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Research Article

Adaptive distributional changes of *Aegithalos caudatus* in the Palearctic region during the Ice Age, present, and future periods

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Abstract

Climate change alters their distribution across a wide geographical range by impacting habitats and bird populations. For the first time globally, this pioneering research integrates climate data; species presence points from field observations, and the international bird data registry. Utilizing various modeling algorithms, it scrutinizes the distribution changes of *Aegithalos caudatus* across a significant portion of its Palearctic biogeographical range across five distinct periods: the Last Interglacial, the Last Glacial Maximum, the mid-Holocene, the present, and future scenarios, encompassing both an optimistic outlook with sustainable development policies and a pessimistic projection with ongoing greenhouse gas emissions. The findings revealed that three algorithms, random forest, support vector machine, and maximum entropy, outperformed other modeling methods in discerning suitable and unsuitable habitats for *Aegithalos caudatus*. Evaluation using these models highlighted that the peak of species distribution, reaching 40%, was observed during the Last Glacial Maximum period. Conversely, its favorable habitat decreased by 29% during the Last Interglacial period. Moreover, climate amelioration during the mid-Holocene and present times has increased the habitat suitability of *Aegithalos caudatus* t across the Palearctic region to 36% and 35%, respectively. In the optimistic scenario for the year 2080, where sustainable policies are adopted to mitigate climate change, there is a notable increase in the distribution and habitat suitability of the long-tailed tit, covering 47% of the Palearctic biogeographical range. Conversely, in the pessimistic scenario, the distribution of this species diminishes to 35%. Across various periods, the annual temperature range emerges as the most influential climatic factor affecting the habitat suitability of this species.

Keywords: climate change, habitat suitability modeling, *Aegithalos caudatus*, species distribution

Introduction

Climate change is one of the most significant environmental challenges of the 21st century, profoundly impacting ecosystems and species. Variations in temperature, precipitation patterns, and extreme weather events can disrupt animal habitats and food resources, leading to shifts in species distributions (Pacifici et al., 2020; Ntwari et al., 2024). Birds, a crucial animal group, are particularly sensitive to climate change. Fluctuations in their distribution and populations can provide essential insights into how climatic changes affect ecosystems (Radchuk et al., 2023). The geographic distribution of birds is closely tied to climatic conditions, and changes in these conditions can alter the habitats available to these species. Therefore, evaluating the impact of climate change on bird distribution is vital for effective conservation planning and habitat management (Sántiz et al., 2016).

Species Distribution Models (SDMs) are valuable tools for predicting and assessing shifts in species distributions under various climate scenarios. With its robust packages such as SDM and ENMTools, R software supports precise analysis and modeling. The SDM package in R includes a range of algorithms for modeling species distributions, including generalized linear models (GLM), Random Forests, Mahalanobis, Maximum Entropy (MaxEnt), Support Vector Machines (SVM), Domain, and Bioclim (Warren et al., 2021). The WorldClim database provides climate layers for three critical historical periods: the Last Interglacial (approximately 120,000 to 140,000 years ago), the Last Glacial Maximum (22,000 years ago), and the mid-Holocene (6,000 years ago). These layers offer past climate data essential for modeling species distributions and analyzing habitat changes in response to historical climate shifts. This historical data allows researchers to study species distribution patterns across different times and make more accurate future predictions (Hijmans et al., 2008; Fick & Hijmans, 2017; Beyer et al., 2020; Naderi et al., 2014). Climate variables SSP126 (optimistic) and SSP585 (pessimistic) are used in habitat suitability modeling to project future climate changes and their impacts on species distributions. SSP126 represents a scenario with reduced greenhouse gas emissions, while SSP585 reflects a scenario with significantly increased emissions. Present-day climate layers establish a baseline for comparing and analyzing future habitat and species distribution changes (Nwoko et al., 2023; Sıkdokur et al., 2024).

