Four key challenges in the era of big data:

Ecology must move beyond Noah's ark

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Abstract

Long-term, individual-level records are of great importance in biological sciences. By understanding how individuals contribute to their populations during representative temporal scales, we can answer pressing questions in ecology, evolution, and conservation biology. These questions include identifying which, how, and where species' populations will go extinct or become invasive. Calls for the collection, curation, and release of these kinds of ecological data have contributed to the open-data revolution in ecology. Birds, particularly, have been the focus of much citizen science and international research for decades, resulting in a number of uniquely long-term studies. However, accessing some of these individual-based, long-term datasets can be challenging. Culina *et al.* (2021) introduce an online repository of individual-level, long-term bird records with ancillary data (e.g. genetics). Similar efforts have also been undertaken for mammals, fish, and even more recently for corals and insects. By releasing these ecological data open-access, the research community is starting to fill "Noah's ecological ark". However, important challenges still lay ahead to address the most pressing research questions. Here, I briefly overview the open-access landscape of long-term animal ecological studies, provide suggestions for how to most efficiently expedite our knowledge of long-term animal population dynamics, and highlight four key challenges in the use (and misuse) of these large volumes of animal ecological data.

KEYWORDS Big data, demography, FAIR, individual-level data, interoperability, open-access, reproducible research.

"I'm not interested in your data; I'm interested in merging your data with other data.

Your data will never be as exciting as what I can merge it with"

Sir Tim Berners-Lee, founder of the World Wide Web

The call to arms to ecologists for a more biogeographically representative, longer-term, open-access body of biodiversity data is not new. In recent years, these calls have become more prominent (Mills *et al.* 2015; Wilson 2017). Recognition of the importance of open-access data and reproducible research pipelines in ecology has led multiple funding agencies (e.g. NERC, NSF, ARC) and journals, including the British Ecological Society (2016), to "strongly suggest", in the first instance or mandatorily require, for published research to be FAIR (Wilkinson *et al.* 2016): Findable, Accessible, Interoperable (*i.e.*, data can interact with other data and workflows), and Reusable. Precipitated by this new research model, but also by ecologists' ethos regarding open-access (Gallagher *et al.* 2020), volumes of ecologically relevant data are being amassed and subsequently released; these titanic efforts continue despite the glaring lack of funding support in most countries to do so (Hampton *et al.* 2013; Farley *et al.* 2018). The recent publication in *Journal of Animal Ecology* by Antica et al. (Culina *et al.* 2021) is an important contribution towards the on-going momentum that is bringing ecology to a new era: one where data, tools, pipelines, and expertise/advise are shared unconditionally and for free across the community.

Despite the great progress made in the last decade in open data in ecology, one should not get too comfortable. The open, big data landscape that is starting to emerge in ecology brings new challenges that may test more traditional ecological mindsets (Hampton *et al.* 2013). Here, I review and provide suggestions regarding how to

navigate the rising tides of big data in ecology. Below, I discuss four key challenges regarding (1) responsibilities, (2) biases, (3) expertise, and (4) community. In each of them, I provide examples of why and how the challenge arises and make suggestions to minimise it.

Challenge 1. Responsibility for open-access data in ecology: With great power (or large volumes of data!) comes great responsibility. Different datasets, even when collected strictly within the same sub-field of ecology (e.g., animal population ecology), can differ vastly. For instance, ornithologists refer to the term 'recruitment' as the age at which an individual first reproduces (J.D. Lebreton, pers. comm. 2015; B. Sheldon, pers. comm. 2021), whereas plant ecologists refer to it as the germination of a seed and establishment of the seedling during a short period of time thereafter (Harper 1977). Thus, it is strongly advised to harmonise (*i.e.*, standardise and homogenise) data from various sources, or databases that house data from different researchers and sub-disciplines, before the proposed analyses are conducted (Nadrowski *et al.* 2013). Indeed, database curators invest significant efforts and time harmonising data and complementing them with metadata, as well as creating thesaurus to help users navigate their rich platforms (e.g., Pey *et al.* 2014; Garnier *et al.* 2017). However, sometimes the information detailed in the original sources, such as MSc/PhD thesis, grey reports, peer-review publications in different languages, does not allow for this task to be performed satisfactorily. When the harmonisation of data is incomplete, users of databases may benefit from the warnings and errors identified by database curators. For instance, in SPI-Birds (Culina *et al.* 2021), warnings are explicitly noted as values that are uncommon or unusual, while 'likely errors' are flagged as seemingly impossible values. Similarly, COMADRE (Salguero-Gómez *et al.* 2016), a database of

animal matrix population models (Caswell 2001), contains metadata information that allows users to identify potential issues in the way reproduction was estimated by the contributing authors, or assumptions regarding life cycle stage survival values.

