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DATA DESCRIPTOR

A dataset of records of alien vertebrates in mountains of the World

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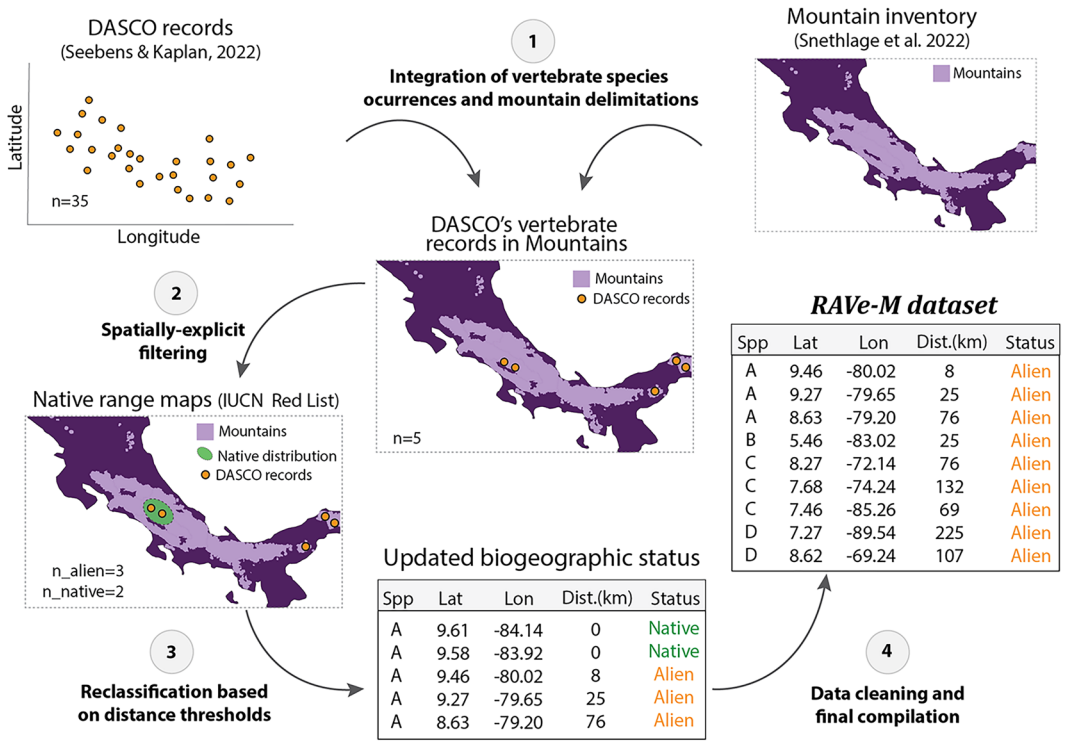
Mountains host highly diverse biota that are increasingly threatened by anthropogenic pressures around the globe. Although biological invasions are a well-recognized driver of global change, the available information on the distribution of alien species in mountains remains fragmented. To advance in filling this gap, we present a comprehensive dataset focused on alien vertebrates that contain roughly 425,000 records of over 700 species reported across ~3,000 mountains of the World. The dataset can be downloaded or visualized through interactive maps that facilitate access to species-specific occurrence records, mountain-specific lists of alien vertebrate species and mountain characterizations based on environmental and anthropogenic features. A workflow for the customized compilation of alien species records for specific taxonomic groups or study areas is also available at the RAVeM repository. Ours is a dynamic dataset open to continuous development based on user feedback, that has the potential to facilitate and support future studies and monitoring efforts of alien vertebrates in mountains worldwide.

Background & Summary

Despite covering a small proportion of the Earth's terrestrial surface, mountains are key features of global biogeography that host strikingly diverse and unique biotas[1]. For example, half of all biodiversity hotspots are in (or contain) mountain landscapes[2] where high levels of endemism are associated with the biogeographic isolation in which mountain biota have evolved[3,4]. Moreover, mountain regions are also home to large human populations[5] to which they provide multiple ecosystem services[6]. At the same time, these regions are under increasing anthropogenic threats, including land-use change, climate change, and biological invasions[7]. Effective monitoring, management, and conservation actions to mitigate these anthropogenic threats require adequate access to information on the spatio-temporal dynamics of these drivers and the species they affect. However, despite the rapid increase in biological and environmental data in recent years, information remains scattered across numerous sources, limiting accessibility for practitioners, scientists and decision-makers.

