

## RESEARCH ARTICLE

# The Movebank system for studying global animal movement and demography

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**Handling Editor:** Edward Codling**Abstract**

1. Quantifying movement and demographic events of free-ranging animals is fundamental to studying their ecology, evolution and conservation. Technological advances have led to an explosion in sensor-based methods for remotely observing these phenomena. This transition to big data creates new challenges for data management, analysis and collaboration.
2. We present the Movebank ecosystem of tools used by thousands of researchers to collect, manage, share, visualize, analyse and archive their animal tracking and other animal-borne sensor data. Users add sensor data through file uploads or live data streams and further organize and complete quality control within the Movebank system. All data are harmonized to a data model and vocabulary. The public can discover, view and download data for which they have been given access to through the website, the Animal Tracker mobile app or by API. Advanced analysis tools are available through the EnvDATA System, the MoveApps platform and a variety of user-developed applications. Data owners can share studies with select users or the public, with options for embargos, licenses and formal archiving in a data repository.
3. Movebank is used by over 3,100 data owners globally, who manage over 6 billion animal location and sensor measurements across more than 6,500 studies, with

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[Corrections added on 13 May, 2022, after first online publication: The copyright line has been changed.]

thousands of active tags sending over 3 million new data records daily. These data underlie >700 published papers and reports. We present a case study demonstrating the use of Movebank to assess life-history events and demography, and engage with citizen scientists to identify mortalities and causes of death for a migratory bird.

4. A growing number of researchers, government agencies and conservation organizations use Movebank to manage research and conservation projects and to meet legislative requirements. The combination of historic and new data with collaboration tools enables broad comparative analyses and data acquisition and mapping efforts. Movebank offers an integrated system for real-time monitoring of animals at a global scale and represents a digital museum of animal movement and behaviour. Resources and coordination across countries and organizations are needed to ensure that these data, including those that cannot be made public, remain accessible to future generations.

#### KEYWORDS

animal behaviour, animal tracking, bio-logging, cyberinfrastructure, FAIR data, GPS, live data, movement

## 1 | INTRODUCTION

Tracking free-ranging animals with animal-borne electronic tags is a primary method for studying animal behaviour and ecology. Early advances in radio telemetry allowed biologists to locate free-ranging animals (Cochran & Lord, 1963) and monitor aspects of their physiology (Lord et al., 1962), but the field was limited for decades by the short range of VHF radio signals and high labour costs required to manually collect the data (Wikelski et al., 2003). The proliferation of GPS technology in the 2000s allowed the automated location of animals at a global scale, while the continued miniaturization of electronics increased the diversity of species that could be tracked (Kays et al., 2015). Not all species can be tracked by satellites, leading to the development of acoustic telemetry for aquatic species (Crossin et al., 2017) and light-level loggers and time of arrival systems for very small species (Lisovski et al., 2020; Weiser et al., 2016). The information available from tracking tags has also diversified through additional sensors documenting animal behaviour, energy use, physiology and surrounding environmental conditions (Brown et al., 2013; Treep et al., 2016). Likewise, publicly available information describing the environment through which animals are moving has grown immensely through remote sensing and weather reanalysis products (Dodge et al., 2013). Many tracking tags transmit data remotely through a growing variety of communication methods, including satellites, GSM and local area networks. These technological innovations have catapulted animal tracking into the realm of 'big data' ecology (Kays et al., 2020), enabling new discoveries, novel conservation strategies and the burgeoning field of movement ecology (Nathan & Getz, 2008).

While the scientific opportunities of big data animal tracking have been celebrated as a new 'golden age' (Kays et al., 2015; Wilmers et al., 2015), the associated challenges for data management have not

received as much attention (but see Campbell et al., 2016; Sequeira et al., 2021). Using the four Vs framework (Volume, Variety, Veracity and Velocity; Farley et al., 2018), we give examples of aspects of modern animal tracking that create challenges in data management not faced by traditional approaches (Table 1). The cumulative effect of these factors is that big data typically 'exceeds the capacity or capability of current or conventional methods and systems' (Ward & Barker, 2013).

Scientists recognized the need for solutions to these challenges early on, drawing on the rapidly advancing technology and software advances in informatics (Urbano et al., 2010). Custom tracking data platforms have been developed to accompany specific tracking devices (e.g. UvA Bird Tracking System, [www.uva-bits.nl](http://www.uva-bits.nl)), to enable joint data management across specific regions (e.g. the IMOS Animal Tracking Database, <https://animaltracking.aodn.org.au>; U.S. Animal Telemetry Network, Block et al., 2016) and taxonomic groups (EuroDeer, Cagnacci et al., 2009). These platforms have met the initial challenge of managing large datasets that came with the advent of modern tracking methods and offer a variety of features that serve researchers specific to their scope and purpose. However, solutions are needed for data owners who do not fall into these groups, and to support global initiatives and organizations collecting tracking data across geographic, taxonomic and methodological domains.

To address these challenges, we created the Movebank ecosystem of tools ([movebank.org](http://movebank.org)), providing a wide range of services to acquire, manage, share, visualize, analyse, discover and archive animal tracking data. This information-technology ecosystem has grown over the past decade in response to user needs and collaboration with researchers, wildlife managers, conservation groups, tag manufacturers and the public, including citizen scientists. While Movebank was formed in 2008, formal description has been limited to the data model (Kranstauber et al., 2011), the EnvData System (Dodge et al., 2014)

TABLE 1 Challenges of big data animal tracking described using the Four Vs Framework (Farley et al., 2018)

