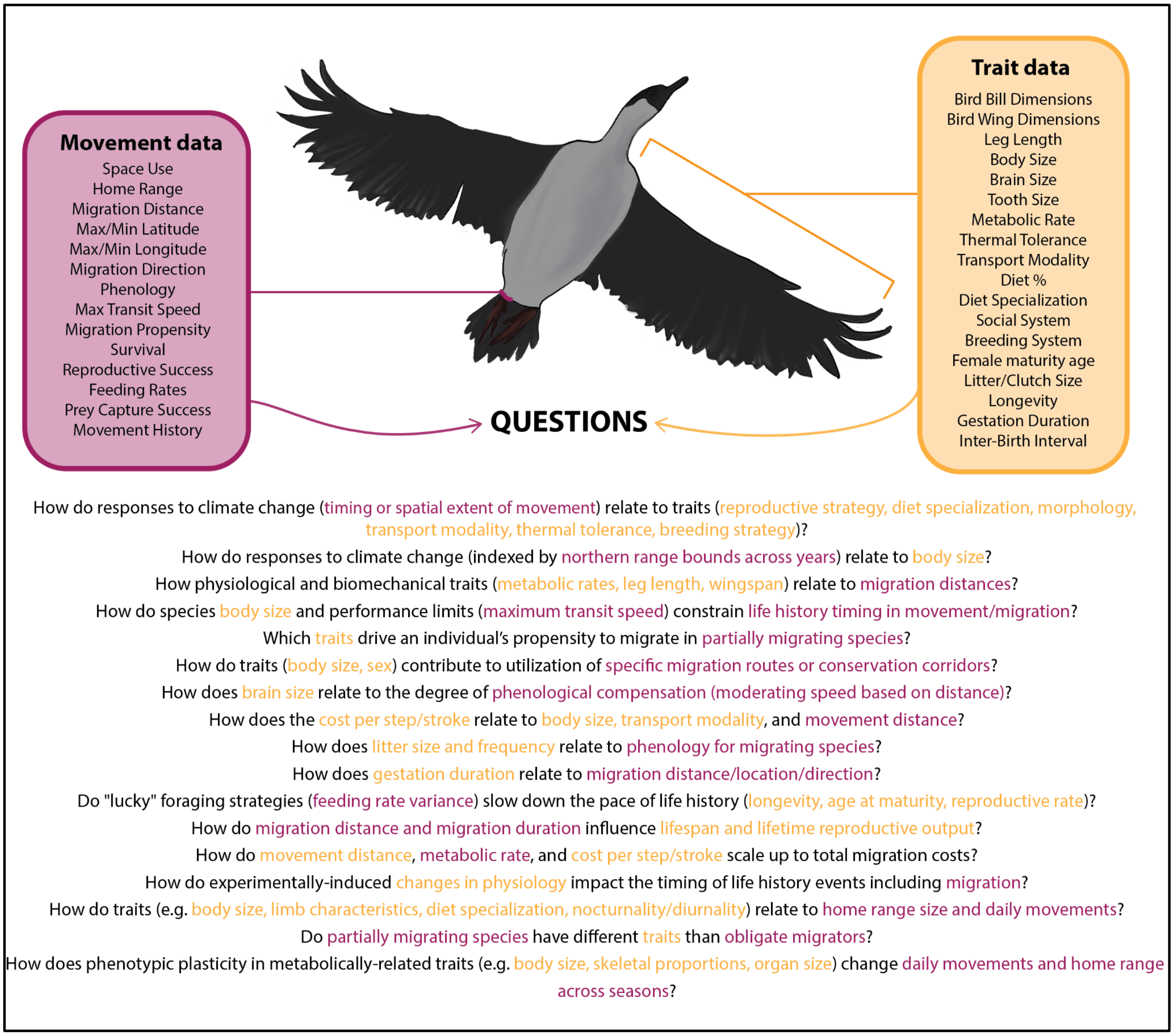


Figure 1. Tracking databases and trait databases contain extensive information about global patterns; their integration could enable researchers to answer key questions about ecological and evolutionary processes. Note that some metrics (e.g., demographic traits) can be represented in both trait databases (e.g., lifespan) and tracking data (e.g., mortality signal).