The long-tailed tit, *Aegithalos caudatus* (Linnaeus, 1758), belongs to the order Passeriformes and the family Aegithalidae, genus *Aegithalos*. This species is divided into three groups: caudatus, europaeus, and alpinus, with 17 subspecies distributed across northern Europe, from Britain to

Scandinavia, and in Asia, from Siberia to Japan, and in northern and western Iran and northern Iraq. The long-tailed tit inhabits various environments, including deciduous forests, gardens, parks, and shrublands. It is characterized by its round body, relatively large head, and long tail, which is nearly twice the length of its body (Harrap, 2020). Two subspecies, *Aegithalos caudatus alpinus*, are found in the Hyrcanian forests of northern Iran, and *Aegithalos caudatus passekii* in the Zagros forests of western Iran. This species is non-migratory, with only local and altitudinal movements (Harrap, 2020).

Understanding the historical distribution of the long-tailed tit through climate variables is crucial. This knowledge can show how the species has responded to past climate changes and help predict its response to future climate shifts. Such assessments are essential for developing management and conservation strategies to maintain biodiversity and ensure the survival and sustainability of these populations in the face of future climate changes (Thomas et al., 2004). This study, the first of its kind globally, examines the effects of climate change and predicts the distribution of the long-tailed tit in past, present, and future periods using climate variables, presence data, and habitat suitability modeling algorithms across the Palearctic region of Europe and Asia.

Material and methods

Study Area

The study area covers the Palearctic biogeographical region, including Europe and Asia, known for its high biodiversity and environmental diversity. This region encompasses a range of habitats, from Southeast Asian rainforests to northern European tundras. The diverse ecosystems provide varied habitats for numerous species. The range of climatic conditions, from Mediterranean to cold continental climates, and diverse topography make this region highly suitable for studying species habitats (Wallis DeVries et al., 2006; Harrap, 2020).

Data Collection

Species Presence Data: Presence data for the long-tailed tit in Europe and Asia were gathered from online databases such as the Global Biodiversity Information Facility (GBIF) and eBird, as well as field observations and scientific articles. This data includes geographical coordinates (latitude and longitude). In total, 53,000 presence points were collected. Spatial errors and incorrect data were removed to enhance accuracy, and duplicate records were eliminated. The locations of presence points are depicted in Figure 1.