Category	Specific challenges for working with big data from animal tracking
Volume	<ul style="list-style-type: none"> <li>• GPS locations collected at shorter intervals (e.g. 1.6 M GPS fixes at 1 Hz, Sherub et al., 2016)</li> <li>• Other sensor data collected at high resolution (e.g. 7.3 M measures of 3-axis accelerometry data from 43 individual birds, Fiedler, Flack, Schäfle, et al., 2019)</li> <li>• More individual animals being tracked simultaneously (e.g. 26 baboons <i>Papio anubis</i> from the same troop resulting in 10 M locations, Crofoot et al., 2015)</li> </ul>
Variety	<ul style="list-style-type: none"> <li>• Dozens of tag manufacturers, multiple localization technologies and many data platforms with no shared industry or domain-wide data standards (Sequeira et al., 2021)</li> <li>• Multiple sensor types for monitoring animal behaviour, physiology and environmental conditions (Flack et al., 2015)</li> <li>• Thousands of environmental variables from remote sensing and weather data products available to relate to animal movement data (Dodge et al., 2013)</li> </ul>
Veracity	<ul style="list-style-type: none"> <li>• Quality control needed to address location outliers and low-accuracy measurements (Douglas et al., 2012)</li> <li>• Critical details of the tracked animal (species) and deployment (date and time of attachment) require curation (Sequeira et al., 2021)</li> </ul>
Velocity	<ul style="list-style-type: none"> <li>• Live data streaming through a variety of communication networks (satellite, phone) and telemetry platforms (Motus, Ocean Tracking Network)</li> <li>• Wildlife management methods that leverage increased speed in data transmission for rapid response (Sheppard et al., 2015)</li> </ul>

and one quality control filter (Douglas et al., 2012). Therefore, our goals in this paper are to describe both the fundamental infrastructure of Movebank as well as recent extensions. Movebank can manage data collected using all common animal tracking methodologies and maintains automated near-live data feeds for over 21 manufacturers using 7 different communication networks. Data are managed through a PostgreSQL database, backed up and secured through user-defined sharing settings. Data are accessible through a website with a graphical user interface (GUI), a mobile app, application programming interfaces (APIs) and a set of community-built analytical apps, including the `MOVE R` package (Kranstauber et al., 2020). These tools are freely and openly available to the scientific community, government agencies and other institutions. Here we describe the system and innovative applications for research and wildlife monitoring that it enables. We illustrate how they work together with a long-term monitoring and life-history study of white storks *Ciconia ciconia* across three continents.

## 2 | MATERIALS AND METHODS

The components of Movebank used to acquire, manage access to and utilize animal tracking data are illustrated in Figure 1 and described below.

### 2.1 | Database

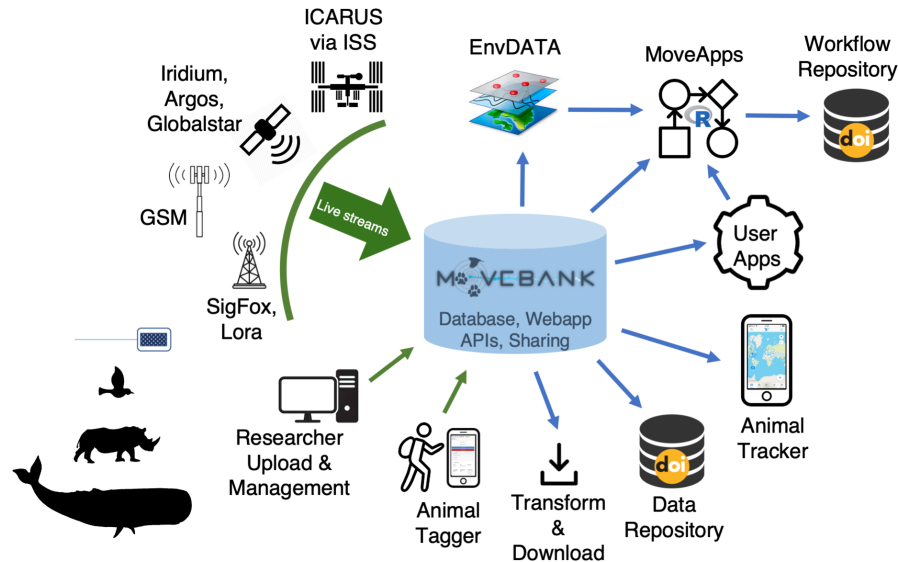
Movebank is designed to work with data from any animal-borne sensor (i.e. wearables for wildlife) that includes a timestamp and relocations or other sensor measurements representing individual animals (i.e. 'tracking data'). While GPS data are the most common, this includes movements recorded using Argos, VHF and

acoustic telemetry, geolocation (light-level logging), and relocations of bird bands, and data collected by accelerometers, barometers, gyroscopes, magnetometers, thermometers embedded into animal-borne tags. The PostgreSQL database is stored on servers at the Max Planck Computing & Data Facility in Garching, Germany. All components of Movebank are centred around the database, which harmonizes all data to a shared data model (Kranstauber et al., 2011) and vocabulary (Max Planck Institute of Animal Behavior, 2021). All data are stored as user-created studies, which include the event and reference data, study-level metadata and data access permission settings (Figure 2a). This design allows owners to work independently, maintaining flexibility and control over their data.

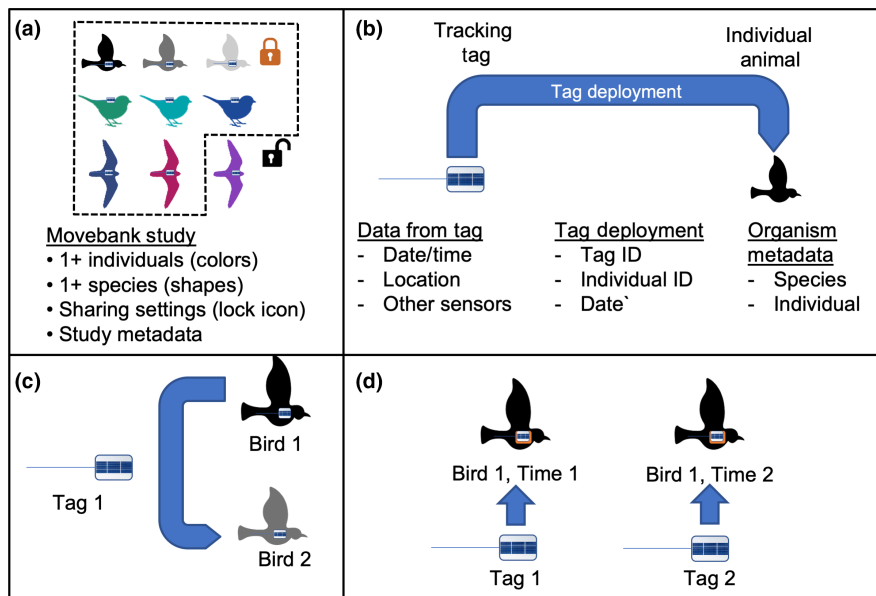
The Movebank data model (Figure 2) relates *events* (timestamped data records) to a *sensor* on a *tag*, and associates *tags* to *animals* with *deployments*. Event records include a timestamp along with one or more measurements or estimates, which can include the location (longitude, latitude) and over 200 other attributes including elevation, depth, acceleration, heart rate, light level, magnetic field and quality indicators. If the tag includes multiple sensors that record information on different duty cycles, events can be stored in separate tables for each sensor, allowing more efficient storage and analysis.

