Where Do the World's Squirrel Hotspots and Coldspots of 230+ Species Go with Climate Change 2100? A First BIG DATA Minimum Estimate from an Open Access Climate Niche Rapid Model Assessment

Moriz Steiner (moriz.steiner.work@gmail.com)
University of Alaska Fairbanks
Falk Huettmann
University of Alaska Fairbanks

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Abstract

Man-made climate change and its impact on the living world remain the problem of our time waiting for a good science-based resolution. Here, we focus on forecasting the global squirrel population as a representative but overlooked species group for the year 2100. This was possible by using 230 publicly available Species Distribution Model prediction maps for the world's squirrels (233 out of 307; 75%). These distribution forecasts are originating from 132 GIS predictors, implemented with an ensemble of three machine learning algorithms (TreeNet, RandomForest, and Maxent). We found that most of the world's squirrel ranges will be shifting (usually towards higher altitudes and latitudes) and remain/ become more fragmented; some species extend their range, and many can 'spill' into new landscapes. Considering that here we just ran a Rapid Assessment of Big Data, dealing with a climate niche envelope of the future but not the entire more holistic perspective of climate change and 2100, we assume wider serious changes will occur for squirrels, their habitats, and the world in the future Anthropocene of 2100. These changes can lead to more stress, genetic loss, extinction, and increased zoonotic disease transmissions, and this process will occur with an increased gradient over time.

Introduction

Man-made climate change caused by unsustainable consumption and subsequent CO2 release remains the problem of our time and for the living world. It is widely unresolved in a scientific matter, with useful data widely missing. While temperatures rise and impacts increase on our planet Earth almost beyond human comprehension, e.g. zoonotic diseases, many species are still not even well assessed or get marginalized for risks, trends, and the effort of science-based management. The squirrel family (Sciuridae) consists according to [1] of 285 species, and according to the tables presented previously [2a] of 307 species (see [3] for a generic taxonomic review). This study attempts to include all global squirrel species (307), however, due to a lack of open-access data only 233 (~75%) can be utilized thus far [3].

Of the over 300 known squirrel species, not all are agreed upon or carry good data (see [3], and [2a]). Thus far, only very few squirrel species are well-studied and present in the research literature, e.g. Eurasian Red Squirrel *(Sciurus vulgaris)*, and Eastern Grey Squirrel (*Sciurus carolinensis*), Eastern Fox Squirrel (*Sciurus niger*), and North American Red Squirrel (*Tamiasciurus hudsonicus*) [4], The rest of the squirrel species (approx. 99% -303/307) are widely understudied, and literature is often absent on many squirrel-related questions. Science-based conservation management is not possible.

In previous work [2b], best-available distribution data for over 230 squirrels has been obtained from the public record via GBIF.org and made available as model-predicted distribution maps. Here, we make use of that public data set and its summary of hot-spots and cold-spots.

Moving beyond coarse global model predictions one can look at IUCN's Top 10 most endangered squirrel species. So we identified in previous work that the genera *Geosciurus*, *Heliosciurus*, and *Paraxerus* were responding strongly to the climate in their distribution modeling [2c]. We therefore used those four cohorts (1. all global squirrels, 2. IUCN's Top 10 most endangered squirrel species, 3. genus *Geosciurus*, 4. genera *Heliosciurus* and *Paraxerus*) for a Meta-Analysis summary, testing how these squirrel groups respond in the absence of detailed studies to future climate scenarios (1. cold, 2. business as usual, and 3. hot) for a first and generic trend.

To illustrate such scenarios, a hypothetical trend model can be seen in Figure 1. This model presents the development of the squirrel population during the last approx. 2000 years, with slowly rising population metrics. From the current day until 2100 and further, the future is unknown. Therefore, four possible population trends have been presented here in Figure 1 which are considered likely for the future. Those models can be done with different algorithms – aspatially and spatially (e.g. [5], [6]).