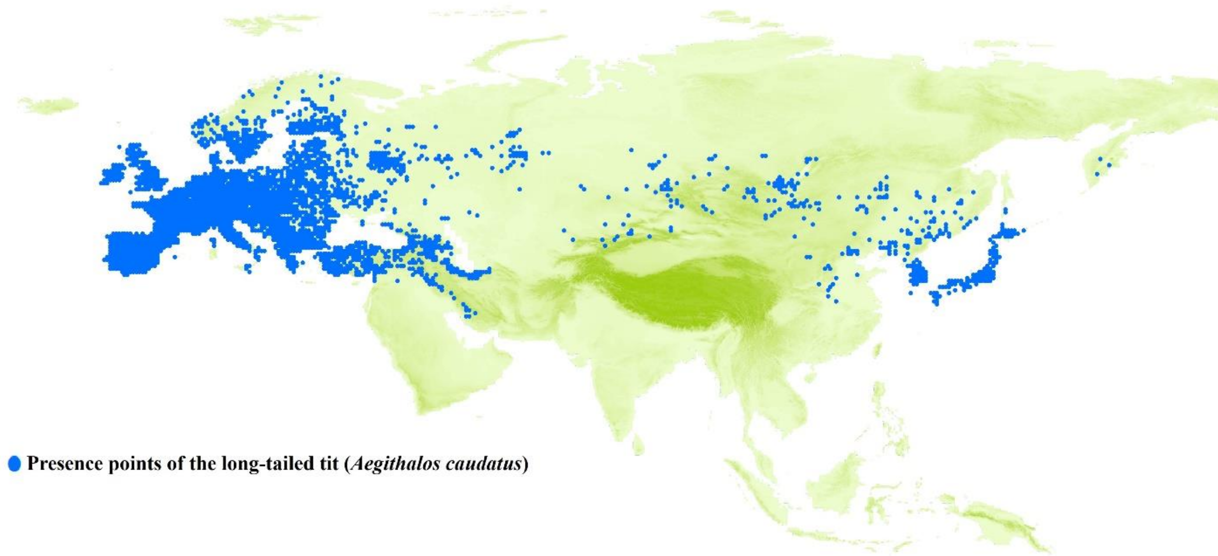

Figure 1. Presence points of the long-tailed tit (*Aegithalos caudatus*) in the Palearctic biogeographical range

Climate Variables: Nineteen bioclimatic variables were extracted from the WorldClim database for five time periods: the Last Interglacial (approximately 120,000 to 140,000 years ago), the Last Glacial Maximum (22,000 years ago), the mid-Holocene (6,000 years ago), the present (1950-2000), and the future (2060-2080). The General Circulation Model (GCM) from the Centro Euro-Mediterraneo sui Cambiamenti Climatici - Earth System Model version 2 (CMCC-ESM2) was used under both optimistic and pessimistic scenarios: the optimistic scenario assumes sustainable development policies, while the pessimistic scenario anticipates increased greenhouse gas emissions (Fick & Hijmans, 2017). Correlation analysis in R software was performed to select appropriate variables, removing those with correlations above 75% to avoid multicollinearity (Haghani et al., 2019). Climate data were normalized, and map scales were adjusted to one square kilometer in ArcMap to ensure uniformity and improve model accuracy. Table 2 lists the variables used for each time.

Implementation of Species Distribution Models: Habitat suitability modeling was conducted using various methods, including generalized linear models (GLM), Random Forests, Mahalanobis, Maximum Entropy (MaxEnt), Support Vector Machines (SVM), Domain, and Bioclim in the SDM package in R software. Model parameters were adjusted for optimal performance.

Model Evaluation and Validation: Model accuracy was assessed through cross-validation. In this study, 70% of presence points were randomly selected for model training and 30% for model performance evaluation. The Receiver Operating Characteristic (ROC) curve was plotted, and the Area Under the Curve (AUC) was calculated to evaluate model accuracy (Haghani et al., 2019). Each modeling method was repeated ten times to enhance accuracy and efficiency. The final habitat suitability map was derived using the weighted average of algorithms with high AUC values in R software for past, present, and future periods. Suitable habitat areas for each time were also calculated in ArcGIS software. Additionally, a line graph depicting percentage changes in habitat suitability over different time periods was created in R software.

Results

The AUC index for evaluating model accuracy across different habitat suitability modeling algorithms for the long-tailed tit during past, present, and future periods is presented in Table 1. According to this table, the Random Forest, Support Vector Machine (SVM), and Maximum Entropy (MaxEnt) algorithms demonstrated the highest AUC index and the best performance in predicting the distribution model of the long-tailed tit over various time periods.

Table 1:. AUC values for algorithms used in habitat suitability modeling of the long-tailed Tit

Time Period	Random Forest	MaxEnt	GLM	Mahalanobis	Domain	Bioclime	SVM
Last Interglacial Period	1	99	86	87	81	87	99
Last Glacial Maximum	99	1	92	90	86	85	98
Mid-Holocene	1	99	86	84	87	89	1
Present	99	1	90	89	82	90	99
Future (OptimisticScenario)	99	99	91	86	89	89	98
Future (Pessimistic Scenario)	99	95	92	86	88	89	98

The results indicate that the annual temperature range variable had the most significant contribution in determining the habitat suitability of the long-tailed tit for the Last Interglacial, Last Glacial Maximum, mid-Holocene, present, and future (optimistic) periods. Additionally, the maximum temperature of the warmest month was the most influential climate variable in determining habitat suitability and distribution of the long-tailed tit under the pessimistic future scenario. The percentage contribution of each climate variable to habitat suitability is presented in Table 2.