Our knowledge of the status of global change in mountains varies not only among drivers and regions but also across taxonomic groups. For instance, the effects of land use and even more of climate change on mountain biodiversity have been intensively studied in recent years (e.g.,[8–13]). Conversely, biological invasions, despite their recognized role as a major driver of global change[14,15] and biogeographic reconfiguration[16] have received somewhat less attention in mountain regions, and existing efforts are mostly focused on plant invasions

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Spp	Lat	Lon	Dist.(km)	Status
A	9.46	-80.02	8	Alien
A	9.27	-79.65	25	Alien
A	8.63	-79.20	76	Alien
B	5.46	-83.02	25	Alien
C	8.27	-72.14	76	Alien
C	7.68	-74.24	132	Alien
C	7.46	-85.26	69	Alien
D	7.27	-89.54	225	Alien
D	8.62	-69.24	107	Alien

Spp	Lat	Lon	Dist.(km)	Status
A	9.61	-84.14	0	Native
A	9.58	-83.92	0	Native
A	9.46	-80.02	8	Alien
A	9.27	-79.65	25	Alien
A	8.63	-79.20	76	Alien

Fig. 1 Schematic representation of the workflow implemented to develop the RAVeM dataset. (1) In the first step, we integrated point-data information filtered for vertebrate species from DASCO's dataset and polygons delimitating mountains to obtain the subset of DASCO's vertebrate records in mountainous regions. (2) Then, we filtered the resulting occurrences by identifying those native records wrongly classified as aliens in DASCO, based on their overlap with species-specific range maps downloaded from the IUCN Red List. From this task, all DASCO records were (3) reclassified, assigning them an updated biogeographic status (i.e. alien or native). (4) Finally, records flagged as native were removed to obtain a dataset containing exclusively alien records.

(e.g., the Mountain Invasion Research Network, MIREN, https://www.mountaininvasions.org/). Although it is well known that islands and coastal regions are hotspots of invasion[17,18], recent efforts oriented towards documenting the impacts of alien plants in mountains have also shown a rapid advance of invasions in such regions[19–21]. In the context of alien animals in mountain regions, a general picture has been established only recently and for the specific case of vertebrates[22]. Certainly, complementary studies are necessary to address remaining open questions, but a systematic compilation of the available data of alien vertebrates in mountains is currently missing.

To help fill this gap, here we focus on vertebrates and present the first comprehensive and global compilation of Records of Alien Vertebrates in Mountains (RAVeM). Given the good coverage of distribution data for vertebrate taxa, we compiled a dataset that is comparable across continents, providing a full picture of mountain invasions at a global scale. RAVeM integrates information on alien vertebrate species occurrences, global delimitations of mountain boundaries, and current knowledge on species native and alien distribution ranges. The resulting dataset can be explored through a Shiny app that allows visualization of occurrence records of alien vertebrates across the mountains of the world, provides mountain-specific alien species lists and data on environmental and anthropogenic characteristics of the mountains studied. We also provide a reproducible and flexible workflow that allows users to compile tailored datasets, for specific taxonomic groups, geographic extents or study units other than mountains (e.g., bioregions, specific habitats or urban areas).

Methods

Data acquisition and computational processing. To compile the RAVeM dataset, we implemented a workflow that integrates information on occurrence records (i.e., point-data) of alien species obtained from the DASCO dataset[23], vector data on mountain boundaries as delimited by Snethlage *et al.*[24] and species distribution ranges obtained from the Red List of the International Union for the Conservation of Nature (IUCN, 2020) and eBird. The DASCO dataset is stored as a comma-separated values file named "DASCO_AlienRegions_SInAS_2.5.csv" that can be downloaded at https://zenodo.org/records/10054162. The mountain polygons are available as a shapefile layer named "GMBA_Inventory_v2.0_standard_basic.shp" at https://www.earthenv.org/mountains. We obtained the information on species native distributions from IUCN, specifically downloading polygons in shape format (.shp) available at https://www.iucnredlist.org/resources/spatial-data-download for the taxonomic groups of interest: freshwater fishes, amphibians, reptiles and mammals (Data retrieved on February 2, 2025). Distribution polygons for birds were requested at http://www.ebird.org/. The workflow to integrate this information consists of four main steps represented in Fig. 1 and described in detail below.