Throughout this study, such scenarios of climate and the future squirrel population changes (as presented in Figure 1) will be discussed.

Here we aim to present first distribution forecasts for the global squirrel population and four cohorts - - usually an overlooked group in such assessments and legal policies [3]. This aims to start a discussion and to outline the severity of climate change on squirrels, as one aspect of the living world, including future trends towards a higher predicted frequency of zoonotic disease transmission.

Methods

Species Model and Cohort prediction layers

We were able to obtain over 230 SDM layers which are based on 132 environmental predictors ([2b], *sensu* [7]) as ASC (.asc) files which were created with Maxent [8], [9], [10]. These 233 files contain for each squirrel species in the world the individual species distribution model (SDM). Those were then converted into TIFF (.tif) files, and summarized in open-source QGIS and ArcGIS using the Raster Calculator analysis tool to create Global distribution hotspots and coldspots by MS. In principle, this tool merges all SDMs into one file which then allows summarizing the distribution of all its componential species at once (as attempted previously by [11] with other methods and a smaller sample size).

We then selected the 10 most endangered squirrel species by using the IUCN Red List as a reference (www.iucnredlist.org). In principle, we selected all squirrel species that have been classified as critically endangered and as endangered (See Table 1.4 in Chapter 1 – [2], and IUCN Red List. These two conservation classes contain combined 17 squirrel species, however, since for 7 of them no distribution data is available from GBIF.org (download DOI: https://doi.org/10.15468/dl.665b59), only 10 squirrels were able to be included. Table 1 presents these 17 squirrel species and indicates which ones have been used for this and further analyses. Those 10 were extracted from the SDM set (from Chapter 3 – [2]) and summarized as hotspot and coldspot maps by using the raster calculator tool in ArcGIS.

Table 1
List of the 17 most endangered squirrel species according to the IUCN Red List

Species	Conservation status (IUCN)	General Occurrence	Occurrence Reference	Included in the analysis
Ammospermophilus nelson	Endangered	California, USA	SDM -Appendix Chapter 3	Yes
Biswamoyopterus biswasi	Critically Endangered	Namdapha National Park, Arunachal Pradesh, India	IUCN Red List, (Molur, 2016)	No
Cynomys mexicanus	Endangered	Central Mexico	SDM -Appendix Chapter 3	Yes
Cynomys parvidens	Endangered	Southern Utah, Norther Arizona, USA	SDM -Appendix Chapter 3	Yes
Eupetaurus cinereus	Endangered	Karakoram Range	IUCN Red List, (Zahler, 2010)	No
Hylopetes sipora	Endangered	Palau Sipora, Sumatra, Indonesia	IUCN Red List, (Lee, 2016a)	No
Iomys sipora	Endangered	Mentawi, Sumatra, Indonesia	IUCN Red List, (Lee, 2016b)	No
Marmota sibirica	Endangered	Mongolia	SDM -Appendix Chapter 3	Yes
Marmota vancouverensis	Critically Endangered	Vancouver Island, Canada	SDM -Appendix Chapter 3	Yes
Neotamias palmeri	Endangered	Las Vegas, Nevada, USA	SDM -Appendix Chapter 3	Yes
Paraxerus vincenti	Endangered	Northern Zambezia, Mozambique	IUCN Red List, (Kennerley & Kerbis Peterhans, 2016)	No
Prosciurillus weberi	Endangered	Malangke, South Sulawesi, Indonesia	IUCN Red List, (Musser et al., 2019)	No
Pteromyscus pulverulentus	Endangered	Malaysia, Sumatra, Indonesia	IUCN Red List, (Clayton, 2016)	No
Spermophilus citellus	Endangered	Eastern Europe	SDM -Appendix Chapter 3	Yes
Tamiasciurus mearnsi	Endangered	Baja California, Mexico	SDM -Appendix Chapter 3	Yes
Urocitellus brunneus	Endangered	Idaho, Oregon, Washington State, USA	SDM -Appendix Chapter 3	Yes
Xerospermophilus perotensis	Endangered	Mexico City, Mexico	SDM -Appendix Chapter 3	Yes