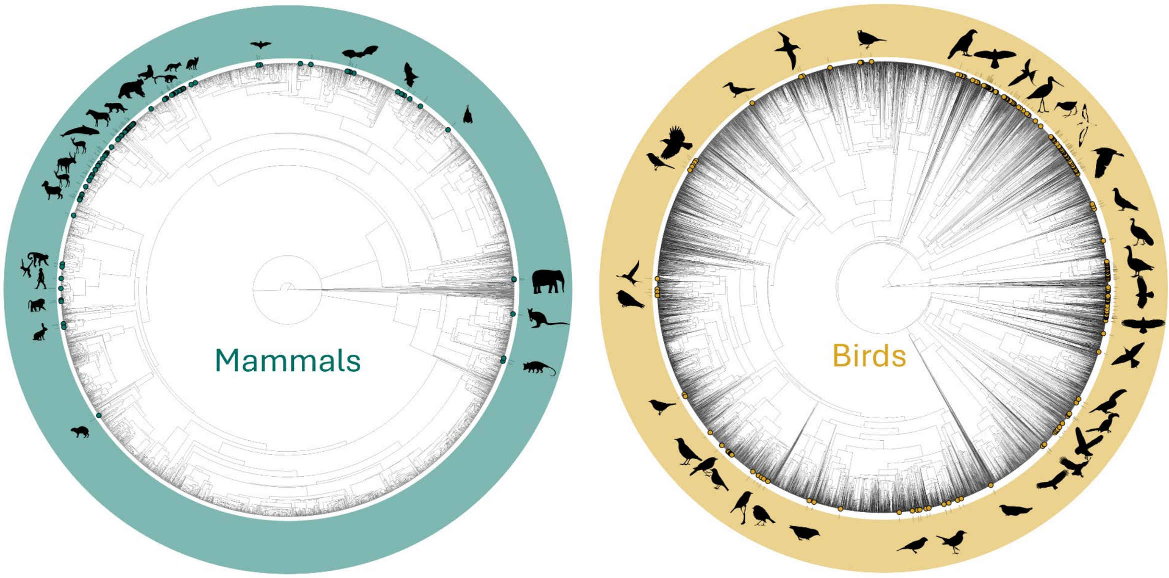


Figure 2. Mammal and bird phylogenetic representation of 240 genera for which both tracking and trait data are available. Based on the D-statistic (*108*), there is extensive phylogenetic clustering of available trait and tracking data (D=0.7971523 for mammals, D=0.6573673 for birds). A subset of 173 genera with available *phylopic* silhouettes are shown.

