


APPLICATION

ECODATA: A toolbox to efficiently explore and communicate animal movements alongside environmental and anthropogenic context using geospatial big data

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Abstract

1. Integrating complex geospatial data into research and applications for wildlife ecology remains a challenge. For example, animations of wildlife tracking data can be useful for developing hypotheses, communicating with stakeholders and infrastructure planning. Conveying an effective message often requires visualizing movements in relation to custom background layers, such as dynamic weather conditions or local transportation features. However, animations are commonly made using software that is easy to use but offers few options for input layers, thus limiting their impact. Alternatively, bespoke solutions require advanced programming skills that are not readily available for many ecologists.
2. We developed ECODATA, a suite of open-source tools to support exploration, analysis and visualization of animal movements and dynamic geospatial data layers. The tools do not require programming skills and guide users through the process of manipulating vector, raster and tabular data files to prepare inputs to custom animations or further analyses. The software was developed by a team of remote sensing experts, quantitative ecologists, wildlife managers and conservation practitioners.
3. We demonstrate the use of ECODATA through two examples. The first describes the use of the software to animate movements of elk (*Cervus elaphus*) and wolves (*Canis lupus*) in relation to roads, wildlife crossing structures and seasonal vegetation green-up near Banff National Park in Canada. The second illustrates the impact of the software on wildlife management, with an animation of caribou

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(*Rangifer tarandus*) movements and parturitions during the calving season. Both examples include processed remote sensing data and feature layers that provide relevant local context.

4. ECODATA offers a novel resource to explore and communicate animals' interactions with their environment, informing management decisions and conservation strategies. The flexible tools for geospatial data manipulation can be used for data visualization, as described here, or to create predictor variables for inclusion in habitat selection or other ecological models.

KEYWORDS

animation, data visualization, GIS, movement ecology, remote sensing, wildlife management

1 | INTRODUCTION

Movements of wild animals across landscapes are affected by environmental conditions, along with human infrastructure and activities (Corradini et al., 2021; Davidson et al., 2020; Fahrig & Rytwinski, 2009). Many species respond to changing conditions by modifying the timing and extent of their movements (Cohen et al., 2018; Tucker et al., 2018). To uncover the causes and consequences of these relationships, animal movements must be assessed within their associated environmental and anthropogenic context. Tracking data—geolocations from animal-borne sensors—provides direct observations of wildlife movements (Kays et al., 2015), and an increasing volume and quality of relevant geospatial data are available through remote sensing products (Chi et al., 2016), weather forecasting models (Hersbach et al., 2020) and geographic vector datasets (Yao & Li, 2018). However, accessing, interfacing and interpreting these complex datasets remains challenging.

Maps and animations of wildlife tracking data can be used to illustrate study results, generate hypotheses and build stakeholder support for conservation actions (Chi et al., 2016; Lacey & Nelson, 2023). There are a growing number of commercial and open-source software for processing and visualizing tracking or trajectory data, including dozens of R packages (reviewed in Joo et al., 2020), several Python libraries (e.g. Graser, 2019; Shenk et al., 2021; Weixler et al., 2021) and applications to build animations (Schwalb-Willmann et al., 2020). However, options to build customized animations of tracking data that integrate relevant environmental context remain limited. In particular, most user-friendly software offer only generic basemaps, with features for visualizing dynamic environmental conditions limited to attributes in the trajectory dataset, rather than datasets representing changing weather and habitat conditions over the surrounding area (e.g. Dodge et al., 2021). Similarly, MoveApps (<https://www.moveapps.org>) (Kölzsch et al., 2022) and the commercial software Firetail (www.firetail.de) are designed for large multi-sensor tracking datasets but with limited capabilities for integrating other geospatial data. Therefore, animations that integrate custom layers with tracking data tend to require custom

coding, a barrier to entry for many users. Another approach is to hire professional cartographers to build animations around well-defined use cases (e.g. 422 South and Movebank, 2020) but these products can be expensive and difficult to update in response to new data or stakeholder feedback. Finally, the difficulty of obtaining relevant contextual datasets and getting them into suitable formats poses another obstacle to their use in animations or downstream analyses. For example, remote sensing and weather reanalysis data from NASA, ECMWF or other data sources are typically provided at resolutions that do not align with those of animal movement datasets (Dodge et al., 2013). Likewise, vector datasets of landscape features are commonly provided by governments for their jurisdictions, requiring wildlife ecologists to manage datasets for spatial domains far larger than their study area or merge datasets to assess transboundary movements.

