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GLOBAL CLIMATE CHANGE EFFECT ON ASIAN *MUS MUSCULUS*; IMPLICATION FROM LAST GLACIAL MAXIMUM TO THE END OF THE 21ST CENTURY

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Abstract.

Global climate change poses unprecedented challenges to biodiversity, prompting urgent investigations into its effects on various species. This study focuses on Mus musculus, a small rodent species and a crucial indicator of ecosystem health. Spanning from the last glacial maximum to the end of the 21st century, employed Species Distribution Models (SDMs) to assess the impacts of climate change on Mus musculus and its four subspecies across Asia (M. m musculus, M. m domesticus, M. m castaneus, and M. m bactrianus). The SDMs reveal nuanced responses among subspecies, with M. m. domesticus, and M. m. castaneus facing potential habitat contractions, while M. m. musculus and M. m. bactrianus shows habitat expansion. This heterogeneity emphasizes the adaptive capacity of different subspecies but also raises concerns about potential overpopulation and ecological imbalance, particularly in expanding habitats. The implications of these shifts extend beyond the individual species, suggesting potential disruptions in ecosystem dynamics, such as altered seed dispersal and changes in predator-prey relationships. From a practical perspective, results underscore the urgent need for tailored conservation strategies: subspecies facing habitat loss may require focused habitat restoration efforts, while those experiencing expansions may necessitate monitoring to mitigate potential overpopulation effects. Moreover, identifying and protecting climatic refugia will be essential for maintaining biodiversity and ecosystem stability in the face of shifting climate patterns. Variable importance analysis highlights the significance of temperature-related variables, indicating the growing impact of rising temperatures on distribution patterns. While models are supported by high Area Under the Curve (AUC) values, indicating robustness, it is important to recognize potential limitations and sources of uncertainty, which include data gaps and the assumption that species distributions are solely climate-driven. Present study not only contributes to the understanding of M. musculus responses to climate change but also provides actionable insights for conservation policy and biodiversity preservation initiatives in rapidly changing ecosystems.

Keywords: *Eurasia, Global warming, House mouse, Rodents, Small mammals*

Introduction

Over the past 150 years, the global average temperature of the Earth has risen by approximately 1.09°C, a phenomenon attributed to anthropogenic activities (Hughes 2000; Wan et al. 2022). This rapid climate change poses a significant threat to ecosystems worldwide, with 16–33% of vertebrates currently facing global endangerment or extinction (Grimm et al. 2013; Dirzo et al. 2014). The resulting disruptions in natural ecosystems extend to modifications in function and structure, impacting species distribution, behavior, phenology, and inter-species interactions (Grimm et al. 2013; Lenoir & Svenning 2015; Rubenstein et al. 2019; Weiskopf et al. 2020; Amir Afzali et al. 2024). Climate change-induced alterations in terrestrial animal ranges are well-documented, with many species shifting towards higher latitudes or elevations (Darvish et al. 2012; Amir Afzali et al. 2017; Chen et al. 2011; Román-Palacios & Wiens 2020). Among these species, small rodents, constituting approximately 42% of mammalian diversity, serve as crucial indicators of ecosystem function due to their short lifespan, high reproductive capacity, and wide distribution (Amir Afzali & López-Antoñanzas 2024; Wan et al. 2022). Notably, studies by Levinsky et al. (2007) suggest that future climatic changes may lead to a substantial reduction in mammalian species richness in the Mediterranean region, with contrasting increases in the northeast and at higher elevations. Small rodents like *Mus musculus* plays significant ecological roles, including seed dispersal, soil aeration, and serving as prey for a variety of predators. Changes in their distribution can have cascading effects on ecosystem dynamics, influencing plant communities and predator-prey relationships (Amir Afzali et al. 2018; Hulme-Beaman et al. 2019). To assess the impacts of climate change on biodiversity, particularly in the context of small rodent populations, Species Distribution Models (SDMs) emerge as invaluable tools (Araújo et al. 2005; Zhang et al. 2019; Yousefi et al. 2019; Amir Afzali 2024). These models utilize species presence points and climatic data to predict species distributions and have been successfully employed in various contexts, including identifying future species distribution, climatic refugia, changes in distribution, and evaluating the effectiveness of protected areas under current and future climates (Ashrafzadeh et al. 2019; Hoveka et al. 2020; Prieto-Torres et al. 2020; Ramírez-Albores et al. 2020; Petersen et al. 2021; Sierra-Morales et al. 2021; Vaissi 2021). Previous studies have applied SDMs to assess the impacts of climate change on various rodent species (Cameron & Scheel 2001; Meserve et al. 2011; Jiang et al. 2013; Bean et al. 2014; Latinne et al. 2015; Gutiérrez-Tapia and Palma 2016; Austrich et al. 2021; Shiels et al. 2022; Wan et al. 2022). However, there is a notable gap in understanding concerning the impacts of climate change on *M. musculus* specifically.