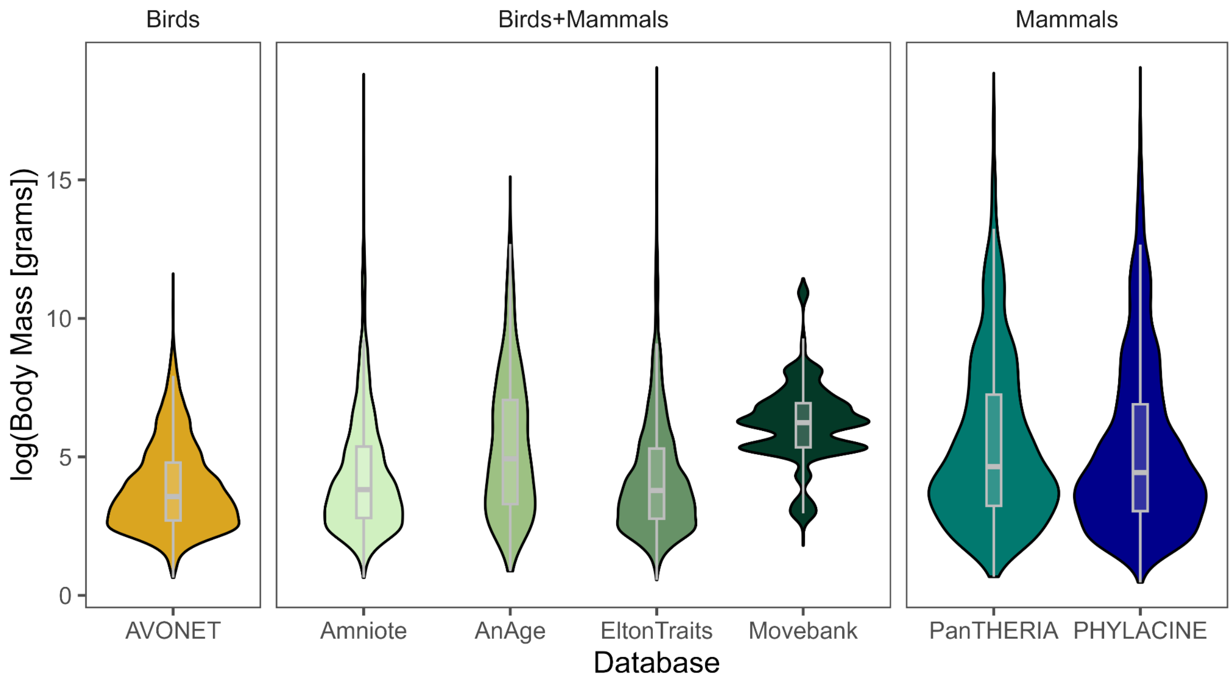


Figure 3. Publicly available trait and tracking datasets overlap in their representation of animal sizes (body masses).