Ultimately, the responsibility to correctly conduct an analysis with open-access ecological databases remains with the user. A critical part of this responsibility is awareness that just because one *can* run an analysis with all the data at one's disposal, it does not mean one *should* do so. In this regard, it is worth keeping in mind the amount of support that curators can provide. Given the current lack of financial support for open-access databases (See Challenge 3; Hampton *et al.* 2013), curators are typically full-time researchers who lead the development of databases during their "free time". As such, database curators may not have as much time to consult with for individual queries. For that very reason, and in an effort to achieve transparency, data curators often publish papers introducing their databases. This is one of many useful resources for users to successfully navigate the open-access data while steering away from mistakes and faulty data/assumptions. Oftentimes, these publications contain a section on "dos and don'ts" that can be invaluable to users (e.g., Salguero-Gómez *et al.* 2015; Salguero-Gómez *et al.* 2016). Additional key materials typically made available by the curators include the metadata, "read me" files, user guides, FAQs in their online platforms, and digitalisation protocols. The latter can be rather enlightening to the user regarding assumptions that data curators made when archiving –and sometimes imputing (Johnson *et al.* 2021)– data. Ultimately, users are responsible for establishing an appropriate set of data quality criteria to filter the databases they wish to utilise. Again, just because one can run an analysis with all of the data in, for

instance, SPI-Birds, does not mean that one should. The "how to" will large depend on the question the user has in mind.

Challenge 2. Biases in open-access data in ecology: As ecology is coming of age, ecologists are gaining a better global understanding of ecological systems at larger scales. Open-access databases, database hubs, and co-ordinated networks of ecological studies are contributing significantly to the exploration of the planetary laws of ecology (Borer *et al.* 2014). Some recent examples of the usage of big, open-access data to examine generality in ecology include the exploration of species richness-productivity relationships (Grace *et al.* 2016) thanks to NutNet (Borer *et al.* 2014), the diversity of ageing trajectories in animals and plants (Jones *et al.* 2014) thanks in part to COMPADRE (Salguero-Gómez *et al.* 2015), COMADRE (Salguero-Gómez *et al.* 2016), and DATLIFE (Scheuerlein 2018), or the exploration of the leading drivers of extinction (Carmona *et al.* 2021) thanks to, among others, TRY (Kattge *et al.* 2020). However, when examining these relationships, one must be aware that, just like in the religious tale of Noah's Ark, which was primarily filled with large mammals and some birds (Fig. 1A), biases do exist regarding the locations and taxonomic groups that ecologist are more likely to examine (Fig. 1B-M; Table 1).

Naturally, the search for general laws in ecology will only be as robust as the data that said analyses are based on. In the case of long-term animal ecology datasets, a significant proportion of studies and databases are well represented primarily in areas of the planet with low biodiversity (Titley, Snaddon & Turner 2017), or in areas that are least vulnerable to climate change (Paniw *et al.* 2021). This is a missed opportunity. For instance, of the 12 animal ecology databases depicted in Fig. 1, only CarniDiet

(Middleton *et al.*), Living Planet Index (Loh *et al.* 2005), MoveBank (Kranstauber *et al.* 2011), and TetraDENSITY (Santini, Isaac & Ficetola 2018) have significant coverage in all continents. Across the pool of databases, most animal ecology data available in open-access repositories are for highly charismatic species such as mammals and birds (Troudet *et al.* 2017), with important exceptions such as corals (Madin *et al.* 2016) and insects (Van Klink *et al.* 2021). Moreover, even within our demographic knowledge of charismatic animals, important knowledge gaps have been revealed recently across vertebrates (Conde *et al.* 2019) and mammals (Paniw *et al.* 2021). Likewise, most terrestrial biodiversity is found in countries with low GDP, for which fewer data exist relative to countries with higher GDP (Fig. 1B-M).