Table 2: Climate variables and their percentage contribution to the habitat suitability of the long-tailed tit

Time Period	Climatic Variable and Its Contribution (%)
Last Interglacial Period	Mean Diurnal Range (Bio2): 20, Annual Temperature Range (Bio7): 36, Mean Temperature of Wettest Quarter (Bio8): 13, Mean Temperature of Warmest Quarter (Bio10): 7, Precipitation of Wettest Month (Bio13): 15, Precipitation of Driest Quarter (Bio17): 9
Last Glacial Maximum	Mean Diurnal Range (Bio2): 20, Annual Temperature Range (Bio7): 35, Mean Temperature of Warmest Quarter (Bio10): 10, Precipitation Seasonality (Bio15): 14, Precipitation of Warmest Quarter (Bio18): 8, Precipitation of Coldest Quarter (Bio19): 11
Mid-Holocene	Mean Diurnal Range (Bio2): 23, Max Temperature of Warmest Month (Bio5): 19, Mean Temperature of Wettest Quarter (Bio8): 5, Mean Temperature of Coldest Quarter (Bio11): 7, Precipitation Seasonality (Bio15): 17, Precipitation of Driest Quarter (Bio17): 15, Precipitation of Warmest Quarter (Bio18): 14
Present	Mean Diurnal Range (Bio2): 21, Isothermality (Bio3): 13, Annual Temperature Range (Bio7): 18, Mean Temperature of Wettest Quarter (Bio8): 8, Mean Temperature of Warmest Quarter (Bio10): 9, Precipitation of Warmest Quarter (Bio18): 14, Precipitation Seasonality (Bio15): 10, Precipitation of Driest Month (Bio14): 8
Future (Optimistic Scenario)	Mean Diurnal Range (Bio2): 20, Max Temperature of Warmest Month (Bio5): 15, Annual Temperature Range (Bio7): 16, Mean Temperature of Wettest Quarter (Bio8): 8, Precipitation of Wettest Month (Bio13): 13, Precipitation Seasonality (Bio15): 16, Precipitation of Driest Quarter (Bio17): 6, Precipitation of Warmest Quarter (Bio18): 6
Future (Pessimistic Scenario)	Mean Diurnal Range (Bio2): 11, Max Temperature of Warmest Month (Bio5): 20, Annual Temperature Range (Bio7): 17, Mean Temperature of Wettest Quarter (Bio8): 5, Precipitation of Wettest Month (Bio13): 10, Precipitation Seasonality (Bio15): 13, Precipitation of Driest Quarter (Bio17): 16, Precipitation of Warmest Quarter (Bio18): 8

The final distribution map of the long-tailed tit in Europe and Asia across past, present, and future periods is shown in Figure 2. Figure 3 depicts the percentage of habitat suitability and its trends over different periods. According to these figures, the percentage of suitable habitat for the long-tailed tit during the Last Interglacial, Last Glacial Maximum, mid-Holocene, present (1950-2000), and future periods under optimistic and pessimistic scenarios for 2060-2080 is 40.80%, 28.89%, 36.25%, 35.51%, 47.13%, and 35.77%, respectively. The lowest habitat suitability occurred during the Last Glacial Maximum period, around 22,000 years ago, when 71% of the Palearctic range was unsuitable for this species. The highest habitat suitability was observed during the Last Interglacial period, approximately 120,000-140,000 years ago. Furthermore, the percentage of suitable habitat for the long-tailed tit in the future under optimistic (SSP126) and pessimistic (SSP585) scenarios is projected to be 47% and 35%, respectively. The habitat suitability maps (Figure 2) show that, in Iran, the distribution of the long-tailed tit during the mid-Holocene and Last Glacial Maximum periods was confined to northern areas. However, in the Last Interglacial, present, and future periods, the distribution extends to both northern and western Iran.

