Zoodiversity, 60(2): 149–162, 2026

DOI 10.15407/zoo2026.02.149
UDC: 599.323.4:001.891.57 (1-021.21)

PATTERNS OF RANGE FORMATION IN PALAEARCTIC MICE (MURINAE) BASED ON ECOLOGICAL NICHE MODELLING

S. V. Mezhzherin* & Y. V. Kozlov

I. I. Schmalhausen Institute of Zoology, NAS of Ukraine,
vul. B. Khmelnytskogo, 15, Kyiv, 01054 Ukraine

* Corresponding author

E-mail: s.mezhzherin@gmail.com

S. Mezhzherin (http://orcid.org/0000-0003-2905-5235)
Y. Kozlov (https://orcid.org/0009-0002-8918-6085)

urn:lsid:zoobank.org:pub:8F97FBEA-285B-492C-BE47-AB4724F28AE8

Patterns of range formation in Palaearctic mice (Murinae) based on ecological niche modelling. Mezhzherin, S. V., Kozlov, Y. V. — The home ranges of 25 non-synanthropic Murinae species from the Palaearctic were estimated by modelling their ecological niches using 19 bioclimatic variables. On average, the area with a predicted probability of species presence in suitable habitats of >50% (hereafter referred to as the home range) exceeds the species' range by 10%; the area with a probability of >75% is the same size as the range; and the area with a probability of > 95% is 11% smaller than the range. Meanwhile, the area projected as suitable for species presence at a probability level >50% under the climatic conditions expected in the period 2061–2080 does not differ in size from the current home range. However, as the range increases, the proportion of climatically suitable habitat not occupied by the species decreases. Consequently, the mean potential expansion is approximately 1.5% in the Euro-Siberian bioregion, where ranges are largest; 10.5% in the Mediterranean bioregion; and 14% in the Central-East Asian bioregion. The reason for the limitations of species' ranges at the northern limit of the subfamily's distribution is that home ranges are more fully realised with respect to bioclimatic factors. This implies that geographic constraints on dispersal act as the principal limitation of ranges in the south, determining their smaller size. The diffuse range expansion model is likely to be adequate for species in the Euro-Siberian bioregion, whereas the salvo-invasion model is more suitable for species in the Mediterranean and Central-East Asian bioregions. This suggests that southern mouse species could be considered potential invaders.

Key words: ecological niche modelling, home range, Murinae, Palaearctic Region, Rapoport's rule, biological invasion.

Introduction

The search for patterns in the formation of species ranges, and the analysis of the factors determining their location, size, and dynamics, constitutes a conceptual direction of biogeography (Guisan et Zimmermann, 2000; Guisan et al., 2006; Meynard et al., 2025). Several theoretical aspects remain underdeveloped, making this research particularly relevant. A key question that remains unresolved is what determines range size: the ecological characteristics of a species (the breadth of its ecological niche), or the geographical circumstances associated with geographic constraints on dispersal? Identified in the 1960s (MacArthur, 1972), this biogeographic dilemma continues to be the subject of research in the 21st century (Gaston, 2003, 2009; Sexton et al., 2009; Peterson et al., 2011; Lee-Yaw et al., 2016).

Another controversial issue concerns the relationship between range sizes and their spatial distribution. Rapoport's ecogeographical rule (Rapoport, 1982; Stevens, 1989) is relevant here: it postulates that latitudinal extents of species' ranges are smaller at lower latitudes than at higher latitudes. With respect to the Palaearctic, this tendency is evident in many cases and often does not require special analysis. The rule has stimulated studies of geographic patterns of species distribution (Stevens, 1992, 1996; Arita et al., 2005; Dyer et al., 2020). However, subsequent analysis (Gaston et al., 1998) raised doubts about the universality of Rapoport's rule. In that context the same dilemma arises: when the pattern is observed, is it determined by ecological factors or by geography?

The capacity of species to expand their ranges to varying degrees has not been sufficiently explored. Current research addresses plant species (Svenning & Skov, 2004; Dullinger et al., 2012), to varying extents particular groups of invertebrates (Pfenninger et al., 2007) and vertebrates (Cunningham et al., 2016; Nekrasova et al., 2019). Nevertheless, it remains unclear which species are more prone to range expansion and, accordingly, to expansion/invasion: those with large ranges or those with narrow ranges. This property, like range size itself, may depend both on the ecological characteristics of the species and on the geography of the range.