Ecologists aiming to capitalise on open-access databases in ecology to search for planetary laws in ecology must be aware of geographic and taxonomic biases. Otherwise, exploring macroecological patterns with biased data will inevitably lead to partial or even wrong conclusions (Trimble & van Aarde 2012). Some reasons include (1) community interactions changing with aridity (Maestre *et al.* 2009) in conjunction with tropical regions being under-examined, relative to the biodiversity they house (Trimble & van Aarde 2012), (2) the biodiversity of certain regions of the planet being limited differently by Nitrogen or Phosphorus (Menge, Hedin & Pacala 2012), or (3) a few regions around the globe containing disproportionately high numbers of endemic species, found nowhere else, and which may have a completely different set of ecological strategies (Partel, Bennett & Zobel 2016). Ultimately, these current research limitations and features of Earth mean that reported patterns may only represent a narrow spectrum of the ecology of animals –and other creatures– around the world. In this regard, the application of conservation prioritisation in data-poor

countries to expedite ecological data collection is a promising avenue of progress (Kujala *et al.* 2018; El-Gabbas, Gilbert & Dormann 2020). An additional way to fix this limitation is to develop lasting partnerships between researchers in developed and developing countries to build capacity (Donhauser & Shaw 2019).

The aim of the suggestions above is to stimulate careful thinking about how to most efficiently fill up Noah's ecological ark with representative data. In the meantime, however, ecologists need not remain idle. With the large volumes data already at hand, much can be –and is being– done. Contextualising the results of "biggish" and biased ecological data should be done more frequently rather than making clear blanket statements about a finding being consistent "worldwide" (Pettorelli *et al.* 2021). Likewise, phylogenetic approaches offer numerous tools to impute missing data following patterns of phylogenetic inertia – but one needs to be aware of which tools fit the job better (Gallagher *et al.* 2020). Finally, cross-matching algorithms to improve the overlap of interoperable databases can drastically increase the analytical power of big data approaches (Pennell, FitzJohn & Cornwell 2016).

Challenge 3. Expertise in big data in ecology: Linked to challenge 1, above, is the need to acquire the necessary expertise in the field to harness the full potential of the data. The multitude of records made available by, in this case, the SPI-Bird data hub contains great potential. However, these large volumes of data cannot be a substitute for the invaluable ornithological expertise of the researchers who collected the data, nor the quantitative skills of researchers who are used to analysing them. Unfortunately, this kind of expertise also tends to be geographically clustered in countries with high GDP and relatively low biodiversity (e.g. UK, United States, France,

the Netherlands). Oftentimes, database curators, as experts themselves in the specific subdiscipline, take it on themselves to improve skills deficiency in different regions of the globe. Examples include workshops for data access, wrangling, and analyses that database curators often offer. At COMPADRE and COMADRE, for instance, we have run workshops in three different languages and in four continents on over 30 occasions. Moreover, recently we adopted a strategy where we prioritise attendance of researchers from developing, biodiverse countries.

Related to the aforementioned tenet of big data "just because you can… does not mean you should", researchers aiming to use big data repositories are encouraged to equip themselves with the appropriate quantitative skills prior to launching big-data analyses. Alternate to this approach, or in parallel to it, users may want to consider collaborating with quantitative ecologists to aid in their research. With regards to the intricacies of each datum in the analysis, however, the invaluable expertise of the data collector cannot be substituted by fancy methods. Correctly interpreting seeming outliers and odd patterns will require that the user to either spend the hundreds of researchers' lifetimes that it has taken for the data to be collected and curated… or simply to engage with the data contributors in a collaborative manner. The latter approach may be fairer for the data contributors (See Challenge 4, below), and –in my experience– results in much more robust scientific findings.