Deployment-level records, that is, *reference data*, define when a tag was deployed on an animal and are used to relate event records with the individual being tracked. These records can also include information about animals (taxon, sex, mortality), tags (manufacturer, model), captures (deployment site, animals' condition and morphometrics) and methodology (duty cycle, attachment technique) needed to interpret the event data.

This Movebank data model allows management of multi-sensor datasets and multiple deployments of different tags and animals over time (Figure 2). Together, the data model, vocabulary and studies provide a shared format for data storage and access control that all other components of the system can rely on.



**FIGURE 1** The Movebank cyberinfrastructure ecosystem of tools to acquire, manage and analyse animal tracking data. Location information from animal-borne tags is acquired through live streams using one of seven communication networks or imported by researchers. The 'Animal Tagger' app can be used to record and transmit capture data in the field, and the 'Animal Tracker' app can be used to view animal movements in near real-time, as well as encourage citizen scientists to observe and recover data from tagged animals. Researchers maintain full ownership of their data and can use Movebank's collaboration tools to securely share data with others, make them publicly available for viewing or download, or formally archive them with a DOI and citation. Movebank's APIs allow researchers to directly access their data through custom protocols or community-built apps, and also connect with the EnvDATA System for environmental data annotation and the 'MoveApps' platform for no-code analyses



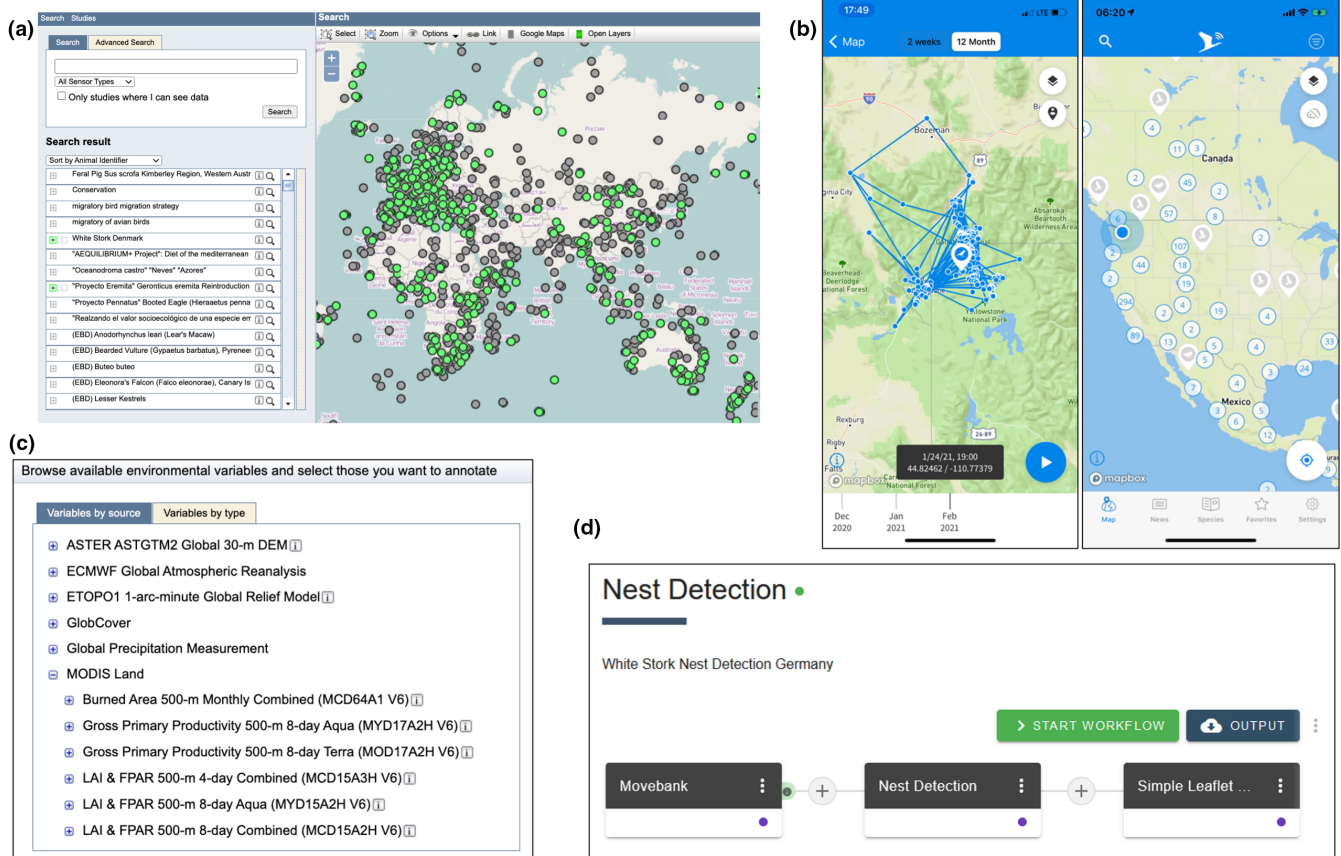
**FIGURE 2** Data in Movebank are organized into owner-managed studies (a) which can include multiple individuals and species, along with data sharing settings and project metadata. The Movebank data model (b) associates event records with sensors on tags, and links tags with animals through deployments. This allows the same tag to be deployed on multiple animals over time (c), or multiple tags to be deployed on the same animal over time (d)

## 2.2 | Web application

The Movebank website ([movebank.org](http://movebank.org)) provides a central place for documentation and a core web application (hereafter 'webapp') that supports data import, mapping, management, discovery and access (Figure 3). This is the platform through which most data owners manage projects and data, and through which the public can browse data, connect with owners and access data for which they have appropriate permissions.