Answers to these questions can be obtained by modelling the ecological niche using a broad interpretation of the home-range concept (Burt, 1943) — i. e., by predicting suitable territory based on the distribution of bioclimatic parameters (Guisan et Zimmermann, 2000; Tytar, 2011; Alvarado-Serrano & Knowles, 2014; Dallas & Kramer, 2022; Chen et al., 2024), defining the area suitable for a species' full existence, and then comparing it with the actual range. A priori, any home range should consist of the range confirmed by specimen finds and a zone of potential presence, where the species has not been recorded but bioclimatic conditions are suitable. Obviously, if a range is predominantly limited by bioclimatic circumstances, the homerange area should approach the size of the range. However, if purely geographic constraints on dispersal are of fundamental importance, the home range will clearly exceed the range.

A suitable object for such a study is the subfamily of true mice, Murinae of the Palaearctic region. The Palaearctic is the largest realm, characterised by sharply contrasting bioclimatic conditions and highly variable range sizes. Mice are a southern group of rodents of tropical origin within the Palaearctic and include about 30 species with different levels of genetic differentiation, belonging to five genera. An important component ensuring the correctness of the study is the taxonomic revision of the two most species-rich genera represented in the Palaearctic, *Apodemus* Kaup, 1829 sensu lato and *Mus* Linnaeus, 1758 (Mezhzherin, 1997 a; Musser & Carleton, 2005; Auffray & Britton-Davidian, 2012; Mezhzherin & Tereshchenko, 2023), based on numerous genetic studies (Mezhzherin, 1997 b; Filippucci et al., 2002; Bellinvia, 2004; Liu et al., 2018; Ge et al., 2019). This allows operation with taxa of clear status and strictly defined range boundaries. The goal of this study was to identify trends in range formation for this group of species based on ecological niche modelling, and to determine the sizes of theoretical distribution zones for species beyond their current ranges and the patterns of their distribution.

Material and Methods

Modelling objects. Home ranges of 25 non-synanthropic mouse species of the Palaearctic were modelled based on range maps provided in The IUCN Red List of Threatened Species (IUCN, 2025). Exceptions were *Sylvaemus flavicollis* (Melchior, 1834) and *S. ponticus* (Sviridenko, 1936), the ranges of which in that database are incorrect; for these species the author's interpretations were used (Mezhzherin, 1997 a).

Species were classified into three bioregions based on their range characteristics (Table S1).

Data sources. Ranges of the designated species were taken from The IUCN Red List (2025) in ESRI Shapefile format, provided in the unprojected geographic coordinate system WGS 1984 (EPSG:4326). To calculate areas, the sf package in R version 4.3.3 was used.

Forecasts of areas were made using two independent sources of primary data. The first approach used species occurrence records obtained from the Global Biodiversity Information Facility (GBIF; https://www.gbif.org). The principal period considered was 1970–2000, corresponding to the period of the bioclimatic data. For narrow range species, if the number of records in the GBIF database for this period was fewer than 10, which is insufficient for reliable modelling (<10) (Pearson et al., 2007), records from other periods were included. Prior to modelling, raw occurrence data underwent rigorous spatial filtering: (1) removal of records located at sea or outside the terrestrial boundaries of the Palaearctic; (2) exclusion of records identified as fossil, captive, zoo, or garden occurrences; (3) exclusion of records with coarse spatial precision (for example, coordinates reported only at one-degree resolution) or with evident geographic errors, which may reflect species misidentification or data-entry inaccuracies; (4) for species with an excessive number of presence points (>500), the data were rarefied using the spThin package (Aiello-Lammens et al., 2015).

The second approach followed the standard procedure of generating theoretical presence points located at centroids of grid cells intersecting species ranges (Tytar, 2011). The Palaearctic territory (Kryzhanovskiy, 2002; quoted in Beron, 2018) was transformed to a Lambert azimuthal equal-area projection using SAGA GIS (Conrad et al., 2015) and divided into 354 numbered squares with a side length of 450 km. A single hypothetical occurrence point (the centroid) was generated within each grid cell that intersected the species' range.

Modelling procedure. Occurrence samples for each species were divided into training (90%) and test (10%) subsamples. When high spatial autocorrelation was detected (> 0.4), the test sampling volume was increased to 45%. The balanced_cluster_split function was used for spatial blocking (Valavi et al., 2018). The balance was 1:1 (presence:pseudo-absence) as recommended by Barbet-Massin et al. (2012) and Rausell-Moreno et al. (2025).