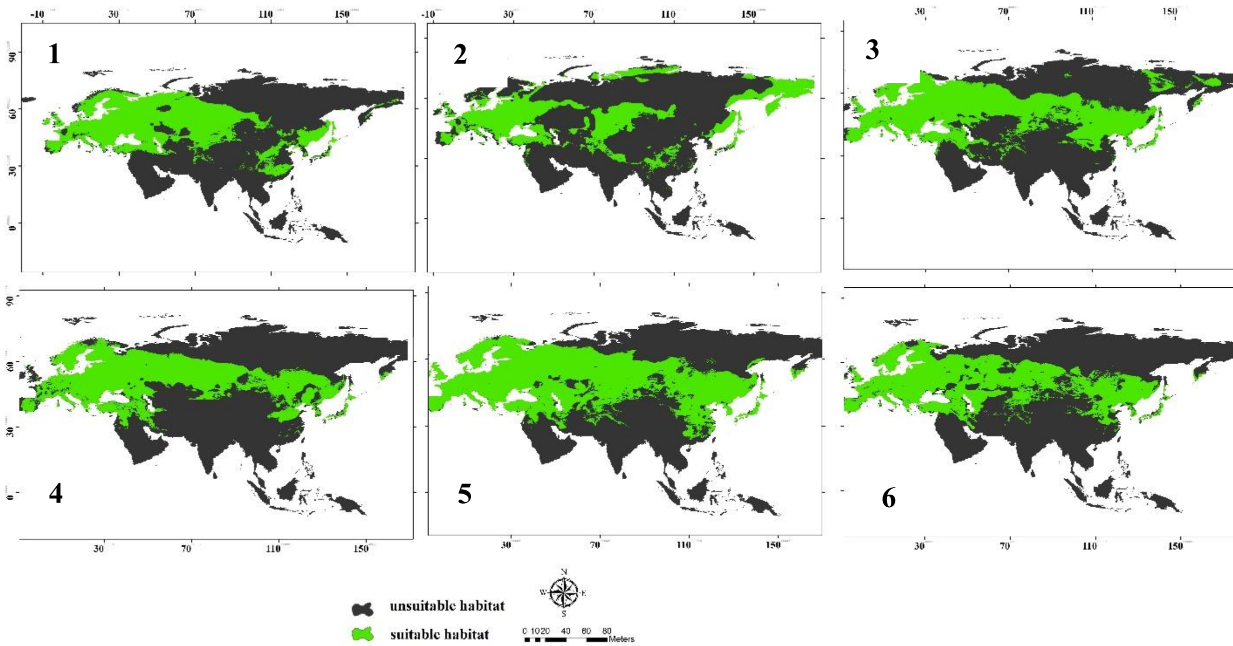

Figure 2: Distribution map of the long-tailed tit (*Aegithalos caudatus*) in different time periods: 1. Mid-Holocene, 2. Last Glacial Maximum, 3. Last Interglacial, 4. Present, 5. Future (optimistic), 6. Future (pessimistic)