## 2.3 | Application programming interfaces

Movebank's HTTP- and JSON-based RESTful APIs support transfer of data into and out of Movebank, thus allowing automated interactions with tag manufacturers, analysis software, other websites and mobile apps and advanced users. These allow development of third-party applications and provide scaling to transfer large volumes using automated procedures. All data transfer by API is subject to the same data model and access permissions as the database and webapp.



**FIGURE 3** Examples of Movebank's graphical user interfaces (GUIs) showing (a) the map view for visualizing tracks. The Animal Tracker mobile app (b) can be used to view data in the field and report back notes or photos about tracked animals. It works off-line and can resync when back in network. The EnvDATA System (c) annotates location data with remote sensing data. One example workflow from the MoveApps system (d) shows Apps combined to access data from Movebank, identify nest sites, and visualize results

### 2.4 | Sharing and security

Those who collect tracking data maintain ownership over the data stored in Movebank, with flexible tools to administer data sharing within each study through user roles and terms of use. Movebank's Data Policy strongly encourages public data archiving in Movebank, while recognizing that many studies are still in progress and that some data access is restricted due to permits, funding, organizational policies and legislation. Furthermore, location data for some species can be sensitive, and making it freely available could put animals at risk of harassment or death (Lennox et al., 2020). Thus, data security is of highest priority, and our development process follows state of the art best practices (e.g. OWASP; <https://owasp.org/www-project-top-ten>). Furthermore, we have implemented an access control mechanism so that the application and database servers are not directly reachable from the internet, but are protected behind a reverse proxy. Finally, Movebank is hosted by a secure data facility in Germany, with backup copies in multiple locations.

There are three user roles in Movebank (Table 2): Data Managers, Collaborators and the public. The user who creates a study becomes a Data Manager for that study and can assign other registered users as Data Managers or Collaborators. Data Managers for a study can

**TABLE 2** Roles within Movebank and their data access

Role	Edit	Download	See map	See study summary
Data Manager	Yes	Yes	Yes	Yes
Collaborator	No	Optional	Optional	Yes
Public	No	Optional	Optional	Yes

The colours shading pink indicates No; green indicates Yes; yellow indicates Optional.

choose to allow Collaborators or the public to view locations within the webapp or download data. Owners choose a Creative Commons license for publicly downloadable data and define terms of use for controlled-access data.

### 2.5 | Data import

After creating a study and defining sharing settings, data owners can import data by uploading data files in standardized (e.g. Argos DIAG files) or custom tabular text (e.g. CSV) formats and mapping each data field to

Movebank's vocabulary (Max Planck Institute of Animal Behavior, 2021) within the webapp, including format and unit conversions to harmonize values. For deployed tags, users can subscribe to import data through automated, manufacturer-specific feeds. Due to the lack of data standards across biologging devices and platforms (see Sequeira et al., 2021), each feed requires custom development and curation to transmit and correctly read data. There are currently 21 data feed providers that transfer data transmitted through seven communication networks: Argos, Global Star, GSM, Icarus, Iridium, LoraWAN and SigFox (Figure 1). Reference data about the animals, tags and deployments can be loaded through the webapp or using the Animal Tagger mobile app (Figure 3).

## 2.6 | Data management

Once data are imported, the webapp offers tools to manage and edit event and reference data and to upload additional ancillary data files associated with the study, such as image files and analysis scripts. Data owners can view and edit deployment periods and reference data in the Deployment Manager, and interactively view and edit event data as a table and map in the Event Editor. A key quality control step for animal tracking data is to identify and flag location outliers, typically low-quality or erroneous estimates from the sensor. Movebank has implemented filters that detect outliers based on duplicate values, speed between consecutive locations and values in any data field, as well as filters specific to Argos Doppler-based location estimates (Douglas et al., 2012).

## 2.7 | Data archiving

Movebank promotes FAIR Principles (Wilkinson et al., 2016) to improve the findability, accessibility, interoperability and reuse of data, and to minimize eventual loss of access-controlled data. Movebank's Data Policy asks all data owners to create an archiving plan to ensure data availability for future beneficial use. This includes steps to ensure that data can be understood (e.g. quality control, sufficient study-level metadata and reference data describing the study animals and methods) and accessed (i.e. made public, and for cases when this is not possible, implementing a chain of ownership to address future requests for use). Recommendations for specific tracking methods have also been developed in coordination with domain experts (e.g. Lisovski et al., 2020). Movebank's user manual, archiving and citation guidelines, terms of use and user agreement help data owners to implement archiving plans and ensure appropriate data reuse.

Data managers can choose to make the data publicly available by allowing public download and choosing a Creative Commons license (CC0, CC BY or CC BY-NC) to provide clear and globally applicable terms of reuse. Embargo options allow Data Managers to prohibit public access to recent data (30 days to 3 years) or to schedule a future date on which data will be made public.

Movebank's formal archiving tool is the Movebank Data Repository, through which data from Movebank studies can be

published and receive a DOI, citation, Creative Commons Zero license, persistent link and DataCite metadata. This process makes published datasets discoverable through resources such as Web of Science and Google's Dataset Search. The Repository is hosted by the Communication, Information, Media Centre of the University of Konstanz (<https://www.kim.uni-konstanz.de/en/>), Germany, runs on DSpace-based software and follows the model of Data Dryad (<https://datadryad.org/>) in publishing packages of data files that are described in a public written work, typically a peer-reviewed journal article. All published datasets are first reviewed within Movebank to ensure that the data are organized in line with the archiving best practices described above.

## 2.8 | Discovery and outreach

The Movebank database allows for data discovery and access, as well as public engagement. Within the webapp (Figure 3) the public can search for studies, view tracks and download data if allowed by the data owners, and contact data owners to discuss their research or possible uses. Data can be transformed and downloaded from the webapp in a variety of formats. The webapp is used by the research community, conservation organizations, journalists, students and the public to find data and data owners. In addition, the APIs support basic queries and data access for advanced users and allow development of discovery and data access tools within other applications, broadening possibilities for collaboration and analysis, including real-time applications.