To address these gaps, we developed ECODATA, a suite of free, open-source tools to support exploration, analysis and visualization of animal tracking data alongside environmental and infrastructure data layers. ECODATA includes a set of sophisticated GUI-based tools to process remote sensing and other geospatial data products, including gridded, vector and tabular layers, and create custom animations of animal movements along with these contextual datasets. ECODATA was designed by a group of experts in software development, remote sensing, statistical analysis, wildlife management and land conservation (see Acknowledgements). Through this collaborative approach, we were able to design the tools around the needs of multiple projects and jurisdictions. The software is designed as an extension to the Movebank platform, which hosts harmonized data for thousands of users (Kays et al., 2022).

2 | SOFTWARE DESCRIPTION

2.1 | Overview

ECODATA consists of two software programs for handling large geospatial data files: ECODATA-Prepare and ECODATA-Animate (Figure 1). ECODATA-Prepare is a set of apps for manipulating

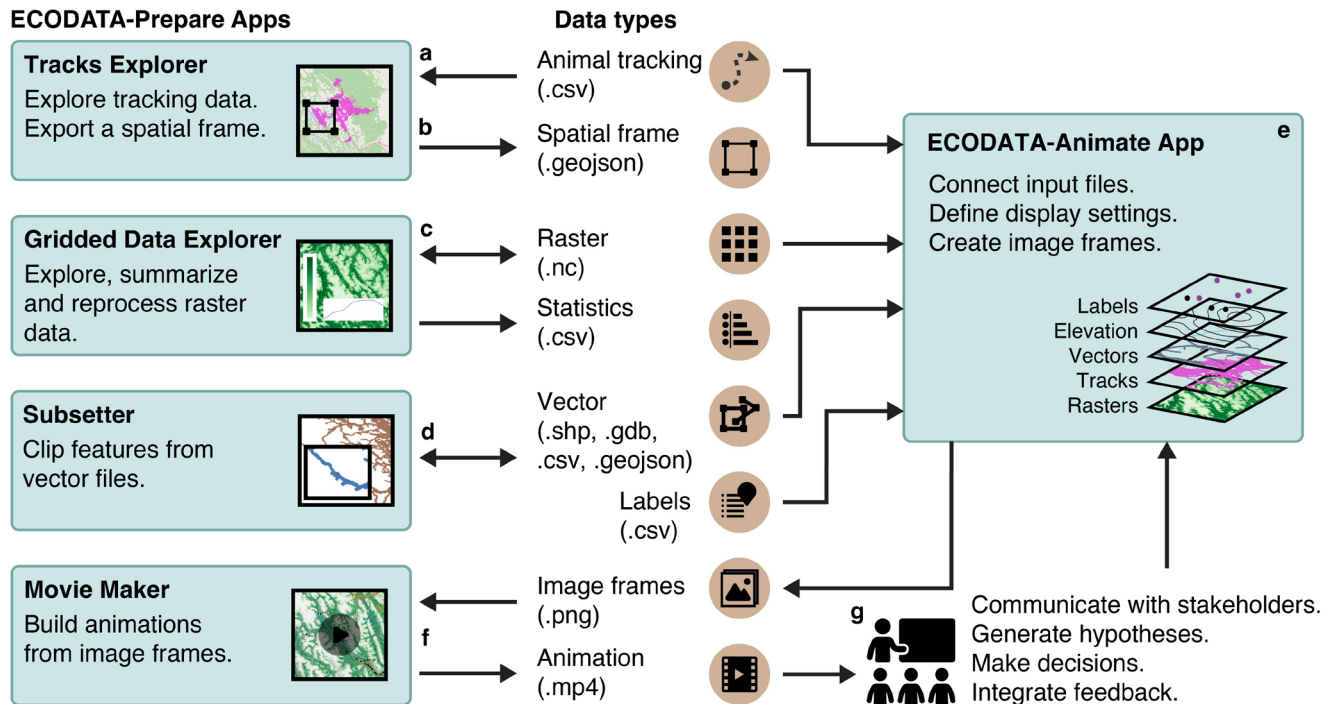


FIGURE 1 Overview of the ECODETA Apps (blue boxes) in relation to the types of geospatial information they process. The apps can be used independently to visualize and manipulate data in preparation for geospatial analyses. The case studies detail workflows that use the apps together to create movement data animations, and that use these animations to support wildlife management.

geospatial data layers to assess animal movement with respect to environmental conditions. With ECODETA-Animate, users can design custom animations that integrate wildlife movement with environmental datasets created using ECODETA-Prepare.