In all cases except *A. hyrcanicus*, test sets for square models were the same as for point models. This methodological independence addresses the problem of obtaining truly independent external presence data to test the second approach, since it uses actual detection points and provides a more robust and conservative estimate of model generalizability than traditional internal validation of square models, which would otherwise be performed on pseudopresence points (centroids). In the case of *A. hyrcanicus*, due to the small sample (4 centroids and 15 points), the test sets for the square model were the training subsamples of the point model (15 points) of *A. hyrcanicus*, and for the point model the test sets were the training subsamples of the square model (4 points), respectively.

Pseudo-absences were placed randomly outside species ranges across the land region 25° W–180° E, 0–90° N. The choice of this extensive region, which essentially covers the majority of the Palaearctic, was deliberate to align with the macroecological scale and the specific goals of this study.

To model species distributions, the Bayesian Additive Regression Trees (BART) algorithm was used with hyperparameters optimised for both small and large samples. The principal model was fitted to normalised training data using bart.step from the embarcadero package (v.2.0.0), which implements modified algorithms for environmental modelling (Chipman et al., 2010).

Projections were performed for 2061–2080 using the Earth System Model IPSL-CM6A-LR (Institut PierreSimon Laplace, France) under the SSP2-4.5 scenario (a moderate emissions pathway). For a detailed description and evaluation of the IPSL-CM6A-LR model, see Boucher et al. (2020).

Model accuracy was assessed by differences in AUC, TSS and spatial autocorrelation indices (Moran's I) between training and test subsamples.

Analysis of limiting bioclimatic factors. The study included 19 normalised bioclimatic variables (WorldClim v2.1, 1970–2000) (Fick & Hijmans, 2017), as well as normalised elevation above sea level and latitude and longitude coordinates where inclusion reduced autocorrelation. Data for test subsamples and projections were normalised using thresholds derived from the training subsamples (min–max scaled to 0–1). Spatial resolution varied from 30 arcseconds (~1 km, for point models) to 2° (for square models in the case of *S. flavicollis*), depending on sample size, data quality, and model stability.

The significance of each bioclimatic factor in habitat formation was assessed using two sets of primary data by comparing mean values of specific factors within predicted habitats and outside them. A key feature of the analysis was the search for patterns in the influence of groups of factors on species at the bioregional level, rather than focusing solely on the influence of individual factors on individual species. To this end, the statistical significance of a factor's influence on a given species' range was first assessed using the t-test. Next, the mean t-test t-statistic for that factor was calculated across species, taking into account the direction of differences at the bioregional level. The average regional values were then used to determine the mean influence of each factor on Palaearctic mice ranges as a whole.

Concepts and thresholds used. Range: the geographic distribution of a species established from actual records of specimens. Theoretical zones of predicted suitability**:** calculated using standardised speciesspecific thresholds based on maximum predicted probability (Pmax) and a pseudo-absence threshold (Cutoff), which reflects the likelihood of species occurrence in a given area. Habitat suitability classes**:** three probability levels were defined. First, the home range or general suitable area — a zone of possible expansion where individuals occur with probability ≥ 50%. Second, the central core of the home range — a zone where individuals are concentrated with probability ≥ 75% (probability > Cutoff; core area). Third, the high suitability core — a zone where individuals are concentrated with probability ≈ 95% (operationalised as probability ≥ (Pmax – Cutoff) × 0.9 + Cutoff).

Results

Analysis at the Palaearctic scale

Range sizes of Palaearctic mice vary widely. Minimum and maximum areas differ by more than three orders of magnitude (Table S2), with an average range size of 2.8 million km^2. As a result, 19 of the 25 species had range sizes smaller than the mean, producing a markedly skewed distribution (mean/SD = 2.8/4.43 million km^2) (Fig. 1). Using the common logarithm normalises the distribution (mean/SD = = 5.90/0.16) (Fig. 2).

The largest empirical areas belong to the Trans-Palaearctic species *Micromys minutus* (18.2 million km^2) and *Apodemus agrarius* (11.5 million km^2), whose distribution largely falls within the Euro-Siberian bioregion. Other species of this zoogeographic zone also have very extensive ranges. Moreover, the distribution area of the eastern species *A. peninsulae* exceeds the ranges of the western species *S. sylvaticus*, *S. flavicollis* and *S. uralensis* (8.9 versus 5–7.2 million km^2). The ranges of island species *A. speciosus* and *A. argenteus* are predictably smaller (~0.3 million km^2) than those of mainland species. Most southern species have relatively small ranges, from 0.1 to 0.96 million km^2. Only four southern species (*S. arianus, M. macedonicus, A. draco, R. pyctoris*) have ranges close to the mean of 1–2 million km^2; the latter two, representing the Eastern Palaearctic, have larger ranges. The minimum ranges are found in one Mediterranean species, *S. hyrcanicus* (0.05 million km^2), and two East Asian species, *A. semotus* (0.03 million km^2) and *A. gurkha* (0.01 million km^2) (Table S2). These trends persist when range sizes are evaluated on a logarithmic scale (Table S3).