Therefore, this study employs SDMs to predict the effects of climate change on the distribution of *M. musculus* and its four subspecies across Asia (*M. m musculus* Linnaeus, 1758; *M. m domesticus* Schwarz and Schwarz, 1943; *M. m castaneus* Waterhouse, 1843; and *M. m bactrianus* Blyth, 1846). As this study delves into this investigation, it is essential to consider the potential cascading effects of climate change on *M. musculus* and its subspecies. Small rodents play a crucial role in ecological processes, including seed dispersal, predation, and as prey for larger predators (Amir Afzali et al. 2018; Hulme-Beaman et al. 2019). The intricate web of ecological interactions involving *M. musculus* makes it imperative to understand how changes in their distribution might reverberate throughout the ecosystem. Moreover, exploring the historical context of *M. musculus*'s response to past climate fluctuations, such as during the last glacial maximum, can provide valuable insights into their adaptive capacity. Investigating the species' resilience to climatic shifts over evolutionary timescales aids in predicting their potential responses to the rapidly changing climate of the 21st century.

This study aims to address several key research questions: I) How will climate change affect the distribution of *M. musculus* and its subspecies in Asia? II) What are the primary climatic variables influencing these distribution changes? III) How might these shifts impact broader ecosystem dynamics? This study not only addresses the current gaps in knowledge but also aims to lay the groundwork for understanding the complex dynamics between climate change and *M. musculus* populations. By examining the species' distribution over a vast temporal range, from the last glacial maximum to the present and projecting into the future, this study seeks to contribute to a comprehensive understanding of the challenges and opportunities these small mammals face in the wake of global climate change. The findings from this study highlight the need for targeted conservation strategies. Identifying and protecting climatic refugia, implementing habitat restoration efforts, and monitoring expanding populations are crucial steps in safeguarding *M. musculus* and its subspecies. Integrating these strategies into conservation policies will enhance the resilience of these populations against ongoing and future climatic changes.

Materials and Methods

Study area and occurrence points

Occurrence data for *M. musculus* and its subspecies were sourced from the Global Biodiversity Information Facility (GBIF.org, 2023), providing a comprehensive dataset for the study. Additionally, incorporated opportunistic observations made by the author, enriching the dataset with localized insights. Upon compilation, the collected data underwent a rigorous processing phase to ensure accuracy and reliability. The distributions of *M. musculus* and each subspecies were meticulously mapped individually, employing Geographic Information System (GIS) techniques to visualize and analyze spatial patterns (Fig. 1). To maintain data integrity, conducted a thorough examination, removing outliers and duplicates that might compromise the precision of the analysis. This process involved the careful scrutiny of spatial coordinates and cross-referencing against existing literature and taxonomic databases. Following the quality control measures, the dataset comprised 340 records for *M. musculus* (ALL), 82 records for *M. m. domesticus* (DOM), 32 records for *M. m. musculus* (MUS), 205 records for *M. m. castaneus* (CAS), and 21 records for *M. m. bactrianus* (BAC). Each record represents a crucial data point contributing to the understanding of the distributional dynamics of *Mus musculus* and its subspecies across the studied region. The spatial distribution map (Fig. 1) provides a visual representation of the geographic spread of *M. musculus* and its subspecies within the study area, offering insights into their ecological preferences and potential habitat associations. This robust dataset forms the foundation for Species Distribution Models (SDMs), enabling to predict and analyze the potential impacts of climate change on the distribution of *M. musculus* across Asia.

Potential Biases in Data Collection

Geographic and temporal gaps can introduce biases in the dataset. Geographic gaps may arise due to uneven sampling effort across different regions, potentially leading to an underrepresentation of certain areas. Temporal gaps could be due to varying time frames of data collection, which may not capture recent changes in species distribution. To mitigate these biases, data were cross-referenced with existing literature and taxonomic databases, and robust quality control measures were employed. Despite these efforts, it is essential to consider these potential biases when interpreting the findings.

Climatic variables

Nineteen bioclimatic variables were obtained from the WorldClim series (Hijmans et al. 2005; http://www.worldclim.org) to characterize the environmental conditions for our species distribution models under Last Glacial Maximum (LGM), Current Condition (CC) and Future projection (F). CCSM4 used as general circulation model for the last glacial maximum and Future projection. For year 2070 (Future projection) considered high greenhouse gas emis-