Step 1. Integration of alien vertebrate's occurrence data and mountain polygons. Occurrence records. To compile occurrence records of alien vertebrate species in mountains, we extracted point data from the DASCO dataset[23]. DASCO provides occurrence records derived from a semi-automated workflow that uses GBIF (Global Biodiversity Information Facility, www.gbif.org) and OBIS (Ocean Biodiversity Information System, www.obis.org) records to downscale regional checklists on the occurrence of alien species in a region. The checklist data are derived from different global alien species databases (e.g., the Global Avian Invasion Atlas [GAVIA;[25]] or the Distribution of Alien Mammals database [DAMA;[26]]) which are standardized and consolidated as a single source in the SinAS (Standardising and Integrating Alien Species data) dataset[27]. DASCO cleans these occurrences by removing spatially inaccurate records and applies multiple validation checks to identify erroneous coordinates that are then discarded. In a final step, the cleaned occurrence records and the checklists are used to identify valid alien occurrences. These records are then consolidated in a final output, like the one we used here (DASCO version SInAS 2.5; https://zenodo.org/records/10054162) which contains in its full version over 46 million occurrences of fungi, plants, invertebrates, and vertebrates. Given our interest in vertebrates and the data availability on these taxa that allow cross-validation of alien occurrences, we filtered the DASCO dataset to keep records of freshwater fishes, amphibians, reptiles, birds and mammals, resulting in over 16.5 million records from 2,068 species. For this filtering step, we first pulled information on higher taxonomy for all the species in DASCO from GBIF's Taxonomic Backbone. Then, using this information, we filtered all records available for vertebrate species.

Mountain delimitations. We used the most recent global mountain inventory[24] to map occurrences within these regions. This inventory provides a standardized delineation of the world's mountains following a definition that discriminates between mountainous and non-mountainous regions based on terrain ruggedness. Moreover, mountains are classified in different hierarchical levels of aggregation from small subranges in local settings to the continental scale. The smallest mapping units are called basic features and have no overlapping subunits (i.e., they do not contain portions of other delimited mountains), which avoids any potential duplication of records in our final dataset. We used the polygon layer named "GMBA_Inventory_v2.0_standard_basic.shp" that is publicly available at https://www.earthenv.org/mountains and which consists of delimitations for 6,717 non-overlapping mountains. From the subset of DASCO records for vertebrate species, we removed those belonging to the marine realm and then overlapped the remaining (i.e., terrestrial and freshwater species) with the mountain polygons. Once filtered, we obtained a dataset containing all alien vertebrate records included in DASCO and located in mountains.

Step 2. Spatially explicit filtering. DASCO relies on subregional (mainly country-level) lists of alien species to determine whether a given record is non-native. This approach may result in some occurrences being wrongly assigned to the subset of alien records. For instance, occurrences could be flagged as alien when a species' distribution is both alien and native in different parts of a given country. For example, a species native to southern China and introduced into northern China will likely appear in the country-level list of alien species, increasing the risk that all points in the country end up being classified as alien. To account for this issue, we additionally implemented a spatial filtering of the subset of DASCO records documented in mountain ranges using species' range maps. This information was downloaded from the IUCN Red List of Threatened Species for fishes, amphibians, reptiles, and mammals (https://www.iucnredlist.org/) and from BirdLife International for birds (https://www.birdlife.org/). These polygons are expert-derived products resulting from the joint efforts of regional specialists to conduct the extinction risk assessments of each taxonomic group[28] and have been widely used for biogeographic purposes over the last two decades (e.g.,[29,30]. Nevertheless, an important limitation of these sets of maps in the context of our work is that such polygons are not available for all species. For this reason, we were unable to implement the spatial filtering approach for 198 species, representing 14% of all alien vertebrates recorded in mountains (n = 1,412 spp.) according to DASCO. These species were removed from the subsequent processing steps.