Average areas of species' distribution zones calculated from specific occurrence records and from theoretical centroid points within range squares do not differ statistically (Table S3). This circumstance permits the combined use of generalised data obtained from different primary data sets.

The average area of the home range (the zone with ≥50% probability of presence), calculated from results obtained for both occurrence points and range squares together

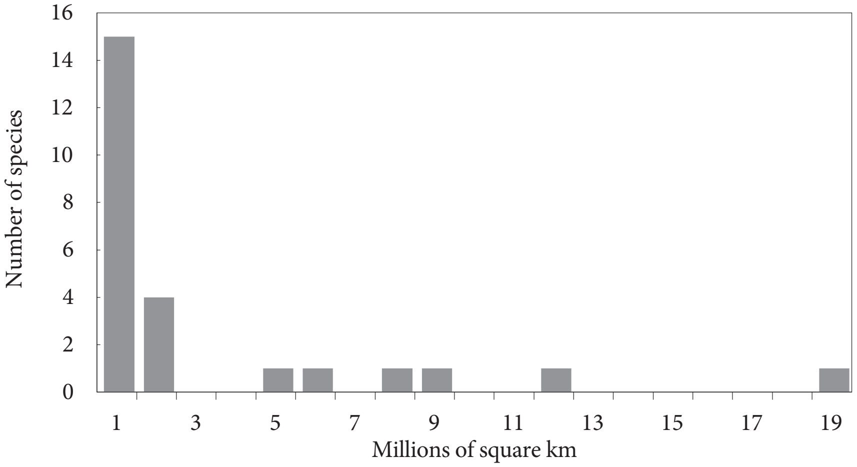

Fig. 1. Distribution of the ranges of Palaearctic mice by absolute area (millions of km^2)

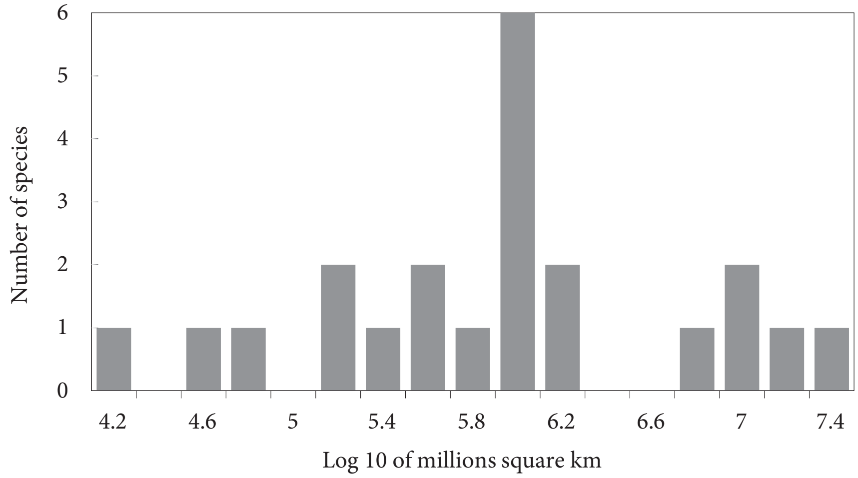

Fig. 2. Distribution of the ranges of Palaearctic mice by decimal logarithms of absolute areas ($\log_{10}$ (area in million km^2))

and presented in Table S3, amounted to 6.46 $\log_{10}$ (area in million km^2) (SE = 0.09; N = 50), while the average area of ranges was 5.90 $\log_{10}$ (area in million km^2) (SE = 0.16; N = 25), which is significantly smaller ($t = 3.02$; df = 75; $p < 0.01$). The zone with ≥75% probability had mean $\log_{10}$ area 6.09 (SE = 0.10; N =50) and does not differ in size from ranges ($t_{st} = 1.03$; df = 75; $p > 0.05$). The zone with ≥95% probability (M $\log_{10}$ = 5.28; SE = 0.11; N = 50) is smaller than the average range ($t_{st} = 3.2$; df = 75; $p < 0.01$). The predicted distribution area for 2061–2080 averages $\log_{10}$ = 6.45 (SE = 0.09; N = 50), which is larger than modern ranges ($t = 3.0$; df = 75; $p < 0.01$) and is almost identical to the average homerange values ($t_{st} = 0.01$).