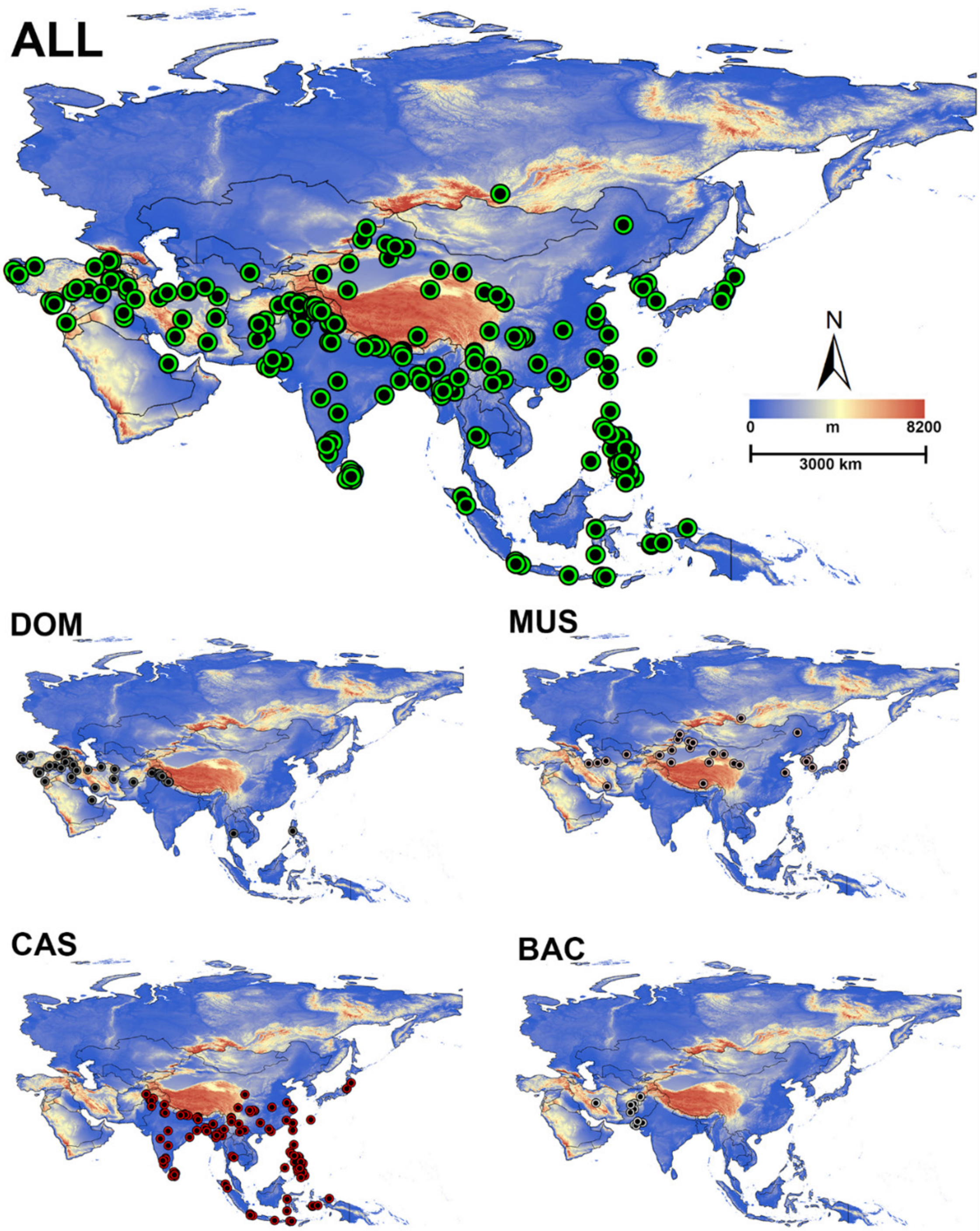

Figure 1. Spatial distribution map illustrating the geographic ranges of *Mus musculus* and its subspecies; *M. musculus* (ALL), *M. m. domesticus* (DOM), *M. m. musculus* (MUS), *M. m. castaneus* (CAS), and *M. m. bactrianus* (BAC) across the Asian continent.