Further, we also used the genera *Geosciurus* as one group, as well as *Heliosciurus*, and *Paraxerus* combined as another species group, from the global set of 233 squirrel species. These three species groups have been selected for a specific reason: namely, in our assessment (see [2b]), they responded most significantly to climate predictors in the meta-analysis. The species from the genus *Geosciurus* responded most significantly to the IUCN conservation status classes Meta-analysis, and the genera *Heliosciurus* and *Paraxerus* responded most significantly to the IUCN population trend metric of the Meta-analysis. The species from the latter two genera have been merged since they occur in the same regions and very similar environments and have responded highly similar to the climate predictors. Similarly as above, those were then extracted from the SDM set and their hotspot and coldspot maps have been created in raster calculator using the raster calculator tool in ArcGIS.

Climate Scenario predictor data

The state of the climate 2100 is uncertain, and not well-agreed upon for a commonly used approach, namely, what models and future scenarios employ and how to approximate future conditions such as for 2100 [12], [13], [14]. Worldclim.org (BioClim) offers good and transparent data with options to do so, and here we used seven BioClim predictor layers and one elevation predictor to describe an assumed 2100 [15]. The elevation layer is also obtained from Worldclim.org, however, here it is often left out in the discussions as it is a layer of reference that will likely not change between 2000 and 2100. We then implemented the three scenarios as described by the following authors ([16] for MRI, [17] for IPSL, [18] for MIROC).

Climate Modeling with Bioclim Predictors and for 2100

The hotspot and coldspot maps were derived from SDMs based on 132 environmental predictors. However, those predictors do not all exist for 2100. Therefore, we used instead agreed-upon 2100 matching proxy predictors from Worldclim.org (BioClim) to transfer models in the climate space. Namely, we used BIO1, BIO7, BIO 10, BIO11, BIO12, BIO16, and BIO 17 (see predictor overview in the table of Supplemental Information 3). We recognize their limits and making models coarser when using 7 predictors instead of 133 but in the absence of better information on a global scale for 2100, that is what has been used, as commonly done elsewhere across locations and disciplines [12], [13], [14], [19].

In order to present different climate scenarios, we have used three Global Climate Models (GCMs) that have also been utilized by WorldClim.org (MIROC6, MRI-ESM2-0, and IPSL-CM6A-LR). For this study, the MIROC6 scenario may be considered as the low-temperature increase scenario, even as a certain cooling scenario [18]. The MRI-ESM2-0 scenario is considered as a low-medium temperature increase of an approximate global increase of 2 degrees Celsius [16]. One might refer to it as a '*business as usual*' model. Lastly, the IPSL-CM6A-LR scenario is considered as a medium-high increase of temperature of approx. three degrees Celsius [17]. While this is perceived as a high/ extreme scenario, it should be stated that climate change – and when left unabated – has no real limits and can increase way beyond ten degrees Celsius (see [20] for parts of the Arctic easily reaching 12 degrees Celsius and more).

We then modeled the four squirrel cohorts (Global Squirrels, Top10 Endangered Squirrels, *Geosciurus*, as well as *Heliosciurus* with *Paraxerus*), with those seven Bioclim predictor layers (see predictor overview in the table of Supplemental Information 3) for the three scenarios of 2100 (MRI, IPSL, MIROC).

To be more robust and stable, and to increase the models' accuracy/ quality, we used ensemble-based three leading machine learning (ML) algorithms to do so: Random Forest & TreeNet (https://www.minitab.com/en-us/products/spm/), and Maxent (https://biodiversityinformatics.amnh.org/open_source/maxent/) (details in [21], [22]).

For the mapping visualization, we used the Jenks (Natural Break) Legend with 5 categories in ArcGIS as this shows sufficient details of the changes and it suits the step-functions of the (tree-based) ML algorithms [23].