This means that the average home range (area with ≥50% probability of presence), as well as the distribution zone simulated for 2061–2080, exceeds the average range of Palaearctic mouse species by approximately 10% (the ratio of home range to range is 1.095); the zone with ≥ 75% probability does not differ from the range (ratio 1.032); the zone with ≥ 95% probability is only 89% of the range (ratio 0.893).

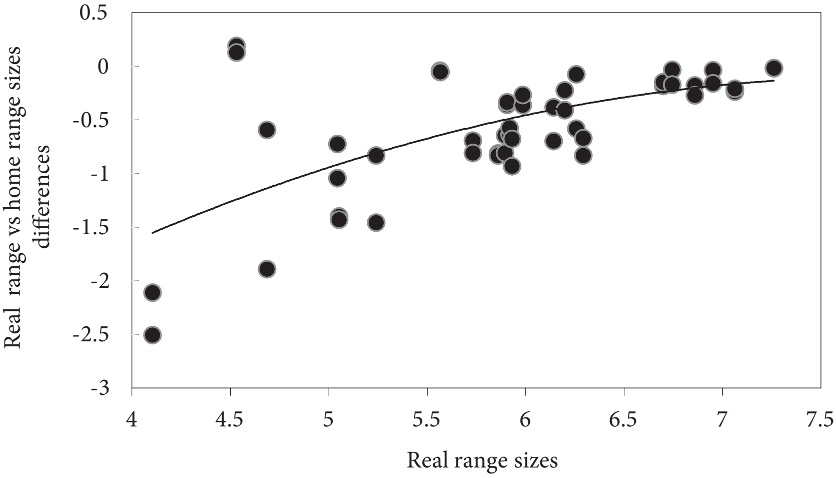

Fig. 3. Scatterplot of the realization of the home range ($\log_{10}$ million km^2) calculated from differences between range and home range sizes ($\log_{10}$ million km^2) for Palaearctic mouse species. There is a significant positive correlation between range sizes and range vs home range size differences ($r = 0.61$; $N = 50$; $p = 3E6$) as well as a significant effect of range size on variation of range and home range size differences (oneway ANOVA, $F = 5.0$; $df1 = 3$; $df2 = 46$; $p = 0.005$)

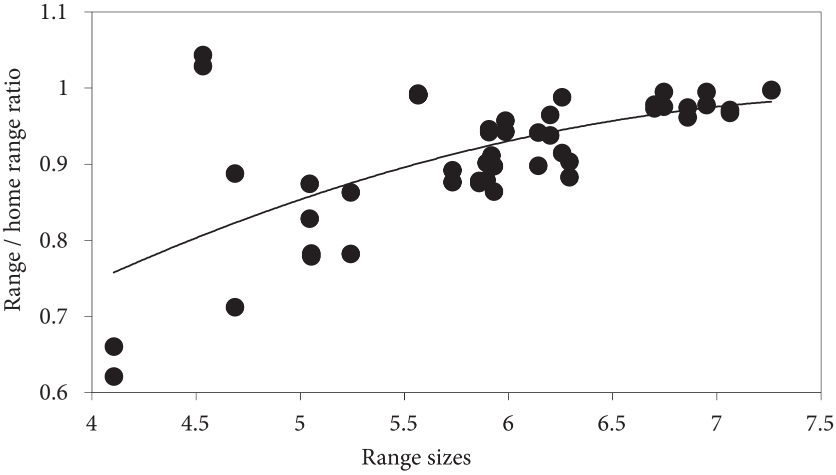

Fig. 4. Scatterplot of the realization of the home range calculated from the range/home range size ratio for Palaearctic mouse species. There is a significant positive correlation between range sizes and range/home range ratio ($r = 0.62$; $N = 50$; $p = 2E6$) as well as a significant effect of range size on variation of range/home range ratio (oneway ANOVA, $F = 5.2$; $df_1 = 3$; $df_2 = 46$; $p = 0.004$)

The degree to which the home range is filled by the range exhibits speciesspecific variation. Furthermore, the larger the species' range, the higher the realization of its home range. This trend is evident from analysis of both absolute (Fig. 3) and relative (Fig. 4) differences between empirical and home range sizes.

The relationship between range sizes and the degree of deviation from them by zones with different probabilities of presence in suitable habitats is apparent in three out of four possible comparisons. Thus, the mean correlation coefficient between range sizes and the differences (home range size — range size), calculated from four more specific correlation coefficients (Table S4), is $r = -0.63$ ($p < 0.001$).