Step 3. Occurrence status reclassification. For those species with IUCN distributions available, we first extracted the polygons depicting the species' native ranges. Then, we used these to identify potential native records classified as alien in DASCO. In addition, for all the points falling outside the species' native polygon we calculated the minimum distance to the native range. This step is crucial for identifying records that are outside native range polygons but are very close to native range polygons. Given the substantial mobility of many vertebrates, such occurrences may in fact likely belong to native-range occurrences (e.g. vagrant or migrating individuals). Therefore, for every single record documented outside the species' native polygon we measured the minimum distance to the nearest native range polygon. The dataset we provide contains all records that fall outside the respective species native polygon, this is: values > 0 in the column named "Distance to Native". Given that ecologically reasonable thresholds depend on the biology of each taxonomic group, we strongly recommend users to consider the information in this column to filter out records that might represent native populations not well captured by the available range polygons, spatial mismatches due to different georeferencing systems or instances of recent natural range shifts[31].

Step 4. Data cleaning and dataset compilation. Based on the previous assessment, we then identified native records incorrectly classified as aliens (distance to native range = 0) in DASCO and removed them from the output dataset. The final dataset contains information on alien vertebrate species occurrences, the associated species taxonomy, the mountain range where they occur and features of the mountain ranges (Table 1). The data has global coverage with records in mountains from all zoogeographic realms. Nevertheless, the global distribution patterns of alien vertebrate richness in mountains vary among taxonomic groups (Fig. 2).

Column name	Definition	Source dataset
speciesKey	Unique code for the species from GBIF's backbone	Seebens & Kaplan, 2022
Taxon	Scientific name of the alien vertebrate species	Seebens & Kaplan, 2022
Class	Taxonomy at the class level	Seebens & Kaplan, 2022
Order	Taxonomy at the order level	Seebens & Kaplan, 2022
Family	Taxonomy at the family level	Seebens & Kaplan, 2022
Location	General description of the record locality	Seebens & Kaplan, 2022
Longitude	X coordinate of the record	Seebens & Kaplan, 2022
Latitude	Y coordinate of the record	Seebens & Kaplan, 2022
MapName	Mountain name	Snethlage *et al.*, 2022[24]
GMBA_V2_ID	Mountain code	Snethlage *et al.*, 2022[24]
Countries	Country(ies) where the mountain is located	Snethlage *et al.*, 2022[24]
min_distance_nat_range	Minimum distance between the record and the species native range	This study

Table 1. Information contained in the final RAVeM dataset. Column names as they appear in the RAVeM dataset, their definitions and the sources from the data was extracted are provided.