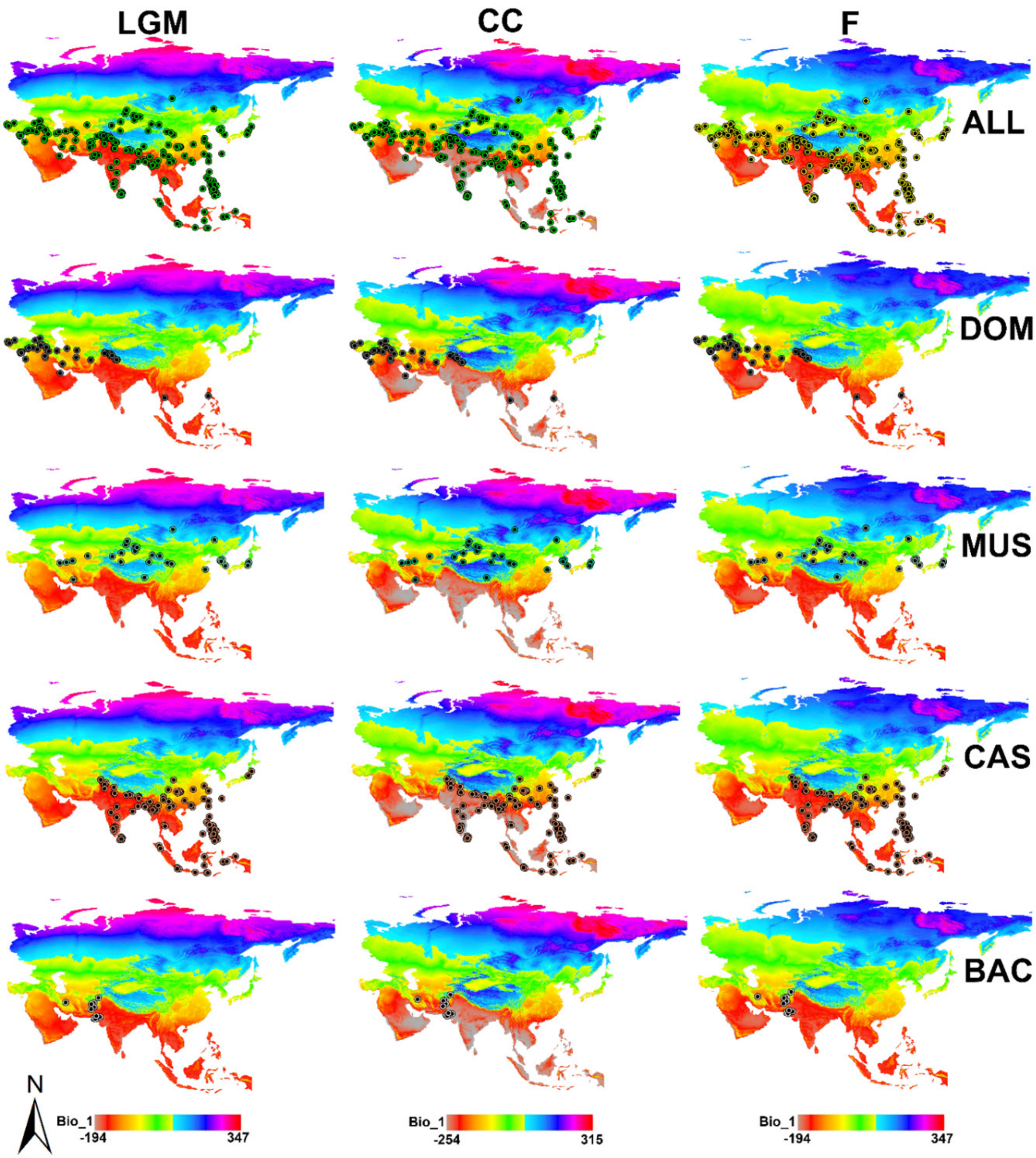

Figure 2. Predicted changes in annual temperature across the study area during three key periods; Last Glacial Maximum (LGM), Current Conditions (CC), and Future projection (F) along with occurrence records of *Mus musculus* (ALL) and its subspecies, including *M. m. domesticus* (DOM), *M. m. musculus* (MUS), *M. m. castaneus* (CAS), and *M. m. bactrianus* (BAC).

sion scenarios, representative concentration pathway RCP 8.5 (Van Vuuren et al. 2011). As Figure 2 shows annual temperature predicted to increase in the future across the study area.

The selection of these bioclimatic variables was based on their known relevance to the ecology of *M. musculus* and its subspecies. These variables, which include temperature and precipitation-related factors, are critical in determining the species' habitat preferences, distribution patterns, and potential responses to climate change. By incorporating a comprehensive set of bioclimatic variables, key environmental factors that influence the distribution of *M. musculus* are captured.

Species distribution modeling

Maxent 3.4.4 (Phillips et al. 2006) utilized to estimate the probability of species occurrence. To perform this analysis, presence data used in conjunction with environmental variables, following the methodology outlined by Elith et al. (2006), Hernandez et al. (2006), and Rhoden et