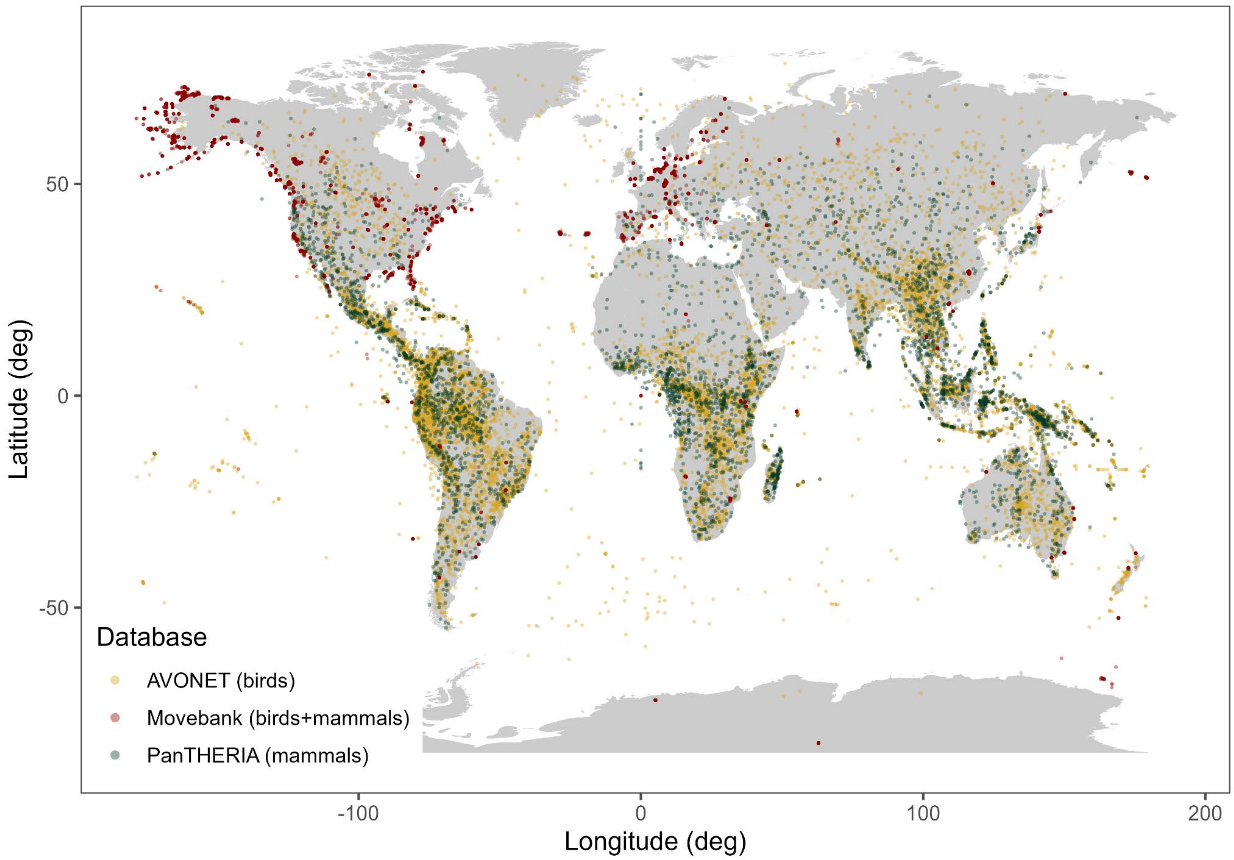
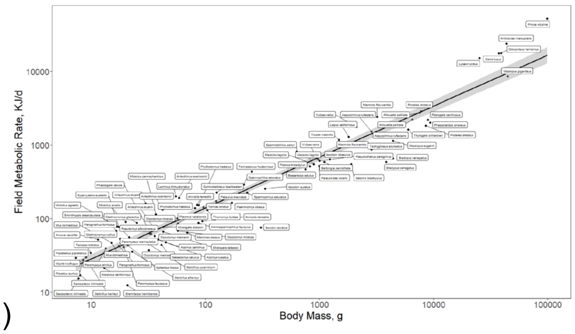
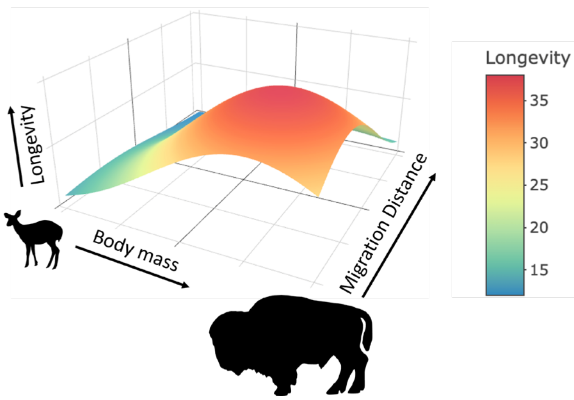