Challenge 4. Nourishing the open-access data community in ecology: The era of big data in ecology is being support by a community composed of –at least– four different entities: data contributors, data curators, funding agencies, and journals/societies. Failure to adequately engage with one of these entities will result in

the failure of the whole enterprise. As such, communication and trust among them four is critical. For instance, one of the main reasons that researchers may choose not to share data and contribute them to open-access databases is the risk of being scooped (Laine 2017). This reticence to share data can prevail even though research has shown that researchers who publish second still end up getting a substantial portion of the recognition (Callaway 2019). To overcome fears of being scooped, I argue that ecology has much to learn and adopt from older scientific disciplines such as physics or mathematics, where arxiv-ing preprints is common practice. Fortunately, the number of submissions to BioRxiv and EcoEvoRxiv has increased exponentially in recent years (Kaiser 2017). A way that data curators can support data contributors to overcome this initial concern is by offering an embargo period (something that we do in COMPADRE & COMADRE, but of which <1% of users request), or the possibility of making their data accessible (not open-access) on the condition that they be offered co-authorship. Databases like TRY (Kattge *et al.* 2020) and SPI-Bird (Culina *et al.*) partly follow the latter model, but the percentage of data contributors requesting this option is decreasing (J. Kattge, pers. comm. 2020). The experience of my collaborators and myself in making long-term, individual datasets open-access has always been positive. On a few occasions, database users have freely approached data contributors to ask for help interpreting the results based on the invaluable knowledge I discussed in challenge 3, above. These discussions often result organically in offers of co-authorship, without database curators having to mediate those negotiations.

Database curators should make sure that credit be placed where it is due. Requesting that the original paper introducing a given database be cited when the database is

used seems logical. However, what is even more logical –as well as *fair* and *F.A.I.R.*– is to request the individual contributing authors be cited too. This action to ensure appropriate accreditation may be tricky to implement due to: (1) the lack of database infrastructure to replicate a subset of citations in the final analysis; and/or (2) the lack of space in journal prints to accommodate the potentially hundreds of the citations. For the former, some databases have already developed the functionality to provide database users with a citation summary of the data they have downloaded (e.g. all of the sources used in Figure 1B-M). For the latter, the move by many journals and societies from printed version to online only means that price-per-page is no longer a limitation to citation counts (Fox, Paine & Sauterey 2016). In this way, data contributing researchers can benefit from other user's utilising their data.

Final remarks

Open-access, long-term ecological datasets are required to allow the ecological, evolutionary, and conservation research that is needed to address current and future societal challenges. However, the new era of big data in ecology comes with a new set of challenges. The way ecologists have operated prior to this new wave, working in smaller groups or even individually, may not be conducive to the best, or most effective practices. A testament to this new way of interaction is the 116 authors involved in the recent publication introducing SPI-Birds (Culina *et al.* 2021). To that end, I conclude with a few suggestions to all parties involved in the development of big, open-access data in ecology:

- Data contributors: Consider sampling not-so-charismatic taxa in areas that are (i) poorly represented, (ii) biodiverse, and (iii) vulnerable to climate change. In

deciding whether to deposit the data in a repository, and under what conditions (e.g. fully open, conditional on consultation, co-authorship required, etc.), data contributors need to follow the requirements of the funding agency that –if any– allow for the data to be collected in the first place. Importantly too, when coming towards the end of a long, prolific academic career, potential data contributors can make an ever-lasting contribution to the discipline by developing ways to secure the perpetuity of their precious long-term datasets. All too often have long-term datasets been lost when two key demographic process occur in the life cycle of an ecologist: retirement and death (Specht *et al.* 2018).

- Data curators: Continue exploring novel approaches to supporting the long-term viability of the repositories they create. To give credit where credit is due, curators should facilitate functionality to cite subsets of original sources – and users must take advantage of this functionality and cite the sources they use. Due to the limited funding avenues to support the kind of work required to create and maintain an open-access ecological database, data curators may have to continue exploiting creative funding avenues. Examples may include philanthropic investment or crowdfunding (Grace 2017; Sauermann, Franzoni & Shafi 2019). Going one step further, if the curator is not programming-savvy, partnering up with ROpenSci (Ashander, Chamberlain & Leeper 2021) or similar to develop functionality that allows users to access data (e.g. via API) and efficiently analyse large volumes of data can help raise the profile and usability of the database – and thus chances of securing future funding. For COMADRE, for instance, recent functionality has been developed to this end (Jones *et al.* 2021). A topic that remains quite contentious from this angle is

what constitutes open-access. The definition of "open-access" by Wikipedia emphasises there not being any access barrier, which would include having to register or login to access the data. Sometimes registration and login help the data curators show potential funding agencies the demand for the data, and so careful thought needs to be given to how these steps may violate the definition of open-access to indirectly fuel investment on it.