2.2 | ECODETA-Prepare

ECODATA-Prepare allows users to process environmental data in gridded and vector formats for analysis, and to compile image frames into animations. It is a Python package that provides a GUI to interactively explore, summarize and reprocess data without coding, although the package can also be used directly. ECODETA-Prepare includes user guides for the GUI applications and the Python package (<https://ecodata-apps.readthedocs.io/>). ECODETA-Prepare currently includes four apps that can be used to prepare data for custom animations (as described here) or input to other software and applications, such as habitat selection functions.

The Tracks Explorer App visualizes animal occurrences from tracking data with a variety of background maps, optimized for large datasets and dense occurrence clusters (Figures 1a and 2). It also allows users to define a spatial area of interest around the dataset to prepare a .geojson file (Figure 1b) formatted to request remote sensing data from NASA's EARTHDATA AppEEARS interface (AppEEARS, <https://appeears.earthdatacloud.nasa.gov/>) and define the area of interest for other environmental data requests, such as

from ECMWF weather reanalyses (<https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>) (Dee et al., 2011).

The Gridded Data Explorer App includes a set of tools to visualize and process gridded (raster) data files composed of multiple two-dimensional spatial layers representing conditions over an area at different times (Figures 1c, 3). The app includes an interactive time slider for viewing gridded data over time, with a static plot showing a time series of the spatial average of the dataset at the selected time. The app provides functions to coarsen or interpolate (up- or down-scale), select or mask spatial areas and values (e.g. extract land use classes), filter by time (e.g. by season or time of day) and calculate statistics on the dataset. The app makes use of the powerful Python packages Xarray (<https://docs.xarray.dev/>) (Hoyer & Hamman, 2017) and Dask (<https://docs.dask.org/>) for efficient processing of large gridded datasets, including files too large to fit in the computer's memory.

The Subsetter App provides tools to efficiently subset relevant features out of large geospatial vector datasets, such as shapefiles or file geodatabases, to create smaller, easily manageable files (Figure 1d). For example, it could be used to extract features from a global dataset that overlap with a study area. The app uses the Python packages Fiona (Gillies, Buffat, et al., 2024), GeoPandas (Bossche et al., 2024) and Shapely (Gillies, van der Wel, et al., 2024).

The Movie Maker App produces an animation file from a folder of static images, designed to work with image frames produced by ECODETA-Animate (Figure 1f). It uses FFmpeg (<https://www.ffmpeg.org/>) to create a .mp4 file from this set of frames.