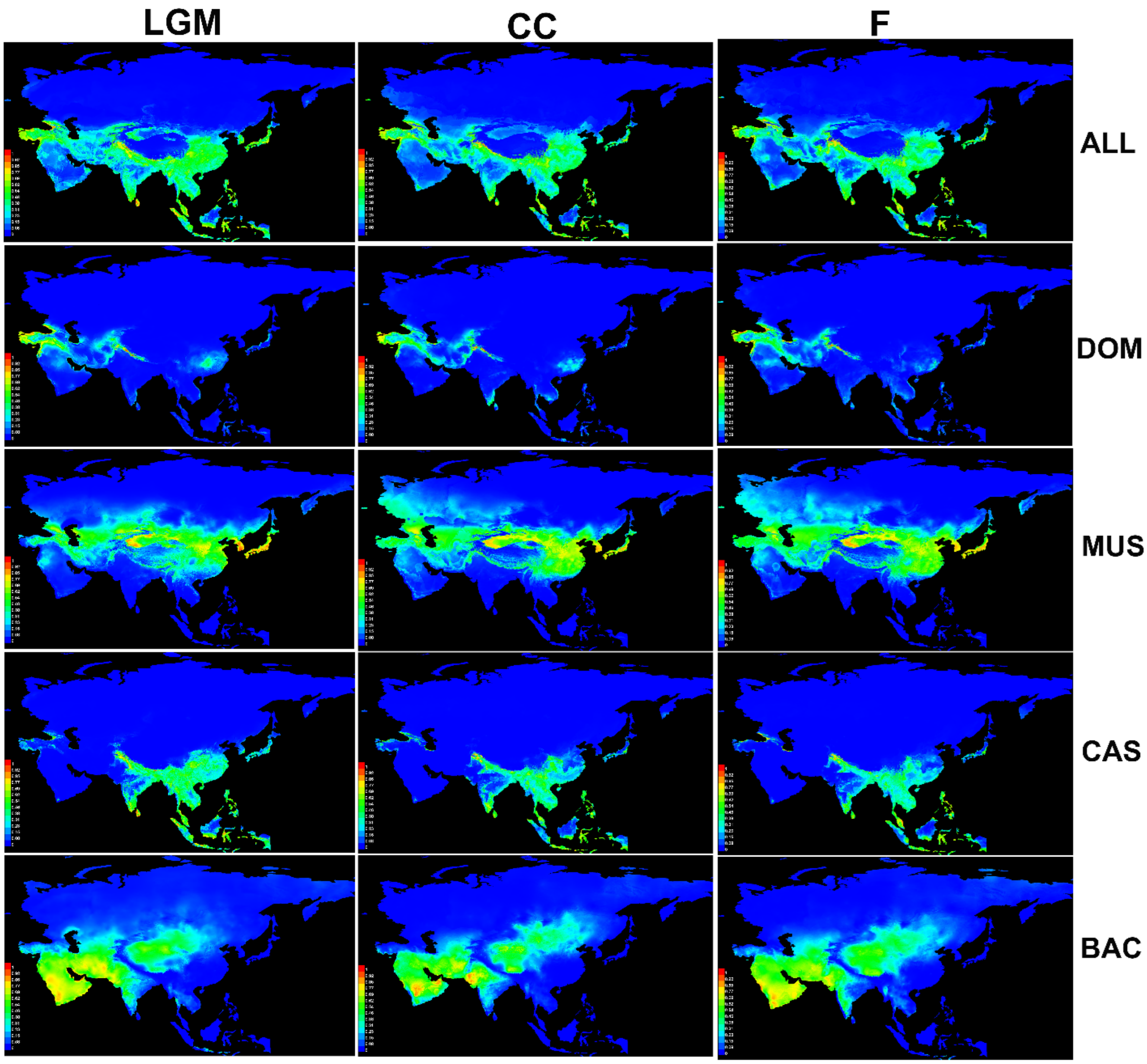

Figure 3. Species Distribution Models (SDMs) depicting the habitat suitability changes for *Mus musculus* (ALL) and its subspecies; *M. m. domesticus* (DOM), *M. m. musculus* (MUS), *M. m. castaneus* (CAS), and *M. m. bactrianus* (BAC) across three distinct temporal periods: Last Glacial Maximum (LGM), Current Conditions (CC), and Future projection (F).

al. (2017). The models ran for three temporal conditions: the Last Glacial Maximum (LGM~22000 years BP), Current Conditions (CC~1960-1990) and Future projection (F~2061-2080). The Community Climate System Model (CCSM4) used as the general atmospheric circulation model. The spatial resolution was set at 2.5 arc-minutes (approximately 5 km^2) for LGM and 30 arc-seconds (approximately 1 km^2) for CC and F. In model training, %75 of the presence records was used, while %25 was randomly selected for testing. The procedure was repeated 15 times, with 5,000 iterations performed. The accuracy of the models was evaluated using Receiver Operating Characteristic (ROC) analysis. The Area Under the Curve (AUC) derived from the ROC plot, ranging between 0 and 1, served as the key metric. A model with an AUC value greater than 0.75 was considered robust and acceptable, while AUC values below 0.5 indicated a random prediction (Elith et al. 2006). To determine the importance of each climatic variable in explaining the species distribution model, conducted a jackknife procedure, following the approach outlined by Sillero & Carretero (2012). This procedure allowed to identify the key environmental variables driving the observed distribution patterns.

Results

Climate Change Models

The models generated in this study exhibited strong performance, as indicated by the Receiver Operating Characteristic (ROC) curve values (AUC) ranging from 0.85 to 0.96 (Fig. 4). Analyses reveal distinct trends in habitat suitability for Mus musculus subspecies. Specif-