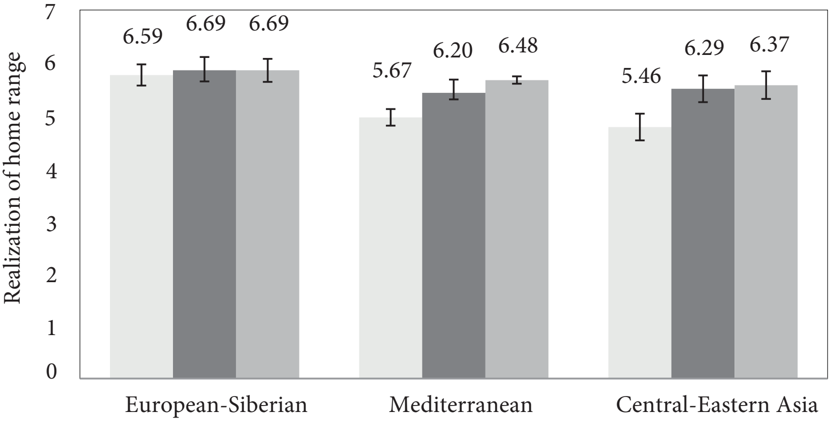

Fig. 5. Mean areas and standard errors of ranges (black bars) and home ranges calculated from occurrence points (dark gray bars) and range square centroids (light gray bars) for three Palaearctic bioregions. Note: area values are presented as $\log_{10}$ million km^2

The mean correlation coefficient obtained from comparing range sizes with the differences between ranges and the 75% presence zone is $r = -0.55$ ($p < 0.001$). The relationship between range sizes and the differences between ranges and the zone of potential distribution projected for 2061–2080 also yields a significant negative correlation ($r = -0.63$; $p < 0.001$). In contrast, a similar analysis for the zone above 95% presence shows a mean correlation coefficient that is not statistically significant ($r = -0.30$; $p > 0.05$).

Comparison of bioregions

Species of the Euro-Siberian bioregion have, on average, larger ranges than those of the Mediterranean ($t = 3.1$; $n = 17$; $p < 0.01$) and Central-East Asian ($t = 3.04$; $n = 17$; $p < 0.01$) bioregions (Table S5). The average range sizes of the Mediterranean and Central-East Asian bioregions do not differ ($t = 0.11$; $p > 0.05$). This trend also persists when comparing distribution zones with ≥75% and ≥95% probability (Table S5). However, average homerange sizes (≥50%) of different bioregions do not differ significantly (Fig. 5, Table S5).

Accordingly, there are no differences in the average sizes of the distribution zones of species in the three bioregions when modelled under the bioclimatic conditions of 2061–2080 (Table S5).

This uniformity of average homerange sizes among bioregions results from the decrease in range sizes of southern species compared to northern ones and from the negative relationship between range size and the degree of homerange reduction at the Palaearctic scale. This trend is statistically confirmed by smaller differences between average ranges and home ranges in the Euro-Siberian bioregion compared to the Mediterranean and Central-East Asian bioregions. It also persists when comparing differences between ranges and presence zones at the ≥ 75% level, but is not observed for differences with the ≥95% presence zone (Tables S6–S7, comparisons involving D-A).

The correlation of the average difference in habitat and homerange sizes to the sizes of home ranges shows that in the Euro-Siberian bioregion the implementation of home ranges is very high and amounts to 98.5%; in the Mediterranean bioregion the imple-

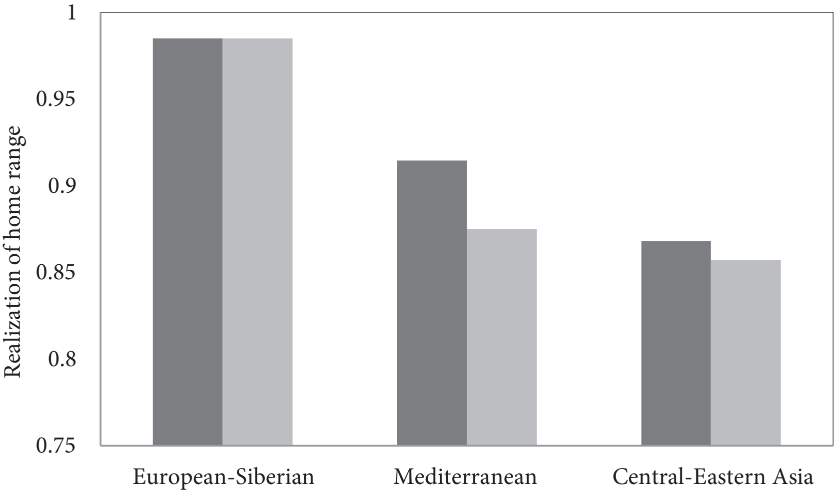

Fig. 6. Extent of home-range realization, estimated from calculations based on actual occurrence points (black bar) and range square centroids (gray bar). Note: bar sizes reflect the scale of modern ranges relative to the home range

mentation is lower at 89.5%; and in the Central–East Asian bioregion it is even lower at 86% (Fig. 6). Accordingly, the possibilities for expansion of habitats provided by bioclimatic circumstances are 1.5%, 10.5% and 14% for the three bioregions, respectively.