## 2.9 | Animal tracker

The Animal Tracker mobile application (Figure 3) offers a public- and smartphone-friendly discovery and citizen science tool designed for following movements of currently deployed tags. Data owners can choose to send their data to the app and share it publicly or privately (i.e. to support fieldwork). Data visualizations, animations and citizen science features support use in areas with little or no internet connectivity. Users can report observations of animals, including a description of their activities and photographs, and receive alerts about potentially dead or sick animals so that they can help recover the transmitter and report what they find. Using the 'Guardian Mode', researchers can allow access to specific devices to allow partners in the field view and follow protected animals. Such a system is, for example, implemented within Kruger National Park's rhino observation and protection group.

## 2.10 | Env-DATA system

The Environmental-Data Automated Track Annotation System (Env-DATA) allows users to acquire environmental data needed to contextualize animal movements and behaviour. Users choose from

hundreds of environmental parameters provided by global remote sensing products and weather reanalyses (Dodge et al., 2013) to annotate to tracking data, and Env-DATA accesses and transforms data from providers and interpolates values in space and time to the animal locations (Mandel et al., 2011). To support analysis across the field of movement ecology, specifically hypothesis testing, visualization and input to resource selection functions, Env-DATA also allows annotation of generic time-location records, such as simulated tracks, hypothetical 'available' records and gridded raster data. Users can submit annotation requests through a GUI (Figure 3) by browsing available products and variables, or through an API that allows automated annotation requests for advanced users.

## 2.11 | Data analysis and the MoveApps analysis platform

There are a large variety of analysis options for animal movement data and we maintain links on our website to relevant software (<https://www.movebank.org/cms/movebank-content/software>) and training resources (<https://www.movebank.org/cms/movebank-content/teaching-and-training>). The most popular analytical platform for movement ecologists is program R, with 58 related packages identified by Joo et al. (2019). To make these tools more accessible to our users we created MoveApps ([moveapps.org](https://moveapps.org)), a no-code analysis platform to analyse data from Movebank using analytical modules (Apps) linked together into workflows (Figure 3f). For the launch of the platform in February 2021, we created a set of initial Apps supporting common analysis needs (mapping migratory movements (Kölzsch et al., 2021), providing a daily 'Morning Report' for currently tracked animals (Kölzsch & Wikelski, 2021), and identifying nest sites) that will grow through further development and App contributions from the broader community in R and other languages. Apps need movement data input but are otherwise not limited in their type of analysis or complexity, and any existing R packages can be integrated. MoveApps thus empowers developers to share Apps that analyse and visualize tracking data from Movebank and empowers biologists without coding experience to access state-of-the-art analysis tools. Source code for Apps are managed in public Git repositories and include information to ensure correct use and reproducibility, adhering to open science policies, and are then reviewed and released by the MoveApps core developers. These workflows can be scheduled to provide regularly updated results, shared with others, and publicly archived with a DOI and citation in the Movebank Data Repository. Archived workflows include metadata about the workflow itself, such as involved people, Apps and configuration parameters used, as well as the source code and metadata for each App, including copyright and terms of use, citation, dependencies and the complete runtime environment information (for reproducibility).

The architecture of MoveApps allows users to combine modules virtually, independent of the programming language barriers and operating systems. It is a serverless cloud computing facility based on docker containers that can be scaled to community needs and

provide computing power to researchers who might not have such facilities at their home institutions.

## 2.12 | Permits

The tracking of White Storks was carried out under the species protection and animal welfare permits required in the respective countries: G-13/28, G-15/47, G-20/54 by Regierungspräsidium Freiburg; MPI-O 1/14, 35-9MPI-O-1/19 by Regierungspräsidium Tübingen; 42/553-253 by Landesuntersuchungsamt Koblenz; 54-2532.1-14/14 by Regierung von Oberfranken; ROB-55.2Vet-2532. Vet\_02-17-95, 55.2-1-54-2532-22-2015 by Regierung von Oberbayern; Regional Directorate for Environmental Protection (WPN.6401.50.2014. WL) and the Local Ethical Committee on Animal Experimentation in Białystok (73/2013).

## 3 | RESULTS

Since Movebank was established in 2008 it has grown into a global scientific resource used by over 3,100 data owners who manage animal tracking data for over 1,100 species across 6,500 studies. Movebank presently grows by over 3 million new data records daily, with more than 9,000 active tags sending data through live feeds. The database presently contains over 3 billion location records and 3.3 billion records from other animal-borne sensors. Data are publicly downloadable from ~9% of studies and tracks can be publicly viewed for ~16% of studies. Over 700 papers and reports are cited in publicly discoverable studies, and nearly 700 data authors have published 235 datasets in the Movebank Data Repository, providing public and citable data associated with peer-reviewed research. Env-DATA serves over 300 users to meet ~20 annotation requests daily. The Animal Tracker app has over 220K users, 99.9% of whom are non-scientists (i.e. without a linked Movebank account), who have made over 2,500 reports on 559 tracked animals from 120 different studies. Below we present results that highlight the benefits of an integrated system and reflect a wide variety of scientific applications.

### 3.1 | Case study: Life histories and mortality of migrating birds

With the detail provided by modern tracking tags, it is increasingly possible to study aspects of animal demography remotely and in real time, including nesting, migration, dispersal and mortality (Collins & Kays, 2011; Picardi et al., 2020). The global coverage and integrated nature of Movebank, combined with automated data streams, increase the scale and efficiency of such work and are particularly important for studying animal mortality. First, a possible death of a tagged animal can be detected by the sudden clustering of GPS locations and used with patterns in other sensor data (e.g. 3D acceleration and temperature) to distinguish between scenarios

of tag detachment, technical failure and/or mortality (Figure 4a). For tags streaming data to Movebank, researchers can detect mortalities by executing the Morning Report workflow in MoveApps, which can be scheduled to run daily to visualize the latest data and flag potential mortalities through user-set thresholds. For publicly visible projects, researchers can request an alert be sent to all users of the Animal Tracker app asking for help in locating their downed tag (Figure 4b). Local researchers or citizen scientists can then use the Animal Tracker app to navigate to the animals' last known location and conduct a forensic investigation. In the first 6 months after this alert feature was released, researchers sent 15 potential bird mortality events to users of the Animal Tracker app, resulting in seven tags being retrieved from four countries. Users shared information about the tag and/or mortality with scientists through the app, helping them to ascertain the likely cause of death. In two cases, live birds were found in precarious situations and rescued by local citizens.