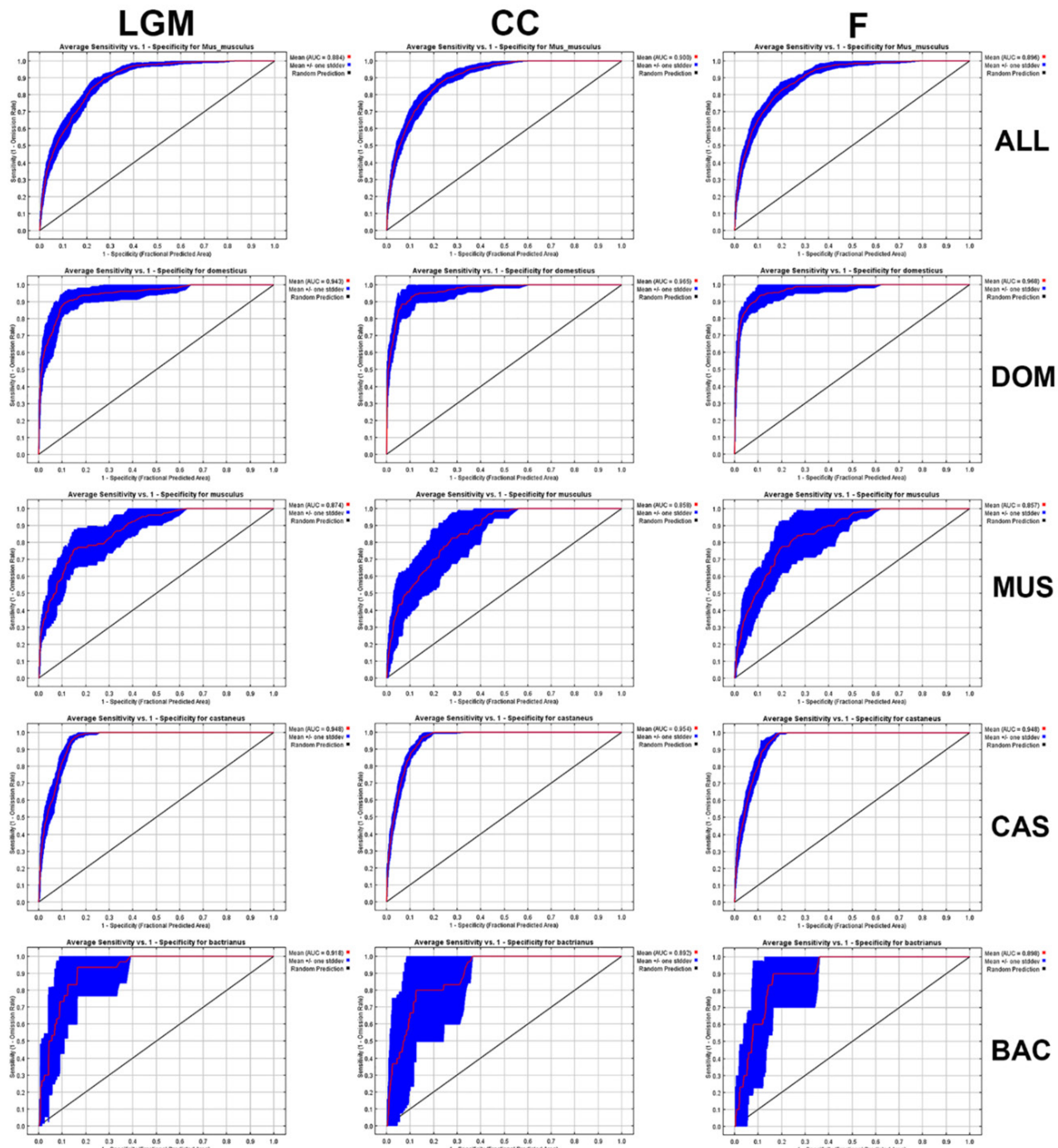

Figure 4. The Receiver Operating Characteristic (ROC) curve and AUC of *Mus musculus* and its subspecies; *M. musculus* (ALL), *M. m. domesticus* (DOM), *M. m. musculus* (MUS), *M. m. castaneus* (CAS), and *M. m. bactrianus* (BAC) during three distinct temporal periods: Last Glacial Maximum (LGM), Current Conditions (CC), and Future Projection (F).

ically, the suitability of habitats for *M. musculus* (ALL), *M. m. domesticus* (DOM), and *M. m. castaneus* (CAS) is projected to decrease. In contrast, *M. m. musculus* (MUS) and *M. m. bactrianus* (BAC) are anticipated to gain new suitable habitats in response to climate change (Fig. 3).

Species Distribution Modelling

In SDM analysis, models ran for the last glacial maximum (LGM), current conditions (CC), and future projection (F) through 15 replicates, all of which demonstrated high predictive power (Figs 3 & 4). The examination of habitat suitability for *M. musculus* revealed dynamic changes across different temporal periods. *M. m. domesticus* (DOM) experienced a transition from LGM to F, exhibiting a reduction in suitable areas in East Asia and South India. However, there is a notable increase in habitat suitability in West Asia, suggesting potential shifts in ecological preferences under changing climatic conditions. *M. m. musculus* (MUS) displayed a significant gain in new suitable areas from LGM to F. The impact of global climate change is evident in the expansion of suitable habitats towards the North Pole and Northeast Asia. Although habitat suitability is anticipated to decrease in East Asia, particularly in Japan, the most suitable habitats persist in Central and East Asia. Conversely, *M. m. castaneus* (CAS) faced a decline in suitable areas, particularly in South and Southeast Asia, from LGM to F. These findings emphasize the vulnerability of certain areas that might no longer support the same level of habitat suitability for CAS in the face of changing climatic conditions. *M. m. bactrianus* (BAC) exhibited a unique pattern, showcasing more suitable habitats during the last glacial maximum compared to the current conditions. This suggests that BAC may have historically adapted to specific climatic conditions, and the contemporary climate might not fully align with its historical habitat preferences.

Ecological Implications

The observed shifts in habitat suitability for *M. musculus* subspecies have significant ecological implications. For instance, the reduction in suitable habitats for *M. m. domesticus* (DOM) and *M. m. castaneus* (CAS) could lead to decreased population sizes and increased competition for resources with other species. Conversely, the expansion of suitable habitats for *M. m. musculus* (MUS) and *M. m. bactrianus* (BAC) may result in these subspecies occupying new ecological niches, potentially altering interspecies interactions. These changes can affect predator-prey dynamics, competition for food, and habitat utilization. For example, an increase in *M. m. musculus* (MUS) populations in new areas could lead to heightened competition with native small mammals, influencing local biodiversity and ecosystem functions such as seed dispersal and soil aeration.

Variable Importance for House Mouse

The assessment of variable importance in shaping the distribution of the house mouse (*M. musculus*) is outlined in Table 1. Key environmental variables that significantly influenced the main models during different temporal periods are highlighted. During the last glacial maximum (LGM), the most influential variables included Bio_19 (Precipitation of Coldest Quarter), Bio_13 (Precipitation of Wettest Month), and Bio_2 (Mean Diurnal Range). These findings underscore the importance of precipitation-related variables during the historical period, indicating the crucial role of moisture conditions in shaping the habitat suitability of house mice. In current conditions (CC), the main influential variables shifted, with Bio_19 (Precipitation of Coldest Quarter), Bio_1 (Annual Mean Temperature), and Bio_15 (Precipitation Seasonality) taking precedence. The shift towards temperature-related variables emphasizes the contemporary significance of temperature patterns in determining the distribution of house mice in Asia. Looking into future projections (F), the most influential environmental variables were identified as Bio_11 (Mean Temperature of Coldest Quarter), Bio_3 (Isothermality), and Bio_1 (Annual Mean Temperature). The increasing importance of temperature-related variables in the future highlights the potential impact of ongoing climate change on shaping the distribution patterns of house mice, with temperature playing a central role. Comparatively, the transition from precipitation-related variables dominating during historical periods (LGM and CC) to temperature becoming more influential in future projections suggests a shift in the primary determinants of habitat suitability for house mice in Asia.