It is not our intention to focus on individual model details and differences here but instead let the models predict to their abilities and then infer (*sensu* [23], and [24]), using the common trends within the model predictions and scenarios and infer on those for prioritization and progress.

We then summarized generic evidence trends from those models and present them in a summary table as a meta-analysis (see approach for instance by [25]).

Results

The in-depth results obtained by the discussed methods can be found in the Supplemental Information section VII since they are fairly extensive for this main results section. However, to provide an overview of the results, they are presented below using a meta-analysis approach. Meta-Analysis

Table 2 summarizes our findings presented in the Methods Supplemental Information section(Supplemental Information VII) in form of a meta-analysis. This summary indicates that across the three scenarios and the three algorithms used, a drastic (tendentially not positive) change in the global distribution range of squirrels if we continue to pursue the 'business-as-usual' approach. We use a parsimonious approach and while most of our models underpredict reality when compared with the initial hotspot and coldspot maps, many metrics of the distribution will still change dramatically either way. Specifically, the ten Most Threatened Squirrels will be affected strongly. Generally, the most changes that are predicted to happen are observed for the metric "General core shift" which indicates a general shift of the core population/ distribution. Followed by the metric "Range decline", which indicates a general decline of the squirrel group's range. After these metrics, the most changes can be observed for the two metrics "Core zone shrinkage", and "Core zone fragmentation". "Core zone shrinkage" indicates in contrast to "Range declines", the decrease in size of the core distribution, compared to the overall distribution. The least amount of changes are observed for the metric "Shift towards flat areas". Thereby, a general shift towards flatter areas is not so likely, following the presented models, and this study's forecast.

Table 2
Summary of Meta-analysis of Distribution Metrics for hotpots and coldspots 2100 for Global Squirrels, Top 10 Endangered Squirrels, Geosciurus, Heliosciurus, and Paraxerus

	Feature of distribution								
Model type	Core zone enlargement	Core zone Shrinkage	Gene-ral core shift	Core zone shift North-wards	Core zone shift upwards in elevation	Shift towards flat area	Core zone frag-men-tation	Range de-clines	**Over-all aver-age**
All squirrels	0.44	0.44	0.67	0.44	0.56	0.00	0.56	0.67	**0.47**
Ten most threatened Squirrels	0.44	0.44	0.78	0.67	0.44	0.11	0.56	0.44	**0.49**
Geosciurus	0.11	0.67	0.67	0.22	0.33	0.11	0.56	0.67	**0.42**
Helioscius & Paraxerus	0.67	0.22	0.22	0.00	0.00	0.22	0.00	0.11	**0.18**
Overall average	**0.42**	**0.44**	**0.56**	**0.33**	**0.33**	**0.11**	**0.42**	**0.47**	**0.39/0.39**

Table 2 represents a summary of the Meta-analysis of the distribution metrics for hotpots and coldspots 2100 for Global Squirrels, Top 10 Endangered Squirrels, Geosciurus, Heliosciurus, and Paraxerus. This summary has been created based on the table presented in the Supplemental Information section2. There, greater details can be observed, where for each created model the changes from the current distribution and the modeled 2100 distribution are being described by the same metrics as in Table 2.

Discussion

Man-made climate change remains unabated, and CO2 release is widely not controlled, with often poor, lacking, or failing future outlooks [26], [27], [28], [29]. Using open access BIG DATA here, we were able to look at the best predicted SDM summary for over 230 squirrel species – a group that is somewhat ignored and marginalized with lacking science-based management, funding, and efforts; even the taxonomy is not agreed on [2a], [3].

We created globally important hotspot and coldspot maps and modeled them forward with bioclimatic variables from Worldclim.org (BIOCLIM), using 3 machine learning algorithms (for TreeNet, Random Forest, and Maxent), globally with 0.5-degree pixel accuracy.