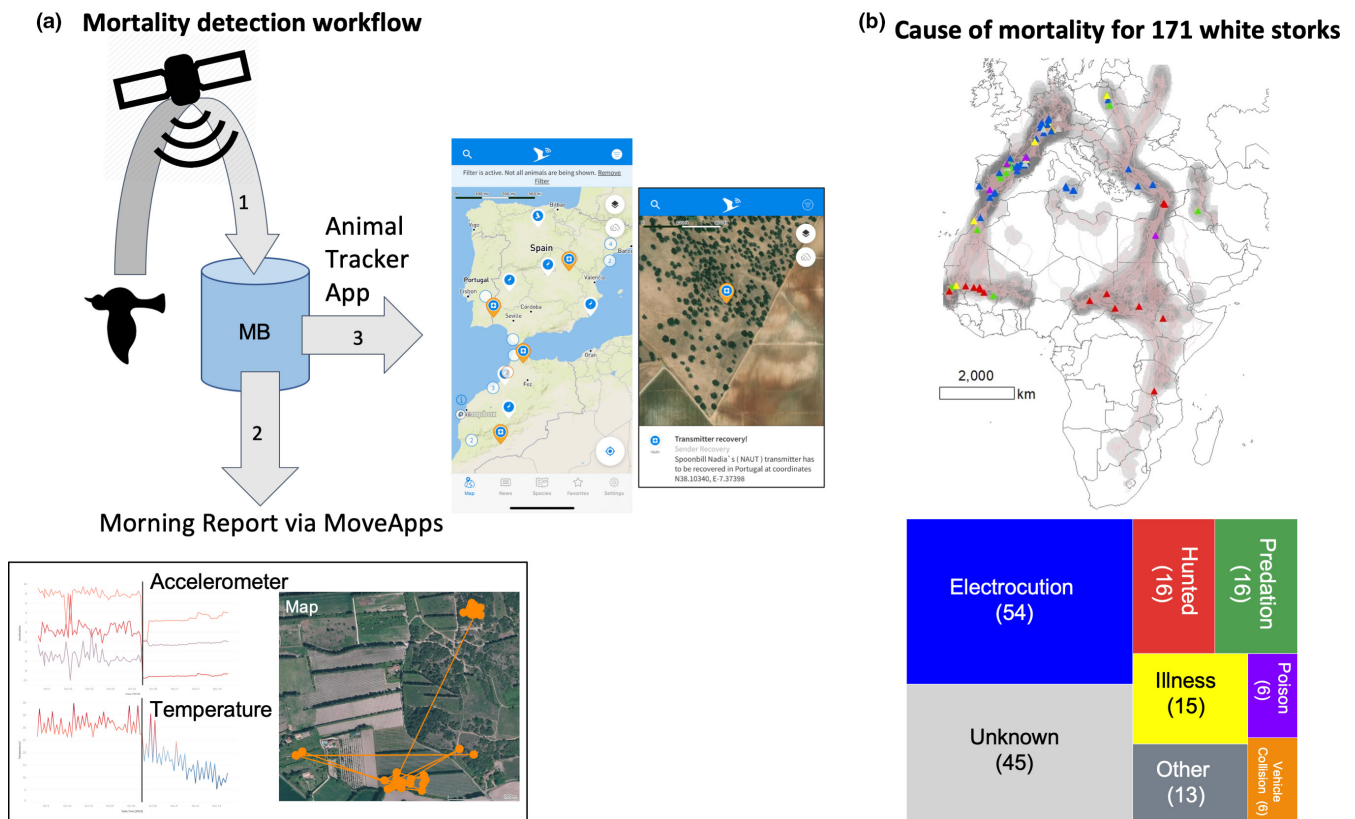
Results from 171 white storks (see Data Availability Statement) tracked from tag deployment until death included fate determination for 74% of animals, with the most common cause of death (31%) being electrocution from landing on power lines (Figure 4b). Cause

of death differed by region, with most deaths in Europe by electrocution and most deaths in Africa due to hunting.

The long life span of solar-powered tracking tags enables the use of Movebank tools to remotely collect a variety of demographic data as shown by our case study of 20 white stork tracked from their natal nests in southern Germany through their fourth year of life. We found that juvenile storks migrate more slowly and winter farther from their breeding grounds than older birds (Figure 5a,b), and that mortality was much higher in the first year of life (Figure 5d). Using the Nest Detection workflow in MoveApps, we characterized nest attempts using movement patterns (Figure 5e, Picardi et al., 2020), documenting the location of 40 nest attempts by 14 birds, and allowing us to calculate their dispersal distances. While most breeding events were within 25 km of their hatching site, some were 100s of km away (Figure 5f).