- Funding agencies: Provide more support to develop and maintain the much-needed resources to continue ecological research and continue conversations with potential data contributors you fund to make sure that data are shared following your requirements. With regards to the first point, In the USA, the NSF launched the Advances in Biological Informatics (ABI) and the Infrastructure Capacity for Biological Research calls, which do support database development. In contrast, in the UK, no national-level funding agency explicitly supports work to develop, maintain, and digitise data for ecological purposes. The UK's NERC Data Centres and open-access agreements with NERC-funded researchers build a commitment towards the release of data based on a mutually agreed timeline. These timelines should be carefully monitored when applications come up for a new round of grant applications, as a sign of their commitment to fulfil what was promised.

- Journals and Societies: Help users and database curators find a common ground so the community of open-access ecologists can continue to grow. Special features, highlighted papers, and recognitions of efforts by researchers regarding open-access is a great way to further fuel this dialogue. A fantastic

way to solidify that commitment is by smoothly transitioning from *no open-access → open-access suggested → open-access mandatory*, as the journal of the British Ecological Society just went through (BES 2016). Regarding open-access data deposition, journals must enforce that their own data requirements be followed through. If a given journal requires for data to be openly deposited, this does not mean the final statistics of an analysis, or a beautiful shiny app that in fact does not allow users to download the raw data points in a non-proprietorial format. From this angle, the requirement should be clear: the raw data, metadata, and any pertinent scripts that will aid in the reproduction of the findings. Journals could add a "badge excellence for reproducible research" to the front page of those papers that adhere to these requirements and give more publicity to them over those that do not.

Noah's ecological ark is beginning to get crowded. However, ecologists, data curators, funding agencies, journals, and ecological societies need to adapt their mindsets, infrastructures, and approaches to fill this ark faster, with fewer biases, and more efficiently. A more coordinated effort between data contributors, curators, users, journals, and societies will result in much-needed interoperability. Ultimately, as Sir Tim Berners-Lee already anticipated (See his quote at the top of this manuscript), the inherent value of SPI-Birds (Culina *et al.* 2021) will grow exponentially when considered in conjunction with, for instance, the long-term trends of the insect populations that birds depend on (via InsectChange; Van Klink *et al.* 2021), human activities (via the Human Footprint Database; Venter *et al.* 2016), climatic patterns (via CHELSA; Karger *et al.* 2017), etc. The promise of big, open-access data in ecology is huge. We must endeavour, as a community, to deliver it.

DATA AVAILABILITY STATEMENT

The GPS data associated with Figure 1 of this manuscript are archived open-access in the respective databases.

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1   **Table 1.** A non-exhaustive list of data sources that contain open-access animal ecological data, with a focus on demographic and

2   life history traits. A more exhaustive account can be found in Stephenson & Stengel (2020).

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Data source	Description	Source
Amniote	Life history trait database of bird, mammal and reptile species	http://onlinelibrary.wiley.com/doi/10.1890/15-0846R.1/abstract
AnAge	Animal ageing and longevity database	https://onlinelibrary.wiley.com/doi/full/10.1111/j.1420-9101.2009.01783.x
BIDDABA	Bird demographic database	https://link.springer.com/article/10.1007/s10336-010-0582-0
BTO survey data	British Trust for Ornithology	http://www.bto.org/research-data-services/data-services
DATLife	Life tables of animals, as well as records of longevity	https://datlife.org/
CarniDiet	Diets for 103 species of terrestrial carnivores	https://onlinelibrary.wiley.com/doi/10.1111/geb.13296
COMADRE	Matrix population models for over 500 animal species worldwide	https://compadre-db.org/Data/Comadre