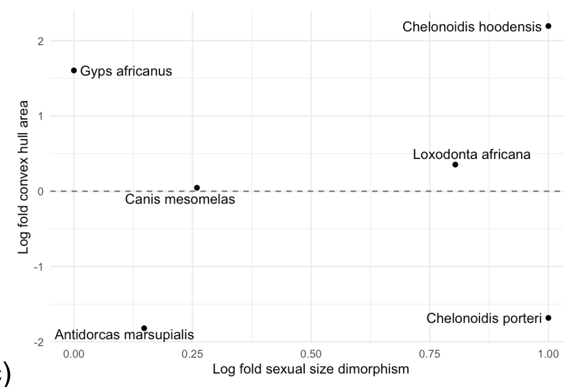
Figure 4. Geographic distribution of publicly available data from trait and tracking databases. Whereas trait data are globally distributed, reflecting increased species richness near the tropics, publicly available tracking data are predominantly collected in the United States and Europe. Note that tracking database points are deployment locations (i.e., 1 point per deployment), not recovery locations or tracking data. Data are only shown for the 33% of available studies (163 studies with 9,640 deployments) that provided deployment location data.



(a)

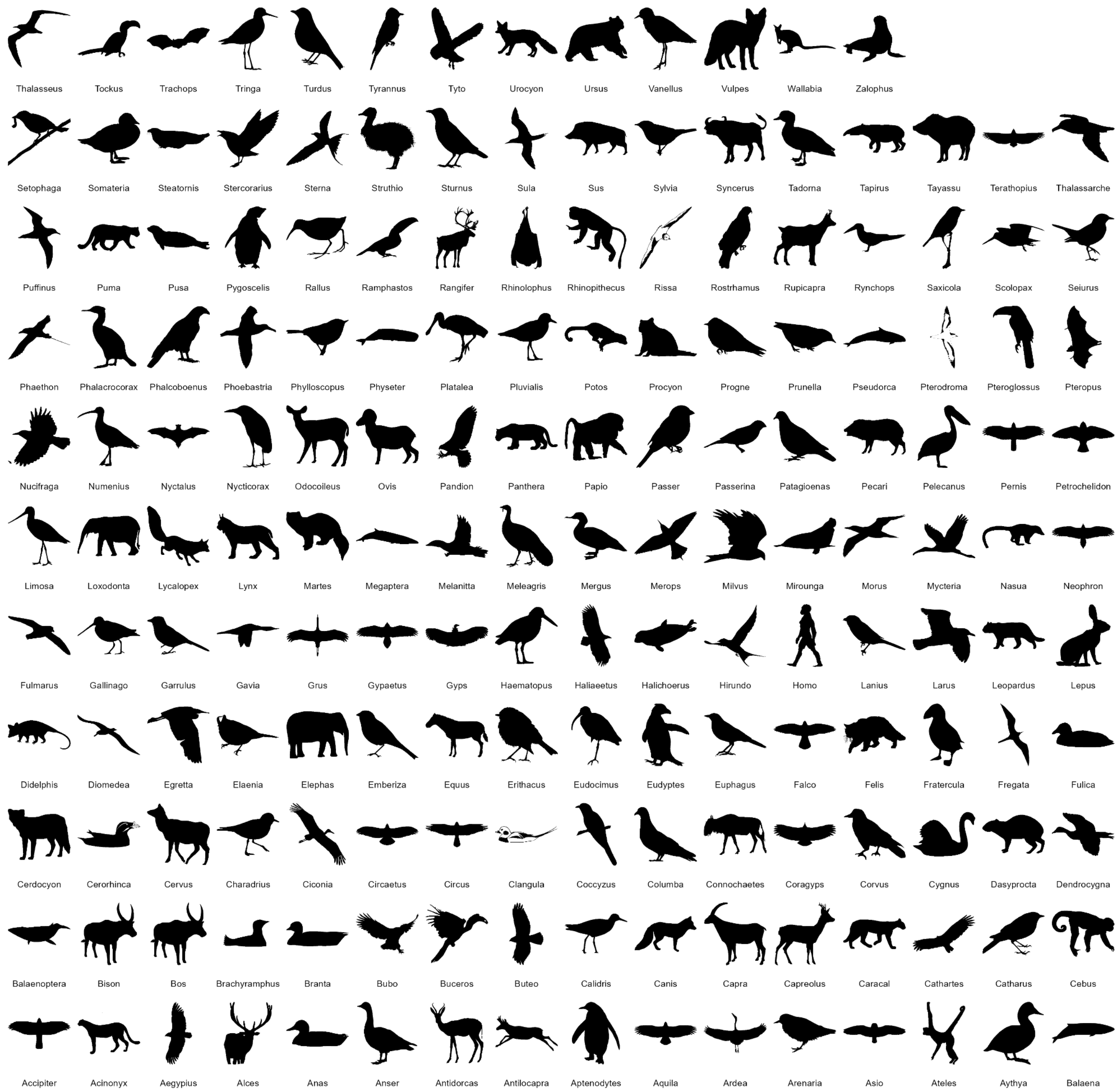


(b)