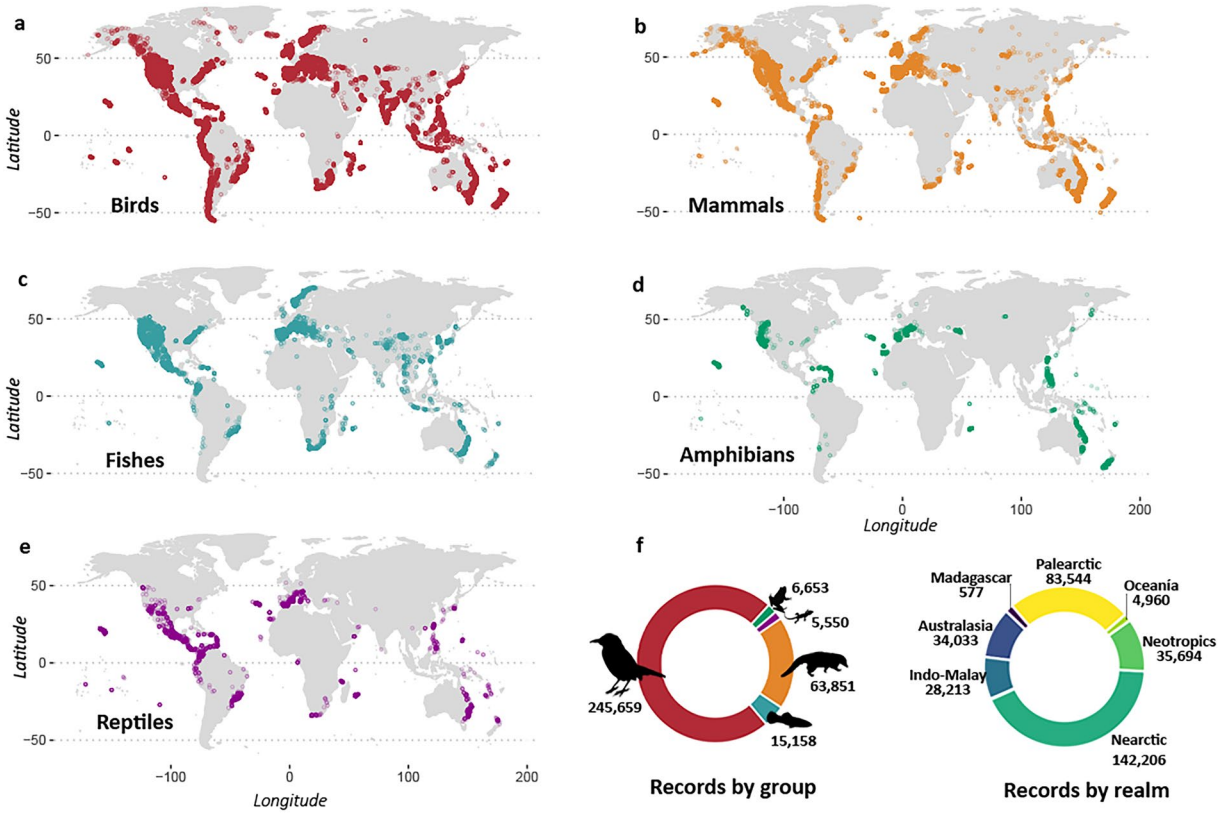


Fig. 2 Geographic distribution of the records contained in the RAVeM dataset after applying the 100 km threshold for alien status classification. Panels a-e, show spatial coverage for each taxonomic group (colored dots). Panel f shows the comparison among the available records for each taxon and for each realm. The species silhouettes used in this and the following figure were obtained from www.phylopic.org/ (*Pitangus sulfuratus* by Kai Caspar, *Pelophylax ridibundus* by Beth Reinke; *Hemidactylus frenatus* by Andy Wilson; *Nasua nasua* by Rebecca Groom and *Poecilia reticulata* by Josefine Bohr Brask).

Data Records

The resulting RAVeM dataset is available at Zenodo: https://doi.org/10.5281/zenodo.17911842[32]. The repository contains: 1) the RAVeM dataset as a comma-separated values file named "RAVeM_fulldataset_v1.1.csv" which includes 12 columns that are defined in detail in Tables 1 and 2) A file named "Mountain_descriptors_v1.1.csv" that provides information on nine descriptor variables of the mountains considered. These variables are area, maximum and minimum elevation, terrain roughness, distance to major cities, distance to major ports, mean biodiversity intactness index, mean human population density, and mean road density (Table 2).

Mountain descriptor	Definition	Source
Area	Total area in square kilometers	Extracted here from data available in Snethlage *et al.*, (2022)[24]
Max and Min elevation	Upper and lower elevation limits of each mountain	Extracted here from data available in Snethlage *et al.*, (2022)[24]
Human population density	Average population density (number of individuals per km2 at 2020) from values extracted for each mountain.	Estimated from data layer available at: https://beta.sedac.ciesin.columbia.edu
Terrain roughness	Difference between the maximum and minimum elevation of a cell and its eight surrounding cells-	Estimated from an SRTM layer 1 km resolution. (https://www.worldclim.org)
Road density	The average meters of road per km^2 per mountain, considering all road types.	Estimated from data in Meijer *et al.*, (2018). Layer available at: https://www.globio.info
Distance to cities	Minimum distance (in km) to settlements with >50k inhabitants	Estimated from data in Nelson *et al.*, (2019)[34]. Layer available at: https://doi.org/10.6084/m9.figshare.7638134.v3
Distance to ports	Minimum distance (in km) to the nearest major port	Estimated from data in Nelson *et al.*, (2019)[34–36]. Layer available at: https://doi.org/10.6084/m9.figshare.7638134.v3
Biodiversity Intactness Index (BII)	The average abundance of native terrestrial species in a region compared with their abundances before pronounced human impacts	Estimated from data in Newbold *et al.*, (2016). Layer available at: https://data.nhm.ac.uk