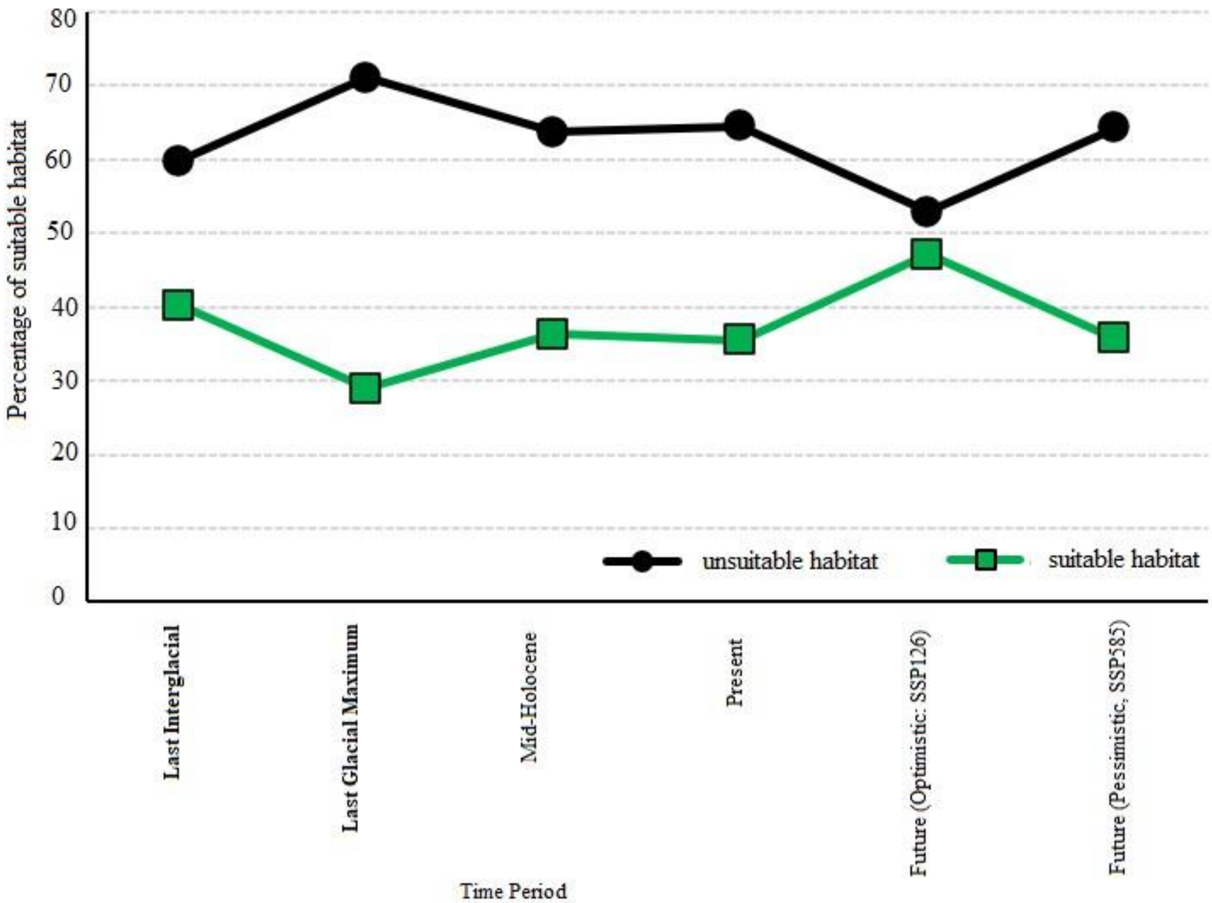

Figure 3: Line graph of the percentage of habitat suitability for the long-tailed tit across different periods

Discussion

The high AUC values for the Random Forest, GLM, and SVM algorithms, indicative of high model accuracy, suggest that these models successfully predicted suitable areas with high accuracy and effectively differentiated between suitable and unsuitable habitats for the long-tailed tit across the Palearctic range during past, present, and future periods. Random Forest, GLM, and SVM algorithms have specific advantages over other algorithms in habitat suitability modeling due to their high accuracy, ability to process complex data, and good generalizability (Maxwell et al., 2018; Guisan et al., 2002; Drake et al., 2006). A cumulative model, created by the weighted average of these three algorithms, was used to produce habitat suitability maps for the long-tailed tit across different periods. Utilizing a cumulative model reduces bias and variance errors, increases accuracy, and enhances stability and reliability, making it an effective strategy to leverage the strengths of each algorithm while minimizing their weaknesses (Marmion et al., 2009; Araújo et al., 2006).