We used three climate scenarios, namely MRI, ISPL, and MIROC. Those come from a wide variety of possible climate scenarios. To start the rapid assessment here, we tried to show three scientifically accepted climate scenario models and apply them to the world's squirrels and some genera belonging to them. Our results indicate underpredictions but already show a generic distribution shift for the majority of squirrel species, especially for the World's Top Ten Squirrel species. Most importantly, we see a shift of the core ranges, as well as a fragmentation of the distribution for squirrels. Such patterns are known to result in population stress, often extinction, especially in island environments [30], [31], [32], [33], [34]. To summarize, an overview of some globally observed trends has been created (Table 3).

Table 3
Selection of landscapes and habitats affected for squirrels by our 2100 models

Landscape/habitat	Selection of countries affected	Comment
Europe	Germany, France, Switzerland, UK, Italy, etc.	A heavy fragmented squirrel habitat and clear shift to Scandinavian/ North-Eastern countries
Western North America	U.S.	A key region for squirrel biodiversity with high abundance
Latin America	Brazil, Ecuador	A key region for squirrel biodiversity
Central America	Costa Rica, Panama	A key region for squirrel biodiversity
Central Asia	Kazakhstan	A key region for squirrel range expansion with higher squirrel density and diversity
North Africa	Algeria, Morocco, Tunisia	Becomes less interesting for an increased warming scenario (MRI, IPSL), but more interesting for cooling scenarios (MIROC).
South Africa	South Africa	Becomes a habitat less desired and populated by squirrels
S.E. Asia	Indonesia, Malaysia	A very diverse landscape with high squirrel biodiversity, but also extinction
Islands		A key area affected by climate change shifts
Mid-elevation mountains	Austria, Switzerland, Alps	A key region for squirrel refugium
Tropics	Brazil, Congo, Indonesia, Malaysia	A key region for squirrel biodiversity
Boreal Forest	Russia, Canada, Alaska	A key region for northern squirrel species

As seen in the maps and a selection presented in Table 3, for landscapes and habitats affected, it is clear that Central America, as well as Latin America, are future conservation hotspots for squirrels, even genera that currently do not occur in this part of the world would flourish there well. The same can be said for Central Europe, parts of western North America, Central Asia, and parts of North and South Africa, and the entirety of South-East Asia. Islands should receive the most attention, as well as some mid-elevation mountain areas, the tropics overall, and also the boreal forest and parts of Patagonia.

These indicated squirrel hotspot regions correlate not surprisingly with the global hotspots of zoonotic disease transmission recently published by [35]. Especially the disease transmission for rodents correlates with the squirrel hotspots. Within these squirrel hotspots, one can find rural, and suburban areas, but also urban areas with a high human density. All this together indicates that the frequency of zoonotic disease transmission between rodents (squirrels) and humans is on the rise, negatively influencing both parties -[36], [37], [38].

This approach here aims to utilize holistic assessment methods and to initiate/ present a workflow with data [39]. We here tried to present the global species trend and some rough subdivisions in order to publish a global big-picture of the situation for rapid assessment actions. In depth-analyses are always a follow-up option that can be achieved starting with the data and methods used and presented here, e.g. by using a regional or species-specific approach (see the

Tropics [2d] and Islands [2e]). The rapid assessment methods used here, primarily aim to present and start such views and initialize debates and discussions on this topic. Without acknowledging a marginalized and undesired scenario/outlook, no betterments can be expected.

While our models just deal with bioclimatic predictors as proxies for the future, the real-world changes in the next 100 years are likely bigger, more complex, and severe. For instance, human population increase is expected, more consumption of natural resources, increased contamination, more pandemics, and loss of wilderness. We believe that our models represent a minimum estimate of what is to come and what squirrels are facing, and those findings should present a good foundation for sustainable action.

We acknowledge that the true future remains unknown; there is no single solution to knowing what 2100 will be like. Here we had to use a narrow and parsimonious approach still. But arguably, the patterns and trends we see are robust, and they are already a concern and most of them are not in favor of a good future for these species in the Anthropocene [40], [41], [42], [43], [44].