Table 2. Mountain features compiled for each mountain studied and available for visualization in the webapp. Description and sources of the variables characterizing anthropogenic impacts on mountains as well as physical and ecological mountain descriptors.

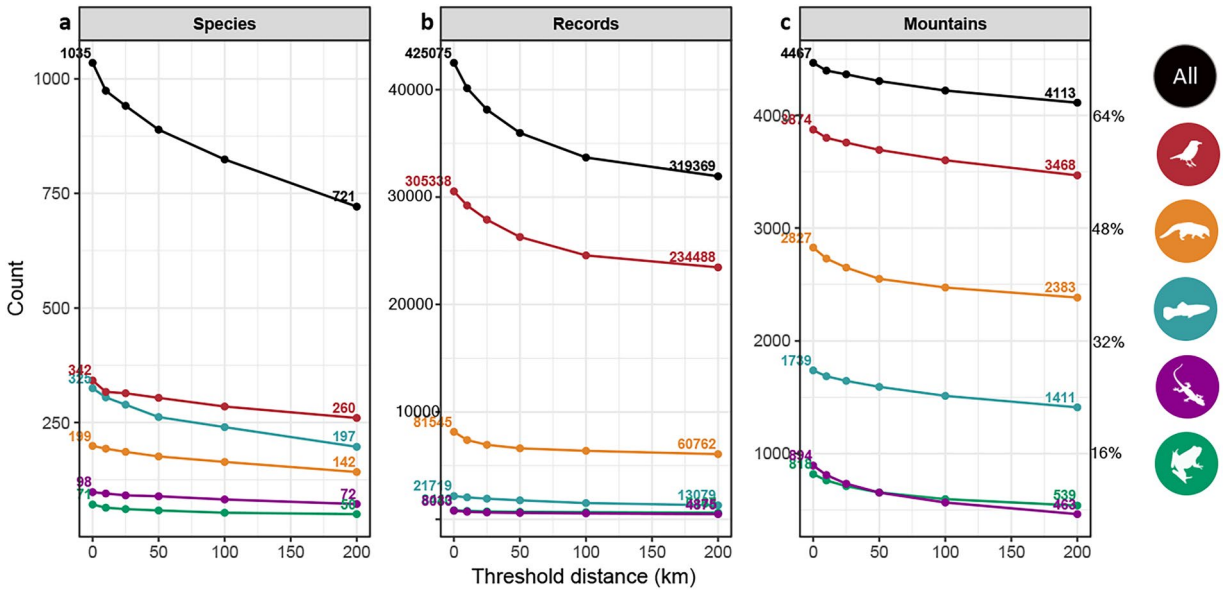


Fig. 3 Overview on the decrease in the total number of alien vertebrate species (**a**), records (**b**) and mountains (**c**) in the resulting RAVEM datasets when applying different distance thresholds (i.e. distance of the record to the next native range polygon) to identify alien occurrences. We quantified the minimum distances to the respective species' native polygon calculated for each record and applied filters for the distances >0 (i.e. zero tolerance: all occurrences outside the respective polygon are considered non-native), >10,>25,>50, >100 and >200 km respectively. In panels a) and b) the black line shows the cumulative number of all vertebrate species and their records included in the dataset. This is not the case in panel c because a given mountain can be repeated among taxonomic groups. In addition to the count of mountains where at least one species of a particular taxonomic group has been documented, panel c shows in the right- y axis a reference of the percentage of mountains with alien vertebrate data in relation to the total number of mountains included in the mountain inventory here used (n = 6166). This provides information on the proportions of invaded and non-invaded mountains.