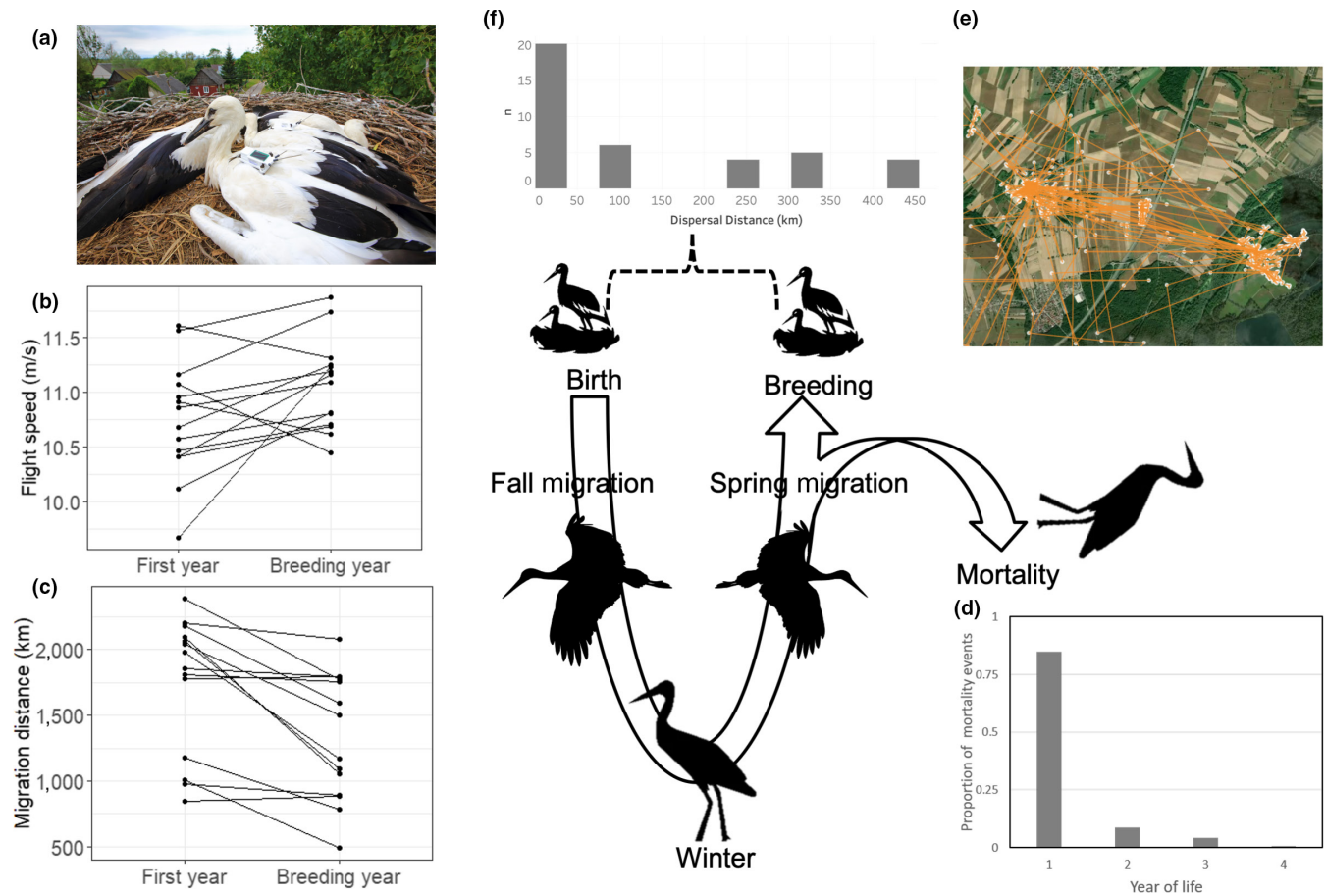
## 4 | DISCUSSION

As branches of biology move into the realm of big data, new data infrastructures are needed to help scientists take advantage of



**FIGURE 4** (a) Using Movebank to study animal mortality at a global scale is enabled by a workflow consisting of (1) near real-time automated data transfer through wireless networks to the Movebank database where (2) an automated daily 'Morning Report' through the MoveApps platform that alerts researchers to the possible death of an animal through sensor streams (examples from a Eurasian blackbird *Turdus merula* with vertical black line indicating time of death). This location is then accessible to staff, collaborators or citizen scientists through the (3) Animal Tracker app so they can conduct a forensic investigation at the site. (b) Results of this approach for 171 storks tracked across Europe and Africa. Shading on the map shows density of tracking locations, pink lines show individual bird tracks and coloured triangles show the location and cause of mortality events





**FIGURE 5** Life-history data from the full annual cycle of white storks from tracking data managed in Movebank. (a) Juvenile storks are tagged in their nest. Young animals are less efficient fliers in their first migration (b), fly longer distances to their wintering grounds (c), and have lower survival (d, see also Figure 4). Nesting attempts can be detected from movement patterns clustered around the nest site (e) and used to estimate dispersal distance (f). Photo by C. Ziegler

these big-volume, large-variety, high-velocity, questionable-veracity datasets. We have built Movebank to address this need for animal tracking and biologging data, providing tools and services to work with data throughout their life cycle from collection to archiving and reuse, and offering tools for basic research as well as applied management and conservation. The system handles management of high-volume, complex datasets during and after data collection, and makes state-of-the-art exploration and analysis available to users around the world through Env-DATA and the new MoveApps platform. Data owners control access to their data through flexible permissions settings and guidance for data sharing, archiving, use and attribution.

Our case study with storks illustrates the broad range of life history and demographic information that can be obtained through modern tracking data, including dispersal, migration, breeding and mortality—even for a transcontinental migrant. The combination of live data streams, interactive visualizations and audience of citizen scientists using the Animal Tracker App has enabled global-scale research, public engagement and applied conservation and management. For example, the poaching of GPS-tagged cranes in Pakistan and the shooting of GPS-tagged European bald ibis (Wald, 2012)

induced public outcries and led to changes in local or state-wide hunting laws (Rauch, 2017). We expect that movement ecologists will continue to devise creative applications using Movebank and hope that Movebank will help more people connect with the amazing stories of tracked animals and strengthen conservation efforts around the world.