Declarations

Data availability

All data generated or analyzed during this study are included in this published article (and its Supplementary Information files).

Author contributions

MS and FH initiated this work together, FH ran and created the TreeNet and Random Forest models and drafted the manuscript. MS ran and created the Maxent models, created most of the tables, and Figure 1. Additionally, MS extended the manuscript text and added the references.

Competing interests

The authors declare no competing interests.

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Figures

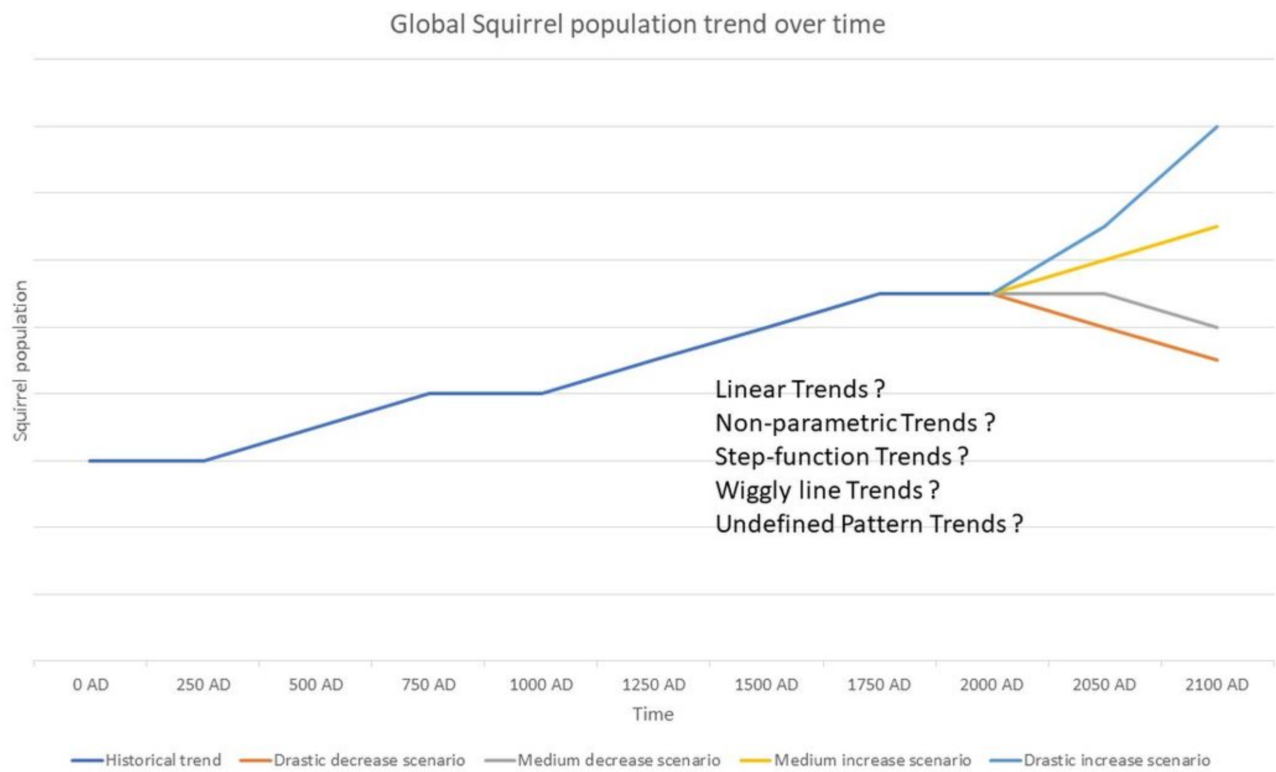

Figure 1

Squirrel population over time with forecast to 2100

Supplementary Files

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- SupInfo1CalibrationGeosciriusRFFH1.jpg
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- SupInfo1CalibrationGlobalSqRFFH1.jpg
- SupInfo1CalibrationGlobalSqTNFH1.jpg
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