Technical Validation

For an additional validation step of our final dataset, we used distance information to create alternative datasets that classify occurrences as alien records located at minimum distances of 5, 10, 25, 50, 100 or 200 km to their native range, respectively. As suggested above, from the full dataset users can derive additional subsets defining a preferred distance threshold to filter based on the distance to the native range. For a general overview, we show the decrease in the number of mountains, records and species in relation to the distance threshold applied (Fig. 3). Independent validation datasets are scarce because most global and regional data for alien vertebrate species ultimately derive from overlapping primary sources, including the databases used in this compilation.

This scarcity underscores the value of RAVeM as a database that can serve both as the current best approximation of alien vertebrate distributions in mountains and as a benchmark against which future independent datasets or alternative methodological approaches can be compared and validated.

The values for all the remaining variables were extracted from available raster layers for each metric, as detailed in Table 2. In addition to the nine variables mentioned above, we classified each mountain range according to its geometry (pyramid, inverse pyramid, diamond or hourglass) based on the relative distribution of elevations following[33]. Details on the methods applied for this classification are provided in[22]. Both the compiled and newly generated data on mountain descriptors is available in full as comma separated values file for the 4200 mountains and can be accessed at https://doi.org/10.5281/zenodo.17911842. This data can also be visualized in the Shiny app available at https://shiny.biodiv.univie.ac.at/RAVeM/.

Usage Notes

We provide three options to access and use the information associated with the RAVeM dataset. The main is, by downloading the full dataset containing species taxonomy, geographic coordinates, mountain related information, and point specific data on distance to native ranges. According to the taxonomic groups of interest and the topography of the studied region, users can filter the records by their distance to the closest native range according to their preferred threshold (see min_distance_nat_range in Table 1). The full RAVeM dataset is freely available for download at https://doi.org/10.5281/zenodo.17911842. In addition, users interested in a particular species or region can explore the dataset via our Shiny application (https://shiny.biodiv.univie.ac.at/RAVeM/), which enables interactive visualization, searches, and downloads by species and mountain range, as well as access to data on physical and anthropogenic descriptors of each mountain with recorded alien vertebrates.

As our data set will be updated regularly, users can either use the most up to date version or run workflow themselves. Given the flexibility in the input data, users can also specify their own study unit by providing a custom shapefile and adapting the workflow to their focal taxa. In such a case, all codes implemented to compile our final dataset are available as a tutorial at https://marce10.github.io/RAVeM/scripts/update_dasco.html. There we provide the codes used and show step-by step how to integrate raw occurrence data with mountain delimitations and apply spatial filters for identification of potential alien records using different distance criteria.

Data availability

The RAVeM dataset (v1.1)[32] is stored on Zenodo (https://doi.org/10.5281/zenodo.17911842). This repository makes available both the full RAVeM dataset (RAVeM_fulldataset_v1.1.csv) containing the vertebrate species records and their associated information and the file containing the variables describing the studied mountains (Mountain_descriptors_v1.1.csv). From the repository description is also possible to access the workflow used to generate the dataset and the visualization using their respective links: https://marce10.github.io/RAVeM/ and https://shiny.biodiv.univie.ac.at/RAVeM/.

Code availability

All codes developed to generate the RAVeM dataset are available as tutorial and can be accessed at https://marce10.github.io/RAVeM/.

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Author contributions

A.G.R., A.S., A.O., B.G., B.L., C.C., F.E., H.S., J.A.V. and S.D. conceived the initial idea of making publicly available a dataset gathering information on alien vertebrates in mountains of the world. A.G.R. developed the workflow and compiled the data with significant help of M.A.S. and D.U. to develop reproducible tutorials. A.G.R. led the writing of the code with valuable input from D.U., M.A.S. and J.A.V. A.G.R. and D.U. developed the shiny app with feedback from all co-authors. A.G.R. wrote the first draft of the text, and all co-authors provided critical input to improve the final version of this manuscript.

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DeclarationsCompeting interests

The authors declare no competing interests.

Additional information

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