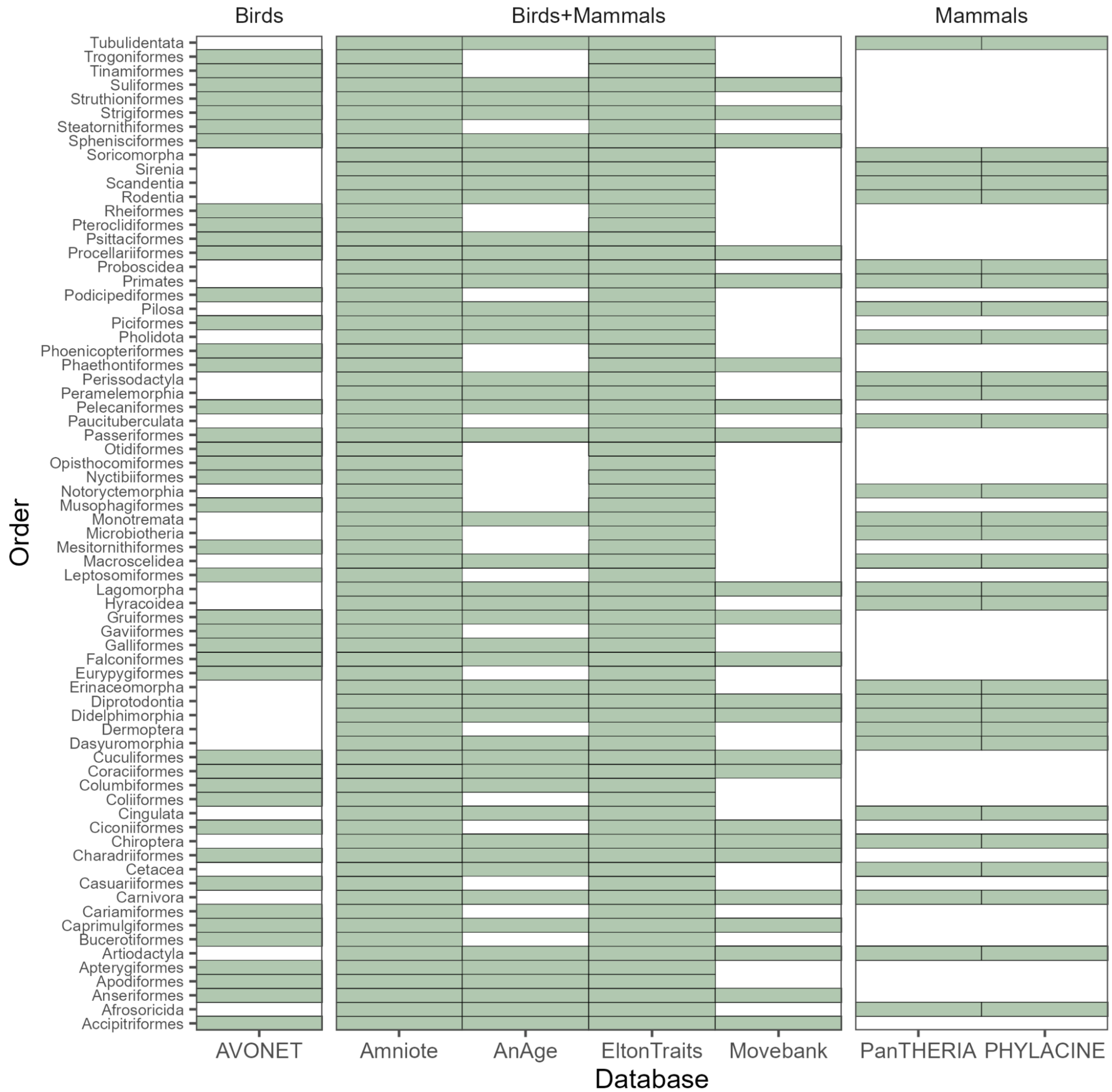


(c)