This shift towards temperature-related variables in future projections indicates a potential realignment of ecological processes. As temperature increasingly influences habitat suitability, it is likely to affect physiological stress, metabolic rates, and reproductive cycles of *M. musculus*. Additionally, the changing climate may alter vegetation patterns, indirectly impacting the food availability and habitat structure for house mice. These ecological shifts can have broader implications for ecosystem dynamics, including changes in nutrient cycling, energy flow, and overall ecosystem stability.

Discussion

The findings of this study shed light on the potential impacts of global climate change on *Mus musculus* and its subspecies in Asia, spanning from the last glacial maximum to the end of the 21st century. The utilization of Species Distribution Models (SDMs) based on a comprehensive dataset allowed us to examine the dynamic response of these small rodents to changing climatic conditions.

The examination of *M. musculus* distribution during the last glacial maximum (LGM) provides valuable insights into the species' historical response to climate fluctuations. The observed increase in suitable habitats for *M. m. musculus* (MUS) and *M. m. bactrianus* (BAC) during LGM suggests a capacity for adaptation and range expansion in response to colder climatic conditions. This adaptive potential aligns with the general understanding that small rodents often exhibit behavioral and physiological adaptations to survive in diverse environments. The study's current condition (CC) models suggest that *M. m. domesticus* (DOM), *M. m. musculus* (MUS), and *M. m. castaneus* (CAS) face potential contractions in suitable habitats. This contraction is particularly evident in East Asia and South India for DOM, East Asia for CAS, and Japan for MUS. In contrast, *M. m. bactrianus* (BAC) shows an expansion of suitable habitats. These projections highlight the heterogeneity in responses among *M. musculus* subspecies, emphasizing the need for nuanced conservation strategies.

The variable importance analysis underscores the role of temperature-related variables in shaping the distribution of *M. musculus*. Annual Mean Temperature (Bio_1), Mean Diurnal Range (Bio_2), and Isothermality (Bio_3) were identified as key influencers during different periods. Notably, the increasing importance of temperature-related variables in future projections aligns with broader climate change patterns, suggesting that rising temperatures might become a predominant factor influencing the distribution of *M. musculus*.

The anticipated changes in *M. musculus* distribution have ecological implications for Asia. For example, the

Table 1. Relative contributions of environmental variables to Maxent models, with emphasis on the top three influential variables for each model.

Variables	***Last Glacial Maximum*** *Percent Contribution*					***Current Condition*** *Percent Contribution*					***Future*** *Percent Contribution*				
	DOM	*MUS*	*CAS*	*BAC*	*ALL*	*DOM*	*MUS*	*CAS*	*BAC*	*ALL*	*DOM*	*MUS*	*CAS*	*BAC*	*ALL*
Bio_1 (Annual Mean Temperature)	0	**20.9**	0.5	0	**17.3**	0.7	**40.7**	1	0	**36.7**	0.3	**30.1**	0.4	**0**	**28.7**
Bio_2 (Mean Diurnal Range)	1.2	2	1.6	**40.8**	1.5	0.4	1.5	0.5	**18.9**	1.2	1	0.7	0.9	**22**	1
Bio_3 (Isothermality (BIO2/BIO7) (×100))	0.4	0	4.3	0	2.8	**22**	1.8	4.1	0	5.2	**33.7**	5.3	3	4.2	5.8
Bio_4 (Temperature Seasonality)	5	4.9	1.5	6	6.1	6.8	3	**25.9**	0.1	6.4	1.8	0.5	**21.3**	0.4	**9.4**
Bio_5 (Max Temperature of Warmest Month)	0	1.1	0.9	0	0.9	0	0.4	1.1	0	1.4	0	0.1	0.9	0	2.1
Bio_6 (Min Temperature of Coldest Month)	**13.5**	**26.5**	**16.5**	0	**33.6**	1.5	0.5	**11.8**	0	0.5	1.8	1.6	**19**	0	1.9
Bio_7 (Temperature Annual Range (BIO5-BIO6))	0.7	4.3	1.5	0	2.5	0.5	1	0.2	0	0.3	0.7	0	0.5	0	0.7
Bio_8 (Mean Temperature of Wettest Quarter)	**10.9**	1.8	1	0	1.3	**7.7**	2	0.9	0.1	1.8	**19.5**	2.7	0.9	0	2.3
Bio_9 (Mean Temperature of Driest Quarter)	3.7	2.8	0.4	**33.7**	0.5	0.5	**4.1**	2.2	**24.8**	1	**16.3**	3.1	1.5	**28.5**	1.5
Bio_10 (Mean Temperature of Warmest Quarter)	0.1	0.4	1.5	0.2	2.8	0.4	0.7	0.6	0	1	1.3	0.2	1.1	0	2.2
Bio_11 (Mean Temperature of Coldest Quarter)	7.6	**23.6**	1.4	1.2	3.7	0.5	**32.6**	3.8	0	**16.3**	1.3	**41.6**	5.2	0	**21.9**
Bio_12 (Annual Precipitation)	0.4	0.1	0.4	**8.3**	1.1	0.4	0.3	2.2	11.4	1.5	0	0.2	1.4	18.8	0.6
Bio_13 (Precipitation of Wettest Month)	0.7	4.5	**55.3**	0.3	**8.7**	0.4	0.5	**33.7**	1.5	10.8	8.8	2.5	**27.2**	0.2	8.8
Bio_14 (Precipitation of Driest Month)	0.1	0.4	0.5	0	0.3	0.2	1.1	1.6	0	0.5	0	1.4	0.7	3.1	0.5
Bio_15 (Precipitation Seasonality)	0.5	0.1	1.3	2.8	1.7	1.1	3	0.5	**40.2**	1	0.5	**5.5**	1.4	**21.8**	1.4
Bio_16 (Precipitation of Wettest Quarter)	2	0.1	1.4	0.7	4	0	0	1.4	0.3	1.5	0.1	0	4.4	0.7	2.7
Bio_17 (Precipitation of Driest Quarter)	0.6	0.5	2.2	1.6	2.4	3.4	0.9	3.2	0.2	1.3	8.1	1.5	4.6	0.1	**7.7**
Bio_18 (Precipitation of Warmest Quarter)	0.7	4.6	**5.4**	4.3	0.9	2.9	2.5	3.8	1.9	0.7	4.3	2.5	5.5	0.1	0.2
Bio_19 (Precipitation of Coldest Quarter)	**52**	1.2	2.1	0.1	7.8	**50.5**	3.5	1.5	0.5	**10.9**	0.5	0.3	0.2	0.1	0.6