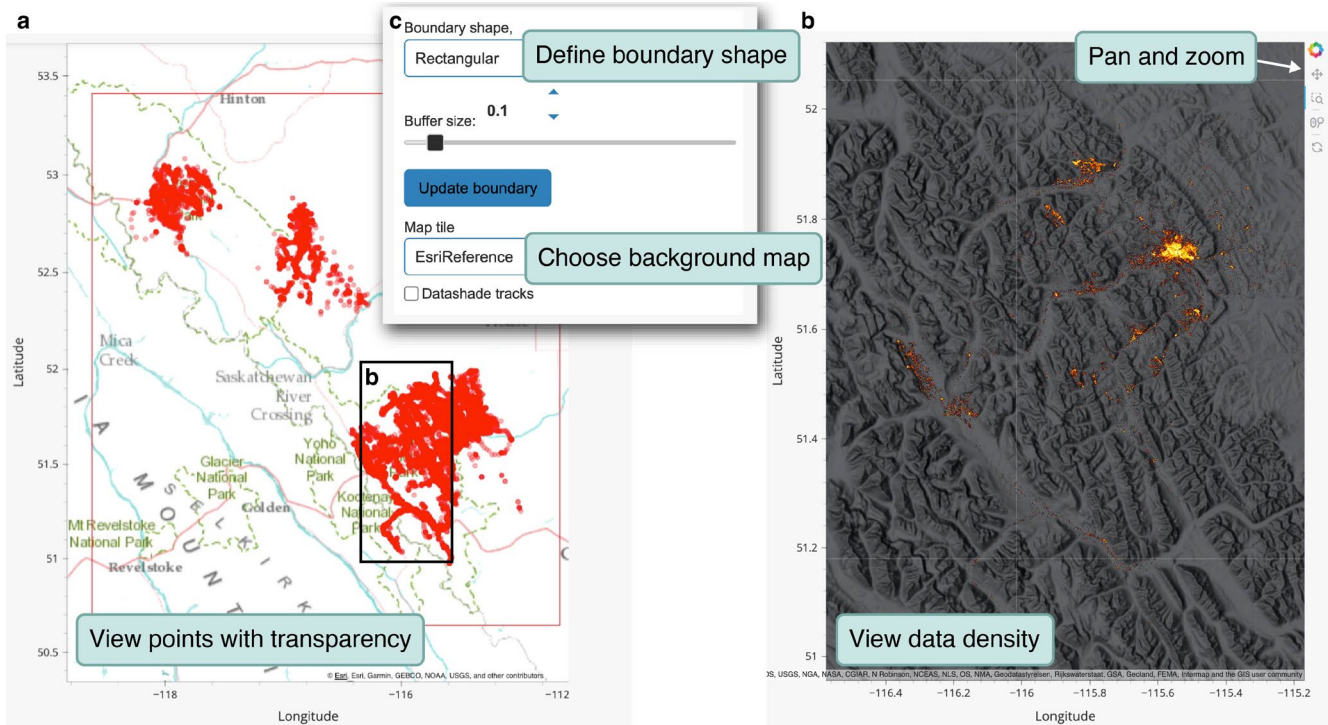


FIGURE 2 The ECODATA Tracks Explorer. Two map views are shown, displaying the tracks used in case study 1 (Hebblewhite, 2025). (a) Each animal occurrence is represented as a transparent point overlaying the EsriReference background map, with a user-defined domain boundary around the occurrences shown as a thin red line. (b) Occurrence density (using the Python Datashader library) overlays the EsriWorldHillshadeDark background map, with options to adjust the map view. (c) Settings allow the user to define the domain boundary and background map. The domain area can be exported to a .geojson file to define the area of interest for subsequent analysis.

2.3 | ECODATA-Animate

ECODATA-Animate creates image frames for custom animations of animal movements along with multiple contextual feature layers, including outputs from ECODATA-Prepare (Figure 1e). ECODATA-Animate is written in MATLAB and is available as a compiled executable, meaning it is freely available, does not require a MATLAB licence to run and is installed with a graphical installer. Inputs accepted by the software include the following:

- Animal track data (required): A .csv file of animal track data with timestamps and geographic locations, following the Movebank format (Kays et al., 2022; MPIAB, 2024). Additional columns, such as annotated environmental covariates (Dodge et al., 2013), can optionally be included to define how tracks are displayed.
- Environmental data (optional): Up to three gridded environmental datasets in netCDF-4 format, commonly used for products derived from satellite imagery or weather and oceanographic reanalysis models, and including outputs from the Gridded Data Explorer App (Figure 1c). These environmental data layers can be displayed as a gridded colour map, contour lines or vector fields. Examples include a colour map of surface temperature derived from satellite imagery, contour lines of snow accumulation and ocean current vectors.

- Shapefiles (optional): One or more feature shapefiles (.shp), including outputs from the Subsetter App (Figure 1d). For example, these could include water bodies, existing or planned roads, protected area boundaries and wind turbine sites.
- Labelled points (optional): A table of geographic locations in .csv format, specifying the placement and text of labels, as well as start and end times to restrict display to specific periods. For example, this layer could include the names and locations of towns, or study results such as the time and place of identified road crossings or mortalities.
- Elevation (optional): Select whether and how to display elevation contours using an included global digital elevation model (Amante & Eakins, 2009; NOAA National Geophysical Data Center, 2009).