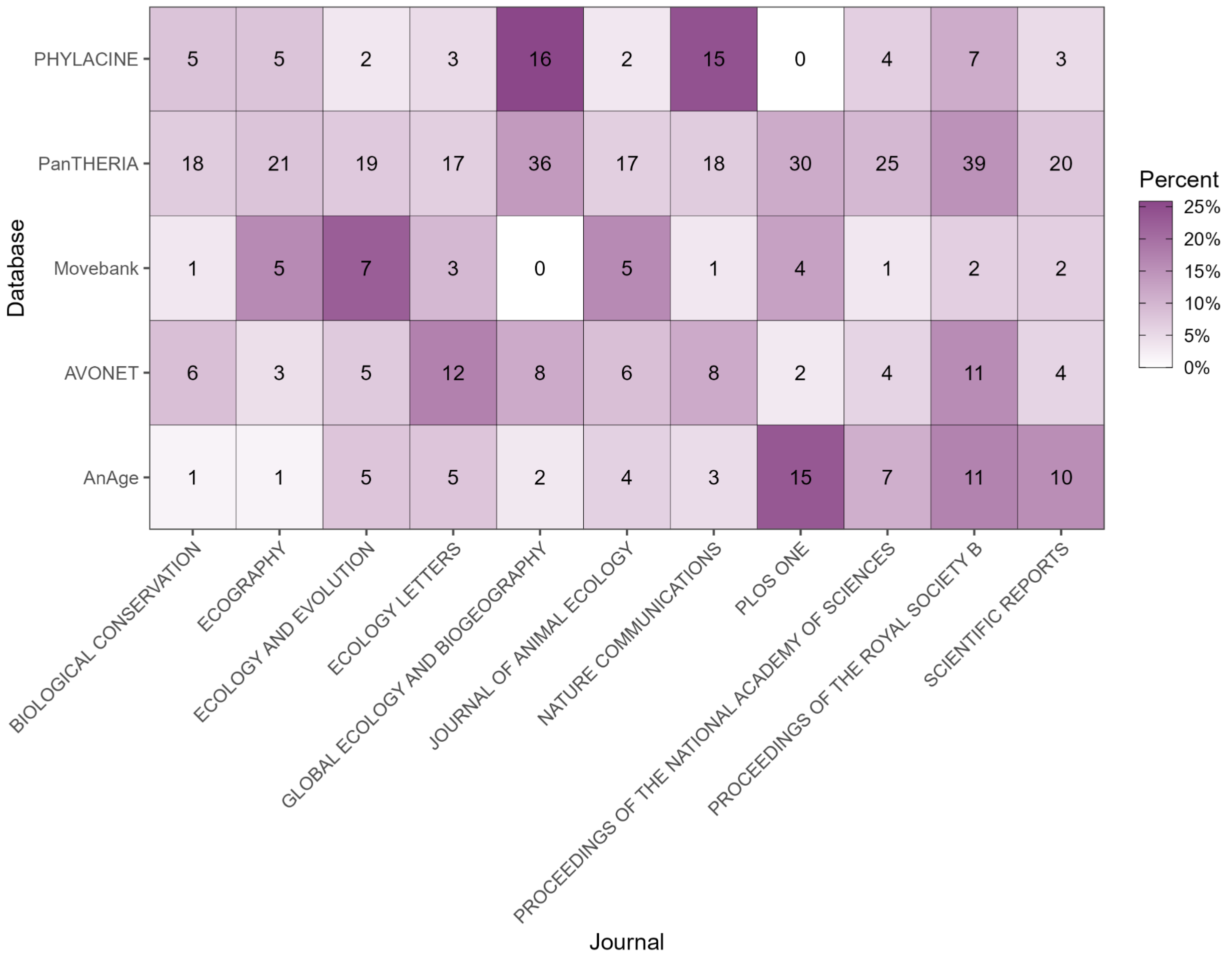
Figure 5. Three case studies showing the potential utility of integrating trait and tracking databases. **(a)** Metabolics case study: field metabolic rate plotted against body mass for 95 species of eutherian and marsupial mammals. Integration of trait and tracking data (e.g., migratory status, daily movement distance) could be used to explain deviations from this line. **(b)** Migration distance case study: the hypothetical relationship between body size, migration distance, and longevity for herbivores. Tracking and trait data are available for dozens of species and could be used to test this hypothesized relationship **(c)** Sexual niche segregation case study: data from trait and tracking data were combined to test whether sexual size dimorphism is related to differences in movement patterns.



Supplemental Figure 1. Birds and mammals from 240 genera have both tracking and trait data available. A subset of 173 genera with available *phylopic* silhouettes are shown here in alphabetical order by genus.



Supplemental Figure 2. Orders represented by each database, using the *taxizedb* package in R to assign each genus and species to an order (based on ITIS). Note that all orders have trait data available (from Amniote and EltonTraits databases) but not all orders have tracking data available (from the Movebank database).



Supplemental Figure 3. Peer-reviewed publications that cite the foundational trait and tracking database papers are published in various journals. Only journals with >30 citations across the foundational publications are shown.

Supplemental Table 1. Table of the 616 publicly available animal tracking studies from Movebank as of April 2024. Each study is referenced as a DOI for the dataset where available, or else as a published paper or report cited in the study where available, and otherwise by the Movebank study name. A study can be viewed by appending the study ID to the following URL: https://www.movebank.org/cms/webapp?gwt_fragment=page=studies,path=study .