The distribution and range of the long-tailed tit have changed across past, present, and future periods due to climate variations (Figure 2). During the Last Interglacial period, around 120,000-140,000 years ago, before the peak of the Ice Age in the Pleistocene epoch, the long-tailed tit species was distributed over a vast area of Europe and Asia and was likely less affected by the Ice Age. The most significant climatic factors during this period were the annual temperature range, mean daily temperature, and precipitation of the wettest season (Table 1). This period is characterized by the expansion of forests and other warm-climate ecosystems into areas later covered by ice during the Last Glacial Maximum. This likely contributed to the widespread distribution of the species across Europe and Asia (Nikolova et al., 2013). During this time, the long-tailed tit was found in northern, western, and small parts of southern and eastern Iran (Figure 2).

The lowest habitat suitability and most significant habitat loss for the long-tailed tit occurred during the Last Glacial Maximum, 22,000 years ago, with the annual temperature being the most critical climatic factor influencing the species' distribution during this period (Table 1). This likely resulted from lower temperatures, increased glaciation, reduced food resources, and changes in vegetation. The cold and dry conditions of the Last Glacial Maximum led to decreased habitat suitability and altered migration patterns for many species, resulting in extensive changes in biological communities and habitats (Lister et al., 2008). Habitat suitability for the long-tailed tit in Central Asia and Northern Europe decreased significantly compared to other regions (Figure 2). Although Iran was not directly affected by massive glaciers during the Last Glacial Maximum, decreased temperature and precipitation led to changes in vegetation cover, particularly in the Zagros and Alborz mountains, likely contributing to the reduced habitat suitability for the long-tailed tit during this period (Kehl, 2009; Stevens et al., 2001). Consequently, the species' distribution was confined to northern refuge areas of Iran, with a significant reduction in its presence in the Zagros Forest regions.

The moderate climate during the mid-Holocene period, approximately 6,000 to 10,000 years ago, following the Last Glacial Maximum, led to an increase in suitable habitats and the expansion of the long-tailed tit across a wide range of the Palearctic. The key climatic factors influencing the species' distribution during the mid-Holocene were the annual temperature range, daily temperature range, and seasonal precipitation. During this period, habitat suitability for the long-tailed tit increased in northern Iran, while its distribution was restricted to small patches in the Zagros forests of southern Iran (Figure 2).

The results of climate change projections for the year 2080 under the optimistic (SSP126) and pessimistic (SSP585) scenarios indicate that habitat suitability for the Long-tailed Tit in the Palearctic biogeographic range will increase in the optimistic scenario but decrease in the pessimistic scenario. Under the SSP126 scenario, which involves reduced greenhouse gas emissions and the implementation of sustainable environmental protection policies, the distribution of the Long-tailed Tit is expected to remain relatively stable. The species is likely to persist in most of its current habitats and may even expand into new areas that become suitable. Conversely, under the SSP585 scenario, characterized by a significant rise in greenhouse gas emissions and a global temperature increase of more than 4 degrees Celsius, the distribution of the Long-tailed Tit is projected to become more restricted, with potential declines in population and the loss of some habitats (Pacifici et al., 2022).

Overall, the trend in the distribution and habitat suitability of the Long-tailed Tit across different periods suggests that, despite habitat losses during the harsh conditions of the Ice Age, this species has managed to maintain its habitat suitability over a broad range of the Palearctic region. The species can likely endure the conditions projected under the pessimistic climate scenario, highlighting its resilience to varying climatic conditions. Moreover, developing distribution maps and assessing the effects of climate change across past, present, and future periods using advanced habitat suitability modeling algorithms can aid in protecting and managing habitats and mitigating the adverse effects of climate change on this species. The findings of this study can inform the identification and protection of sensitive and vulnerable habitats in the future and help in determining large-scale bird migration patterns.

Conclusion

In summary, this study highlights the effectiveness of the Random Forest, GLM, and SVM algorithms in accurately predicting the habitat suitability of the long-tailed tit across different periods in the Palearctic region. Despite significant habitat changes due to past climate events, such as the Last Glacial Maximum, the species has shown resilience, maintaining its presence in suitable areas. Future projections indicate that habitat suitability may either increase or decrease depending on climate scenarios, emphasizing the importance of ongoing habitat management and conservation efforts to protect the species against the impacts of climate change.

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