potential decrease in suitable habitats for some subspecies may impact ecosystem dynamics by altering seed dispersal patterns, as *M. musculus* is known to play a role in the distribution of seeds. Additionally, changes in predation dynamics may occur as predators that rely on *M. musculus* as a food source may need to adapt to shifts in prey availability. The observed shifts in distribution patterns may lead to altered interspecies interactions, potentially increasing competition with other small mammal species for resources such as food and nesting sites, thereby influencing the broader ecological network in which *M. musculus* participates.

The high AUC values obtained for all models indicate the robustness and reliability of SDMs. This suggests that the models are effective in predicting the potential distributional changes of *M. musculus* under different climatic scenarios. Despite the rigor in data processing and quality control, limitations exist in the availability of occurrence data. Incorporating more fine-scale data and continuous monitoring efforts could enhance the precision of future SDMs. Additionally, the reliance on SDMs assumes that species' responses are solely climate-driven, not accounting for potential anthropogenic influences or interactions with other species. Non-climatic factors such as habitat destruction, pollution, and human activities also play significant roles in shaping species distributions and should be considered in future studies.

Given the varied responses of *M. musculus* subspecies to climate change, conservation efforts should adopt a differential approach. Subspecies facing habitat contractions might require targeted conservation strategies, including habitat restoration, while those experiencing habitat expansions may need monitoring to manage potential overpopulation and associated ecological impacts. Identifying areas with relatively stable conditions, such as potential climatic refugia, becomes crucial for conservation planning. Conservation efforts focused on protecting these refugial areas could serve as a strategy to safeguard *M. musculus* populations in the face of changing climates.

This study highlights the importance of incorporating both climatic and non-climatic factors in future SDMs to provide a more comprehensive understanding of species distribution dynamics. Continuous monitoring and the collection of fine-scale data are essential to improve the accuracy and reliability of these models, ensuring that conservation strategies are well-informed and effective in addressing the challenges posed by global climate change.

Conclusion

This study contributes to the understanding of how *M. musculus* and its subspecies may respond to climate change in Asia, offering insights into historical adaptations and future projections. The nuanced examination of different subspecies and their responses underscores the complexity of climate change impacts on small mammal populations. Based on the findings, several concrete recommendations for conservation strategies are proposed: **I) Identifying and protecting climatic refugia**: conservation efforts should focus on identifying areas likely to remain suitable for *M. musculus* subspecies under future climatic conditions. These climatic refugia should be prioritized for protection to ensure the persistence of populations facing habitat contractions; II) **Implementing habitat restoration efforts:** for subspecies projected to experience reductions in suitable habitats, targeted habitat restoration efforts are essential. Restoring habitats to better align with the current and projected climatic conditions can help mitigate the adverse effects of habitat loss; III) **Monitoring and managing expanding populations:** subspecies experiencing habitat expansions should be monitored to manage potential overpopulation and associated ecological impacts. Effective management strategies are necessary to balance population growth with the capacity of available habitats; IV) **Integrating findings into conservation policies**: the results of this study should inform conservation policies and practices, ensuring that they are adaptive to changing climatic conditions. Policymakers should incorporate these findings into broader biodiversity conservation frameworks to enhance resilience against climate change.

As we move forward, it is imperative to integrate these findings into conservation practices and policy decisions, recognizing the importance of preserving biodiversity in the face of ongoing global climate change. Adopting these recommendations can help safeguard *Mus musculus* populations and maintain ecosystem functions amidst a rapidly changing climate.

Declaration of competing interest

Not applicable.

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