Coral Trait Database	Database containing, among other traits, life history trait information for over 1,500 coral species	https://coraltraits.org
EURING databank	Ringing recovery data of bird species across Europe	https://euring.org/data-and-codes/euring-databank
fishdata	A small collection of fish population datasets	https://cran.r-project.org/web/packages/fishdata/index.html
FishTraits	Ecological and life-history traits of fishes of the United States	https://pubs.er.usgs.gov/publication/70156095
Global Assessment of Reptile Distributions	Trait and geographic data on lizards	https://onlinelibrary.wiley.com/doi/full/10.1111/geb.12773
Global Population Dynamics Database (GPDD)	*Ca.* 5,000 time series of population counts of <1,400 species	https://knb.ecoinformatics.org/view/doi:10.5063/F1BZ63Z8
Human Cause-of-Death Database	Continuous human data series of causes of mortality for 16 countries	https://www.causesofdeath.org
Human Fertility Database	Period and cohort fertility data for human populations from 32 countries	http://www.humanfertility.org

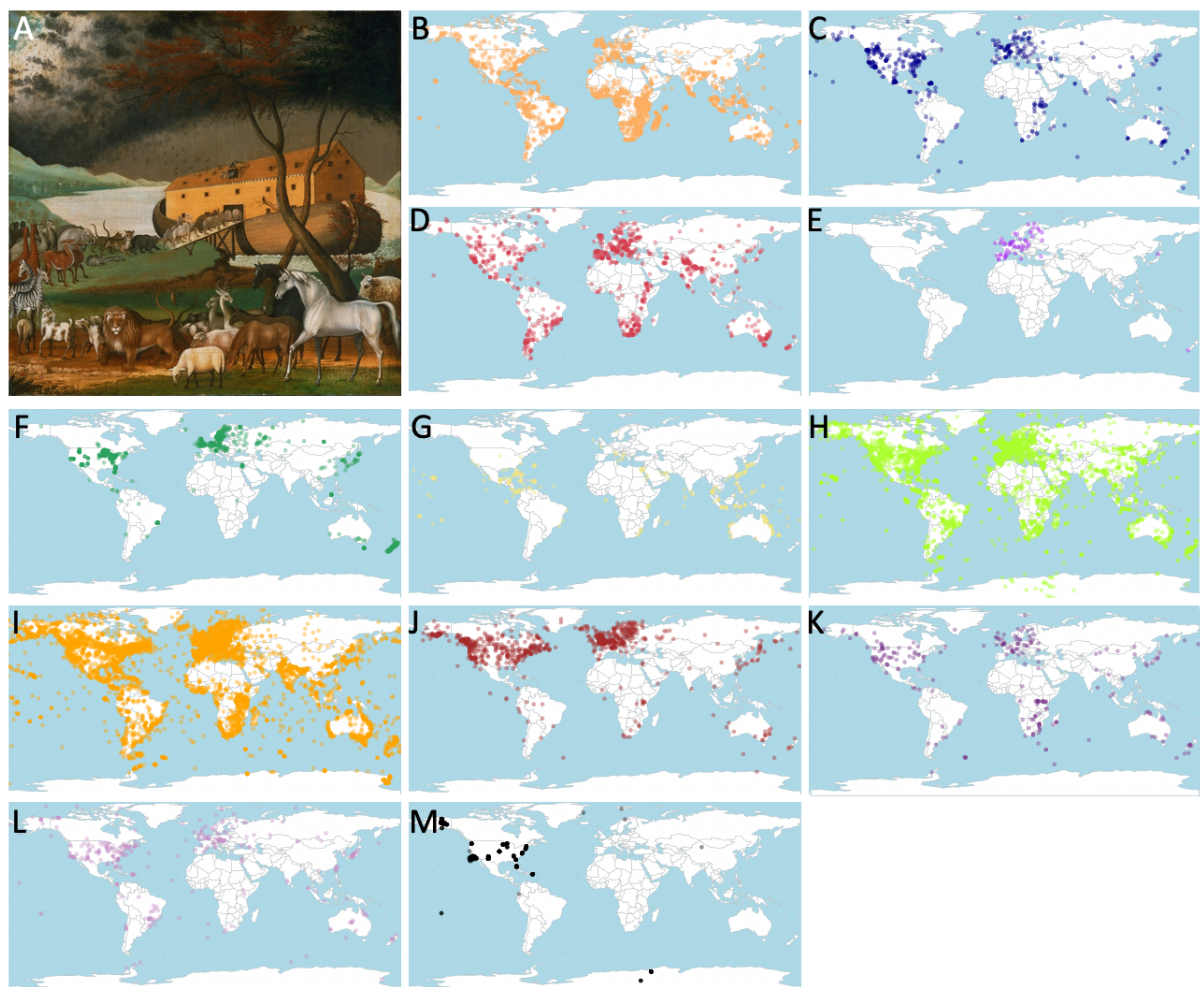|		
Human Life-Table Database	Collection of human population life tables for multiple years across 141 countries	https://www.lifetable.de/cgi-bin/index.php
Human Mortality Database	Human population size and mortality data for 41 countries	http://www.mortality.org
International Database of Longevity	Information about supercentenarians (humans of ages 110 and above) from 13 countries	https://www.supercentenarians.org
International Data Base	Demographic measures of human populations across 288 countries worldwide	https://www.census.gov/programs-surveys/international-programs/about/idb.html
LEDA	A database of life-history traits of the Northwest European flora	https://besjournals.onlinelibrary.wiley.com/doi/10.1111/j.1365-2745.2008.01430.x
Life-history trait database of European reptile species	A database of traits (activity, energy, movement, etc.) of European reptile species	https://datadryad.org/stash/dataset/doi:10.5061/dryad.hb4ht
Living Planet Index	Trends of 27,232 natural populations from 4,784 species through time around the world	https://livingplanetindex.org/home/index
Longevity Records	Life spans for mammals, birds, amphibians, reptiles, and fish	https://www.demogr.mpg.de/longevityrecords/