Analysis of bioclimatic factors

A generalized analysis of differences in mean values of 19 bioclimatic factors (Table S8) within and outside the ranges of Palaearctic mice yields the following results.

First. The number of bioclimatic factors limiting geographic distribution of species in the Euro-Siberian bioregion is significantly greater than in the Mediterranean and Central-East Asian bioregions. In calculations based on occurrence points, the incidence of significant differences in mean factor values for these regions is 15, 9, and 10, respectively, while in calculations based on range squares it is 11, 1, and 2, respectively (Table S8). This demonstrates the greater extent of homerange realization in the Euro-Siberian bioregion.

Second. The direction and magnitude of influence of bioclimatic factors across bioregions and between calculation methods correspond to each other (Table S9). The least correlated variability in the influence of bioclimatic factors is found between the Mediterranean and Central-East Asian bioregions, while the greatest correlation is found between the EuroSiberian and Central-East Asian bioregions. The correlation between variability of bioclimatic parameters in the EuroSiberian and Mediterranean regions is intermediate.

Third**.** Palaearctic territories occupied by mouse ranges are characterised by increased mean diurnal temperature range (BIO2), isothermality (BIO3), maximum temperature of the warmest month (BIO5), temperature annual range (BIO7), mean temperature of the wettest quarter (BIO8), mean temperature of the warmest quarter (BIO10), and precipitation seasonality (BIO15), together with decreased annual precipitation (BIO12), precipitation of the driest month (BIO14), and precipitation of the driest quarter (BIO17). This indicates that Palaearctic mice tend to occupy relatively warm regions of the Palaearctic with relatively low winter precipitation.

Discussion

The variability of range sizes and the results of modelling home ranges for Palaearctic mice permit the following conclusions.

First. Ranges of mice vary substantially in size, and primarily, there is a tendency for range area to change with latitude, which generally corresponds to Rapoport's rule (Stevens, 1989).

There is also a less pronounced trend of larger ranges among Eastern Palaearctic species compared to Western Palaearctic species. These trends can be explained by both environmental factors and purely geographic factors. In the latter case, the larger extent of the northern Palaearctic compared to the southern Palaearctic and the larger extent of the Eastern Palaearctic compared to the Western Palaearctic contribute to the observed patterns.

Second. The mean home-range occupancy rate for mice is approximately 92%, which is a high value and evidence of the ecological success of Murinae representatives in the Palaearctic. The lack of comparable data for vertebrates makes strict comparisons difficult. Thus, among 183 species of alpine plants, 31% have ranges that fill less than 50% of their home ranges (Dullinger et al., 2012). Low levels of home-range filling were also obtained for 55 species of woody plants in Europe (Svenning & Skov, 2004), which have an average occupancy rate of only 38%.

Third. Current home-range sizes of Palaearctic mice can be considered fairly stable, as they do not differ in size from home ranges predicted based on climatic conditions for 2061–2080.

Fourth. Palaearctic mice show a positive relationship between range size and the degree of home range expansion. Species in the southern Palaearctic, which are characterized by relatively small ranges, have larger potential ranges with suitable bioclimatic conditions than northern species with widespread ranges. This means that species in the Mediterranean and Central-East Asian bioregions have a much greater potential for range expansion than those in the EuroSiberian bioregion. Accordingly, it is highly likely that, given current climatechange trends, southern species will expand their ranges to a greater extent by 2080 than northern species.

Similar conclusions are drawn from ecological niche modelling of reptiles in Ukraine (Nekrasova et al., 2019), according to which southern species with Mediterranean type ranges can expand their primary ranges, while forest EuropeanSiberian species do not have such potential.

A study of comparable scope and design on patterns of range formation for 214 amphibian and reptile species within the United States produced largely similar results (Cunningham et al., 2016). For reptiles, northern range boundaries are determined by climatic factors, while southern boundaries are determined by unspecified circumstances; the opposite is true for amphibians. Furthermore, more unoccupied but climatically suitable areas were found beyond the southern range boundaries of reptiles.