Settings offer customizations to control appearance such as colouring, track tracing, legends and the temporal frequency of images. The output of ECODATA-Animate is a set of high-resolution .png images that can be viewed individually, input to models for analysis or used as frames to create an animation with the Movie Maker App or other software. Settings can be saved, reused and updated, allowing users to efficiently create similar animations for different purposes. User guides are available at <https://ecodata-animate.readthedocs.io/en/latest/>.

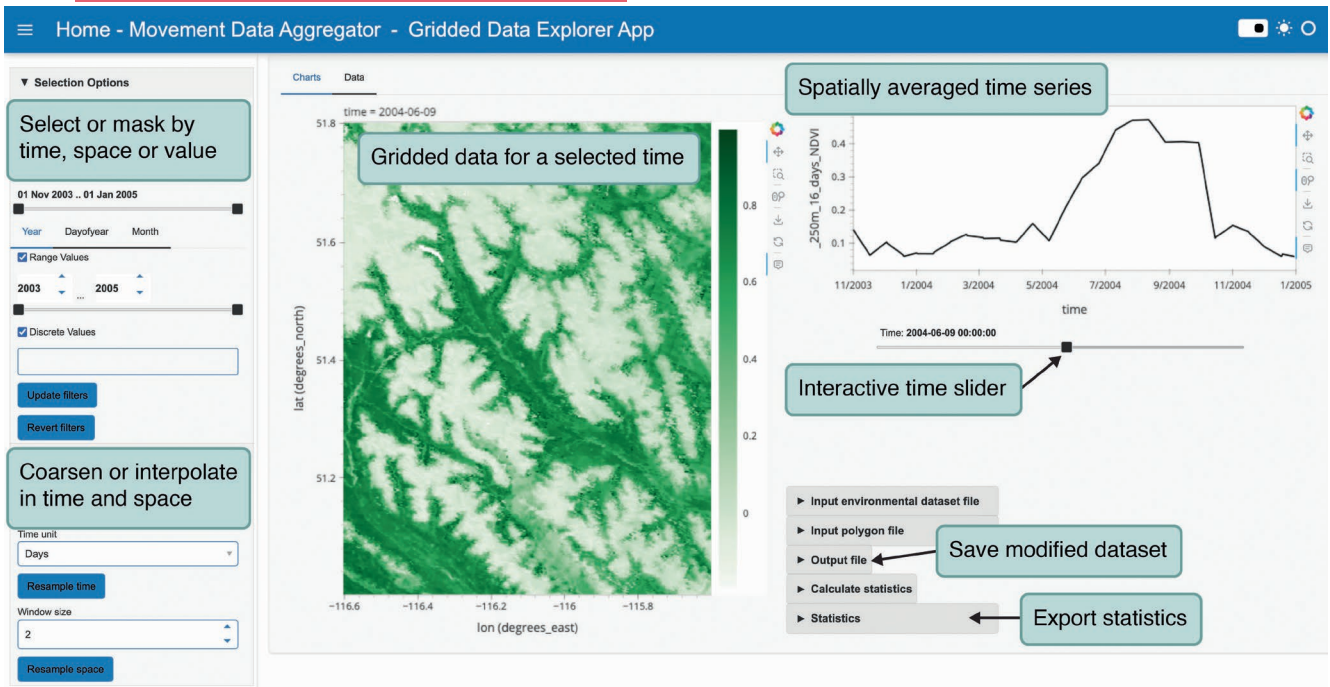


FIGURE 3 The ECODATA Gridded Data Explorer interface. Labels highlight key features of the app. This example shows vegetation data used in case study 1 (MOD13Q1; Didan, 2021), displaying a daily image that interacts with a spatially averaged time series. Functions allow users to extract subsets (e.g. filtered by spatial boundary or time), coarsen or interpolate, and calculate statistics (e.g. mean, standard deviation, min and max) on the gridded dataset.

3 | CASE STUDIES

We consider two case studies that highlight features of ECODATA-Animate that are not available as core functions of common software for animating tracking data, and include geospatial inputs processed with ECODATA-Prepare. In the first, we detail a workflow for animating multispecies movements and interactions with roads. In the second, we describe the impacts of custom animations through an example of ungulate behaviour during the calving season.