Study ID	License type	Reference	Reference type
80479	CC_0	https://doi.org/10.5441/001/1.hp37j8cb	Dataset DOI (Movebank)
82207	CC_0	Movebank study 'BCI Agouti GPS', accessed March 2024	Movebank study
82684	CC_BY	https://doi.org/10.1098/rspb.2010.2383	Paper DOI or PURL
123413	CC_0	https://doi.org/10.5441/001/1.pb653nk3	Dataset DOI (Movebank)
125221	CC_0	Movebank study 'Marc Bechard Hawks ', accessed March 2024	Movebank study
204253	CUSTOM	https://doi.org/10.1525/cond.2011.090243	Paper DOI or PURL
220229	CC_BY	Movebank study 'Tsavo Lion Study', accessed March 2024	Movebank study
230394	CC_BY	Movebank study 'NYSDEC Indiana Bats', accessed March 2024	Movebank study
236023	CC_0	https://doi.org/10.5441/001/1.56pf8220	Dataset DOI (Movebank)
433126	CC_0	https://doi.org/10.5441/001/1.td71sn54	Dataset DOI (Movebank)
433318	CUSTOM	Hirsch BT. 2007. Within-group spatial position in ring-tailed coatis (Nasua nasua): balancing predation, feeding success, and social competition [dissertation]. [Stonybrook (NY)]: State University of New York at Stonybrook. 328 p.	Article or report with no DOI
446487	CC_BY	https://doi.org/10.1007/s10336-010-0492-1	Paper DOI or PURL
446571	CC_BY	Movebank study 'MPIAB Griffon Vulture Argos', accessed March 2024	Movebank study
446575	CC_0	Movebank study 'MPIAB Lake Constance Ducks Argos', accessed March 2024	Movebank study
446579	CC_BY	https://doi.org/10.1016/j.anbehav.2016.02.026	Paper DOI or PURL
446603	CC_BY	http://www.jstor.org/stable/1522237	Paper DOI or PURL
446635	CC_BY	Movebank study 'MPIAB Trumpeter Hornbill Argos', accessed March 2024	Movebank study
446659	CC_BY	Movebank study 'MPIAB White Stork Greece Argos', accessed March 2024	Movebank study
446663	CC_BY	Movebank study 'MPIAB White Stork Oriental Argos', accessed March 2024	Movebank study
446667	CC_BY	Movebank study 'MPIAB White Stork South African Population Argos', accessed March 2024	Movebank study

481458	CC_BY	https://doi.org/10.5441/001/1.f3qt46r2	Dataset DOI (Movebank)
978749	CC_BY	Bauer H-G, Fiedler W, Heine G, Seier I. 2011. Bestandsdynamik, Verbreitung und Brutbiologie der Rostgans Tadorna ferruginea am Bodensee und Hochrhein: negative Auswirkungen auf einheimische Vogelarten? Ornithologische Jahreshefte Baden-Württemberg. 27:103-121.	Article or report with no DOI
1481243	CC_0	https://doi.org/10.5441/001/1.2k536j54	Dataset DOI (Movebank)
1495582	CC_BY	https://pubs.er.usgs.gov/publication/70134558	Paper DOI or PURL
1518377	CC_BY	https://pubs.er.usgs.gov/publication/70134558	Paper DOI or PURL
1760349	CC_0	https://doi.org/10.1111/j.1365-2664.2008.01589.x	Paper DOI or PURL
1764627	CC_0	https://doi.org/10.5441/001/1.j900f88t	Dataset DOI (Movebank)
1818825	CC_BY	Movebank study 'Forest Elephant Telemetry Programme', accessed March 2024	Movebank study
1823143	CUSTOM	Movebank study 'White-faced capuchin, GPS Crofoot Barro Colorado Island, Panama', accessed March 2024	Movebank study
1898591	CC_BY	Movebank study 'MPIAB White Stork Prinzesschen', accessed March 2024	Movebank study
1902221	CC_BY	Movebank study 'Collared Peccary on BCI', accessed March 2024	Movebank study
1918503	CUSTOM	https://doi.org/10.1111/j.1469-1795.2011.00454.x	Paper DOI or PURL
2147218	CC_0	https://doi.org/10.1016/j.biocon.2010.03.041	Paper DOI or PURL
2151381	CUSTOM	Reid N, Harrison AT. 2010. Post-release GPS tracking of hand-reared Irish hare Lepus timidus hibernicus leverets, Slemish, Co. Antrim, Northern Ireland. Conserv Evidence. 7:32-38.	Article or report with no DOI
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6459871	CC_BY_NC	Movebank study 'Peregrine Falcon - NYSDEC', accessed March 2024	Movebank study
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8317873	CC_BY	Movebank study 'Common/King Eiders; Nuuk/Disko Bay/Upernavik, Greenland; Mosbech/Merkel; 2002 and 2003', accessed March 2024	Movebank study

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