The trend toward greater range expansion for species with narrow ranges seems paradoxical. One might expect range expansion to occur primarily through diffuse migrations at range margins. This mechanism, all else being equal, should lead to greater expansion of wide range species. However, modelling shows the opposite.

This implies that radical range expansions are more likely to occur through salvo invasions associated with penetration into new ecologically favorable regions. Southern species are likely to expand their ranges in this manner, while northern species tend to expand their ranges more through individual migrations. Clearly, a diffuse model of range expansion is appropriate for species in the Euro-Siberian bioregion, while a salvoinvasion model is more appropriate for the Mediterranean and Central Asian bioregions. This suggests that southern mouse species are potential invaders.

Fifth. Range boundaries of mice in the Palaearctic are shaped by both temperature and humidity factors, and the nature of these changes corresponds to the ecological preferences of species of tropical origin. Within their ranges, there is a clear trend toward increasing temperatures throughout the year and decreasing precipitation during the coldest period. Northern mouse species develop home ranges under the influence of a significantly greater number of bioclimatic factors than southern species. This means that, from an ecological perspective, range expansion of northern species is constrained by a larger number of climatic variables, whereas southern species are less tightly constrained by the suite of bioclimatic factors considered here and therefore retain larger areas of climatically suitable but unoccupied habitat. Consequently, southern species are more likely to realise range shifts through episodic, longdistance colonization events into newly suitable regions (salvo invasions), while northern species are more likely to expand gradually by diffuse range margin shifts.

Taken together, these results indicate that both ecological niche breadth and geographic context jointly determine observed range sizes in Palaearctic Murinae. Climatic suitability alone does not fully explain range limits: where predicted suitable area closely matches range, climatic factors appear to be the primary constraint; where predicted suitable area substantially exceeds range, geographic dispersal barriers and historical biogeographic processes are likely to play a dominant meaning. The high degree of home-range realization in the EuroSiberian bioregion suggests that climatic suitability and realised occupancy are closely aligned there, whereas the larger proportions of unoccupied suitable habitat in the Mediterranean and Central-East Asian bioregions point to stronger roles for dispersal limitation, habitat fragmentation, or other nonclimatic constraints.

These findings have several implications. First, they refine our understanding of Rapoport's rule in the Palaearctic by demonstrating that latitudinal trends in range size are accompanied by systematic differences in the degree to which climatic suitability is realised. Second, they identify southern Palaearctic Murinae as taxa with comparatively high potential for range expansion under changing climatic conditions, and therefore as groups warranting attention in invasionrisk assessments and monitoring programs. Third, the regional differences in limiting bioclimatic factors underscore the need for bioregionspecific conservation and management strategies: measures effective in the Euro-Siberian bioregion may not be appropriate in Mediterranean or Central–East Asian contexts.

Limitations of the present study should be acknowledged. First, ecological-niche models based on bioclimatic variables capture only one axis of species' ecological requirements; factors such as land use change, interspecific interactions, microhabitat availability, and anthropogenic barriers to dispersal were not explicitly modelled and may further restrict realised distributions. Second, although two complementary occurrence data approaches (GBIF records and rangesquare centroids) were used to mitigate sampling bias, uneven sampling effort and taxonomic uncertainties in some taxa may still influence model outputs. Third, projections for 2061–2080 were based on a single climate model and scenario (IPSL-CM6A-LR, SSP2-4.5); using multiple models and scenarios would provide a fuller picture of uncertainty in future suitability estimates.

Future research should integrate finer scale habitat and land use data, incorporate dispersal models and demographic processes, and employ multimodel climate ensembles to better constrain projections of range dynamics. Genetic and phylogeographic studies could further elucidate historical constraints on dispersal and colonization potential, while targeted monitoring of southern species at range margins would help detect early stages of expansion or invasion.

In conclusion, ecological niche modelling within the home range framework reveals that Palaearctic Murinae exhibit substantial variation in the degree to which climatic suitability is realised across species and bioregions. While climatic factors strongly delimit northern range boundaries, geographic and historical constraints appear to limit southern ranges, producing greater potential for expansion among southern species. These patterns highlight the joint importance of ecology and geography in shaping species ranges and emphasise the need for regionally tailored approaches to forecasting range shifts and managing invasion risk in a changing climate.

Data and Supporting information availability statement. All Supplements we used in our study can be accessed in https://codeberg.org/reviewer12345/Patterns_of_Range

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Received 27 October 2025
Accepted 22 April 2026