3.1 | Application workflow: Road-wildlife interactions

This case study is illustrated by the animation available at https://youtu.be/Uri5hJ_1zrg and the online supplement (Davidson & Hebblewhite, 2025). Wildlife tracking data can be used to explore and quantify behaviour near roads, functional connectivity around human infrastructure (Whittington et al., 2022) and the effectiveness of crossing structures (Edwards et al., 2022). In this case study, we describe the use of ECODATA to visualize movements of an herbivore (elk, *Cervus elaphus*) and a carnivore (wolves, *Canis lupus*) species in 2004 in relation to highways that provide access to Banff National Park, Alberta, Canada, for millions of tourists each year. For context, we include seasonal vegetation and the location of crossing structures that existed at the time.

First, we process data to use for the animation. We evaluate and select an input GPS tracking dataset (.csv file; Hebblewhite, 2025; Hebblewhite et al., 2020) using mapping tools on Movebank and a public data workflow (Davidson et al., 2025; <https://www.moveapps.org/workflows/public/a2d5ed0c-be7b-4982-8ef8-ea147b0d1591>). Next, we explore the selected tracking data in the Tracks Explorer App (Figure 2) and define the spatial bounding box of the animation (Figure 1a), exporting this as a .geojson file (Figure 1b). We then use this .geojson file to request a file in netCDF-4 format of normalized difference vegetation index, NDVI (a measure of vegetation greenness; MOD13Q1; Didan, 2021) for the area and time period of interest from NASA AppEEARS. The MOD13Q1 product provides a raster layer of NDVI estimates at 16-day intervals, which is not suitable for animating sub-daily movements. Therefore, we use the Gridded Data Explorer App to interpolate the data to daily raster layers (Figures 1c and 3). To show landscape features, we retrieved vectors (.shp files) of rivers (Natural Earth, naturalearthdata.com) and roads (Natural Resources Canada, 2010a, 2010b). To make the road data easier to work with, we use the Subsetter App to extract objects within our study area defined by the .geojson file, reducing the data volume by over 99% (Figure 1d). We also prepare a spreadsheet (.csv) with labels for key highways and crossing structures.

Next, we create the animation. With ECODATA-Animate, we link the prepared track, raster, vector and label files, choose settings and build the images (.png) (Figure 1e). Settings include options for colour, line thickness and marker symbol and size, allowing optimization to account for colour blindness and expected screen size and

lighting conditions. An option to generate a single frame allows iterative testing while choosing settings to ensure that features appear as desired. Finally, we use the Movie Maker App to create the animation from these images (Figure 1f).

In this animation, both species migrate from the northeast during late spring to their summer range, where several individuals spend considerable time near highways, coinciding with peak annual traffic volumes. These highways run through mountain valleys and parallel rivers accentuated by elevation contours and greater vegetation that also offer preferred habitat. In the fall, declining vegetation triggers movements back to the winter range in the northeast. Much of the activity near roads occurs along Trans-Canada Highway 1, which has undergone considerable investment in infrastructure to reduce wildlife collisions (Ford et al., 2010). The animation also demonstrates frequent wildlife crossings over the unmitigated Highway 93N, a remaining wildlife mortality hotspot in Banff National Park.

3.2 | Conservation impacts: Caribou calving in the Northwest Territories

This case study is illustrated by the animation available at <https://youtu.be/ww6oEig21-c> and the online supplement (Davidson & Kelly, 2025). Caribou (*Rangifer tarandus*) parturition can be monitored through wildlife tracking to help estimate population growth rates and identify calving ranges (Davidson et al., 2020; DeMars et al., 2013). In our second case study, we describe an animation of movements of female boreal caribou (*R. t. caribou*) in the Northwest Territories, Canada, and describe its conservation impacts. In this animation, caribou movements are shown in the context of vegetation and landscape features known to affect caribou calving ecology, with calving events identified from the movement data using an approach adapted from DeMars et al. (2013) appearing on the map as they occur.