As more animal tracking data are collected and made accessible through Movebank, the scale, diversity and relevance of use cases continue to grow. Movement ecologists are conducting large-scale comparative analyses, leading to discoveries about animal movement syndromes (Abrahms et al., 2017) and influences of climate (Davidson et al., 2020) and anthropogenic disturbance (Tucker et al., 2018) on animal behaviour. Through data harmonization and discovery tools, live data feeds, and the growing community of scientists who use them, Movebank is uniquely placed to facilitate collaborations and host project and government archives (Figure 6a). Data owners and potential users can independently initiate discussions about data sharing and use, execute projects and create archive-quality studies. For example, projects led by the British Trust for Ornithology, EURING, Migratory Connectivity Project, National Audubon Society, Smithsonian Institution and UN Convention

on Migratory Species are currently acquiring avian tracking data through Movebank to develop dynamic visualizations, analyses and mapping tools for migratory birds for public outreach, engagement and conservation (Figure 6b). The Arctic Animal Movement Archive (AAMA), launched in 2020 and hosted on Movebank, provides a 'living' archive supporting collaborative work across hundreds of researchers with data from the Arctic and Subarctic extending back to the 1980s (Davidson et al., 2020). Movebank is partnering with the Covid-19 Bio-Logging Initiative, coordinated by the International Bio-Logging Society, by helping analysts discover and access data on animal movements and behaviour being collected during the Anthropause caused by the Covid-19 pandemic, while data collection for other purposes, and the Anthropause itself, are still underway (Rutz et al., 2020). Numerous government agencies use Movebank to manage data, and some, including the bird ringing scheme for France (CRBPO) and Wyoming Game and Fish Department (WGFD, Figure 5c), use it as a data deposition platform

to meet legal requirements for archiving data collected by permittees. Data in Movebank can be securely shared with relevant agencies as an alternative to developing new agency-run databases.

We believe the MoveApps platform will accelerate scientific discovery through several innovations. First, its no-code GUI will make analytics more accessible to ecologists less comfortable with command-line programming. Second, by breaking workflows into a series of Apps, the platform will help users understand the component steps typically involved in more complex analytics. Third, searchable and citable Apps and workflows will help practitioners explore the rapidly growing options for analyses of movement data (Joo et al., 2019) and provide recognition for App developers. Our goal is for MoveApps to bring together two communities that often have little overlap: programmers providing analytical tools and data owners, particularly wildlife managers, who need software solutions to derive knowledge from complex data. We hope this concept of a flexible and integrative cloud-based analytics, deliberately designed to accommodate open



**FIGURE 6** Use cases for Movebank are diverse as the tool facilitates secure sharing of tracking data across studies, enabling broad temporal and taxonomic comparisons. (a) Reference locations for 4,835 publicly discoverable, user-managed studies reflect the platform's global reach. (b) Migration routes of the Swainson's hawk from the National Audubon Society's new Bird Migration Explorer, compiling data obtained through BirdLife International, eBird and Movebank (Bird Life International, 2020; Bradbury et al., 2020; Fink et al., 2020; Fleishman et al., 2016; Kochert et al., 2011). Agencies including the Wyoming Game and Fish Department (WGFD) use Movebank to manage data collected by their permittees, as shown by a map of the WGFD-permitted projects (c). Most projects allow the public to view a written summary (grey dots) or view but not download data (green dots), with all data accessible to the agency (photographs from WGFD)

science, can serve as a model for research infrastructure applications in other disciplines.

The Movebank database has grown into an ecosystem of tools through broad collaborations and funding from agencies around the world. While early animal tracking data were primarily of interest to those studying and monitoring animal behaviour, the transition of movement ecology to a big data field has broadened the applications of these data to the fields of conservation, ecology, physiology and evolution. Continued technological development and standardization should further extend interest in these data to fields of meteorology, earth science and oceanography (Sequeira et al., 2021). As the size and expense of tracking tags shrink, we will have more opportunities for comparative approaches that have been useful in other areas of biology, but only recently applied to animal movement. As battery life extends, we will increasingly have lifetime tracks of animals, along with extended life histories documented through photographs, field notes, citizen scientist observations, and eventually, the animal itself as a museum specimen.

H.H. Brimely, the first director of the North Carolina Museum of Natural Sciences, said 'A finished museum is a dead museum, and such a one must deteriorate and begin to lose usefulness from the time its growth stops' (Brimley, 1902). The same could be said for modern biological cyberinfrastructure, in particular those intended to serve as data repositories or archives. These require constant development, not just to maintain the status quo (e.g. software and security upgrades), but also to keep pace with the changing needs of scientists and conservation managers working at the cutting edge of their field. In addition to technology upgrades, digital collections need curators and outreach specialists to make sure the collections are preserved, relevant, accessible and provide context for interpretation. As with the physical infrastructure of natural history museums and physical specimens, we see a mixture of funding models needed to maintain Movebank and other biodiversity data infrastructures like eBird, Wildlife Insights, iNaturalist and GBIF. The rapid growth of these 'born digital' records of biodiversity make them challenging to maintain, but more important than ever, given the rapid pace of change to our planet (Kays et al., 2020).

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## CONFLICT OF INTEREST

M.B., J.H., C.H., D.G. and F.S. are employed by a private company or non-profit organisation.

## AUTHORS' CONTRIBUTIONS

R.K., S.C.D. and M.W. are the co-PIs of Movebank and led the writing of this paper; M.B., J.H., C.H., D.G., B.R., G.S., I.L., F.S., G.S., M.L., M.S. and R.W. work on the technical implementation of Movebank tools; W.F., G.B., A.K., A.F., A.L., J.P., M.Q., K.S., A.S. and C.V. work on the biological implementation of Movebank tools. All Authors contributed to the manuscript.

## PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/2041-210X.13767>.

## DATA AVAILABILITY STATEMENT

White stork tracking and mortality data: Publicly available on Movebank in the 'LifeTrack White Stork' studies for Armenia (Study ID 10236270, Flack et al., 2015), Bavaria (ID 24442409, Fiedler, Flack, Schäfle, et al., 2019), Greece (ID 10449535, Flack et al., 2015), Kosova (ID 175720577, Maxhuni et al., data to be published upon paper acceptance), Moscow (ID 10596067, Fiedler, Flack, Schäfle, et al., 2019), Oberschwaben (ID 212096177, Fiedler et al., 2019b), Poland ECG (ID 25166516), Rheinland-Pfalz (ID 76367850, Fiedler, Hilsendegen, et al., 2019), Sicily (ID 79206236, Grasso et al., data to be published upon paper acceptance) and SW Germany (ID 21231406, Fiedler, Leppelsack, et al., 2019). Tracking data participating in the AAMA (Figure 5a): See data access instructions at [www.movebank.org/cms/movebank-content/arctic-animal-movement-archive](http://www.movebank.org/cms/movebank-content/arctic-animal-movement-archive). MoveApps Apps and links to source code are publicly available from <https://moveapps.org>.

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