LTER	US Long Term Ecological Research Network, including long-term records of population size and individual records in some cases.	https://lternet.edu
MALDABBA	Age-specific vital rates and life history traits for >200 mammalian species	https://www.pnas.org/content/suppl/2020/03/18/1911999117.DCSupplemental
PADRINO	Database of integral projection models for hundreds of animals and plants around the globe	https://github.com/levisc8/Padrino.github.io
Pantheria	Mammal life history database	https://ecologicaldata.org/wiki/pantheria
SCALES	Securing the conservation of biodiversity across administrative levels and spatial, temporal, and ecological scales – A database of species traits	http://scales.ckff.si/scaletool/?menu=6
Serengeti bird species occurrence, abundance and habitat	Georeferenced occurrences for 568 species from 1929 to 2017. Records contain feeding location, food source, distribution status, observation locality	https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/ecy.2919

Serengeti: survey of age structure in ungulates and ostrich	Sample counts from 1926 to 2018 of 13 ungulate species and 1 ostrich species	https://www.nature.com/articles/s41597-020-00701-0
SPI-Birds	Database of bird breeding and mark/capture information	https://nioo.knaw.nl/en/spi-birds
TetraDENSITY	Population densities of >18,000 animal records worldwide	https://onlinelibrary.wiley.com/doi/full/10.1111/geb.12756
Traits	Freshwater biological traits database	https://www.epa.gov/risk/freshwater-biological-traits-database-traits

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5   **Figure 1. A**: A depiction of the religious allegory of Noah's Ark by painter Edward

6   Hicks (Source: Public via Wikipedia), which showcases human's unconscious bias

7   towards animal diversity: only large, charismatic mammals and –to a much lesser

8   extent– some birds are highlighted. These biases are prevalent in the collection of

9   long-term animal ecological datasets. **B-M**: Geographic representation of a selected

10 subset of long-term animal ecological databases for which GPS coordinates are also

11 available from Table 1. **B**. TetraDENSITY. **C**. COMADRE. **D**. CarniDIET. **E**. SPI-Birds.

12 **F**. InsectChange. **G**. Coral Trait. **H**. MoveBank **I**. Living Planet Index. **J**. GPDD. **K**.

13 MALDDABA. **L**. BioTIME. **M**. LTER (only animal data shown). For instance, large

14 areas of Latin America, Africa, and Asia are void of long-term animal ecological data.

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