Within the Northwest Territories and Yukon, Canada, ECODATA animations are used in community meetings with local organizations and Indigenous governments to share knowledge about caribou populations, support relationship-building and contribute to decision-making to support sustainable populations of this economically important species (Figure 1g). This animation informed changes in management class designations within the territory's regional draft boreal caribou range plan by illustrating the use of calving areas that were not previously recognized. The inclusion of NDVI data and calving events, along with the caribou movements, illustrates that parturition is widely dispersed spatially, with parturitions primarily occurring in May following the onset of seasonal green-up. Many caribou move towards the Horn Plateau in Edézhíe National Wildlife Area (NWA) and subsequently calve near the slopes of the plateau—which can be distinguished by higher NDVI—but mostly outside this protected area. The custom label for the Edézhíe NWA was included to orient viewers and highlight a locally recognized protected area name that does not currently appear on Google or Bing basemaps.

4 | DISCUSSION

ECODATA offers a suite of tools addressing key gaps in translating wildlife tracking data to generate hypotheses and improve local decision-making. Apps were envisioned and tested based on needs identified by wildlife managers to improve the impact of their wildlife tracking programmes. Environmental context is critical to interpreting animal movements, and ECODATA simplifies and enables the access, retrieval, processing and presentation of data that represent this context. Custom animations offer visual evidence to guide communications with local communities, industry representatives and other stakeholders. Displaying locally known features and environmental conditions not apparent in standard web basemaps orients viewers and adds context to observed patterns of animal behaviour, building trust and interest in study results. For example, in our case study from Banff National Park, we illustrated wildlife movements and roads along with seasonally changing landscape features—relevant to why the animals were near the roads. Visualizing successful highway crossings on over- and underpasses helps managers interpret the efficacy of crossing structures and potentially identify locations for future mitigation. Further, with the saved frame images and settings in ECODATA-Animate, managers can efficiently respond to stakeholder feedback or create alternate versions of animations for different purposes. For example, these could integrate other data sources, such as reported vehicle collisions or mortalities inferred from tracking data, or proposed residential development (Whittington et al., 2022). Longer versions of the animations in our case studies, with each animal shown in a different colour, can allow more detailed exploration of individual movements.

ECODATA complements existing tools by improving access to large environmental data products and supporting custom animations that do not require coding expertise or external contractors. Moving forward, ECODATA has potential for additional uses; for example, to further manipulate remote sensing data and offer novel inputs to resource-use models or human mobility analyses. We welcome future use, contributions and feedback.

AUTHOR CONTRIBUTIONS

Conceptualization: Justine E. C. Missik, Sarah C. Davidson and Gil Bohrer. *Data curation:* Sarah C. Davidson, Mark Hebblewhite, Allicia P. Kelly, Kelsey L. Russell and Mike Sutor. *Methodology:* Justine E. C. Missik, Sarah C. Davidson and Gil Bohrer. *Software:* Justine E. C. Missik, Madeline E. Scyphers and Gil Bohrer. *Supervision:* Gil Bohrer. *Visualization:* Justine E. C. Missik and Sarah C. Davidson. *Case studies:* Sarah C. Davidson, Mark Hebblewhite, Allicia P. Kelly, Kelsey L. Russell and Mike Sutor. *Writing—original draft:* Justine E. C. Missik, Sarah C. Davidson and Gil Bohrer. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/2041-210X.70141>.

DATA AVAILABILITY STATEMENT

ECODATA-Prepare is developed openly in GitHub at <https://github.com/jemissik/ecodata>, available under the MIT open-source licence and archived at <https://doi.org/10.5281/zenodo.11522464> (Missik et al., 2024b). Documentation is available at <https://ecodata-apps.readthedocs.io/>. The package is installable through conda (<https://anaconda.org/conda-forge/ecodata>) and can also be installed as a bundled app on MacOS, Windows and Linux with installers available at <https://github.com/jemissik/ecodata/releases>. ECODATA-Animate is developed openly in GitHub at <https://github.com/bohrer-lab/ecodata-matlab>, available under the MIT open-source licence and archived at <https://doi.org/10.5281/zenodo.8436973> (Missik et al., 2024a). ECODATA-Animate is also available through the MathWorks File Exchange at <https://www.mathworks.com/matlabcentral/fileexchange/136564-ecodata-animate>. Documentation is available at <https://ecodata-animate.readthedocs.io/>. ECODATA-Animate can be installed as a bundled app on MacOS and Windows, with installers available at <https://github.com/bohrer-lab/ecodata-matlab/releases>.

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