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RESEARCH ARTICLE

Predicting the distribution of the caucasus endemic *Carabus exaratus* Quensel, 1806 in the Maxent environment

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Abstract

To investigate how the Caucasian endemic *Carabus exaratus* is distributed in a changing climate, we conducted modeling of its current and predicted ranges using the Maxent environment. Data from literary sources and our own field collections were used for this study, totaling 99 identified habitats. We utilized 20 bioclimatic variables with a spatial resolution of 30 seconds for the modeling. The analysis revealed several significant factors affecting *C. exaratus*: average annual temperature (bio 1), precipitation of the warmest quarter (bio 18), precipitation of the coldest quarter (bio 19), seasonality of precipitation (bio 15), isothermal conditions (bio 3), and elevation above sea level (bio 20). By applying the RCP 8.5 climate scenario, we generated maps showing forecasted ranges under changing climate conditions and calculated the areas of both current and predicted ranges. Our findings indicate that global warming will cause a shift and significant reduction in the bioclimatic range of *Carabus exaratus*.

Keywords

Energy efficient measures, Green Zoom, greenness indicators, integrated residential development, sustainable development, standards

Introduction

Biogeography's crucial task is understanding the spatial distribution patterns of species, especially given rising anthropogenic pressures and global climate shifts. These factors are leading to habitat reduction, fragmentation, biodiversity loss, and potential species extinction. Knowing how climate change impacts species distribution is vital for developing effective conservation strategies. Identifying a species' climatic niche is a key aspect of biogeographic and ecological research.

Bioclimatic variables significantly influence the geographical distribution and range characteristics of poikilothermic organisms. Analyzing these variables helps model their potential ranges and predict changes. Our study focuses on the Caucasian endemic *Carabus exaratus* Quensel, 1806, which is prevalent in the Chechen Republic, spanning from foothill steppes to the subnival zone (Avtaeva et al. 2017; Aidamirova 2011).

MaxEnt, a tool using the principle of maximum entropy, is widely used to model species distribution based on location data while considering habitat constraints. Accurately predicting a species' geographic distribution is crucial for successful conservation efforts (Avtaeva et al. 2019; 2020; 2021; Khomitskiy et al. 2020; Sukhodolskaya et al. 2020; Brygadyrenko et al. 2021).

The advent of GIS technologies has significantly expanded ecologists' capabilities, allowing for the modeling of species range dynamics based on relationships with various environmental factors (Gent et al. 2011; Riahi et al. 2011). Our objective is to model both the current and predicted ranges of *Carabus exaratus* under the context of global climate change using the MaxEnt environment.

Materials and methods

Data for this study were sourced from literary references and our field collections conducted in various years across the Chechen Republic. We identified 99 habitats for *Carabus exaratus* (Figs 1a, b).

For bioclimatic modeling, we utilized 20 variables from the WorldClim global climate database with a spatial resolution of 30 seconds (www.worldclim.org). R Studio scripts were employed to refine the model. Due to high correlation between variables, we employed techniques in R Studio to reduce redundancy. We obtained a matrix and excluded factors with correlations above 0.75. Additionally, an "enmeval-results" csv file was generated in R, containing evaluation statistics for different settings combinations. We selected settings corresponding to the minimum AICc (Akaike information criterion corrected) and AIC (Akaike information criterion) values. We conducted potential habitat modeling in the MaxEnt 3.4.4 environment (American Museum of Natural History, New York, NY, USA; https://biodiversityinformatics.amnh.org/open_source/maxent/), using spatial cross-validation with 10 replicates for independent datasets.

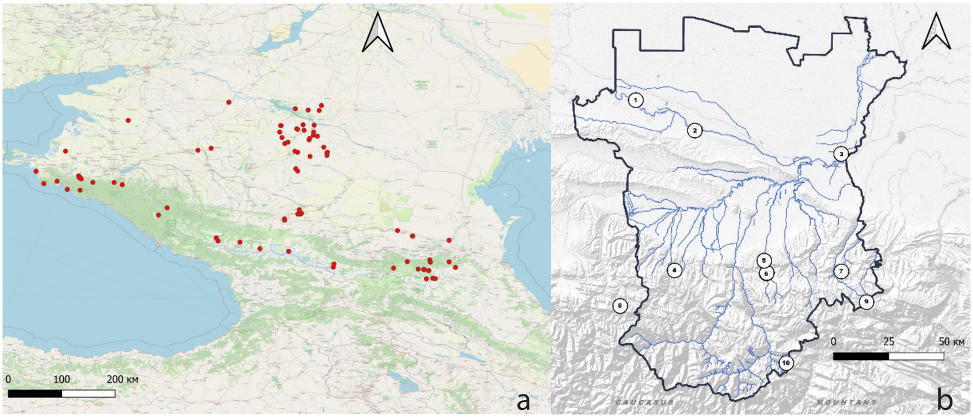

Figure 1. Location of *Carabus exaratus* habitats: a – in the Caucasus, b – in the Chechen Republic.

For predictions of encounter probabilities and spatial distribution modeling of *C. exaratus*, we applied the "cloglog" complementary log-to-log transformation. Each simulation ran a maximum of 500 iterations. Model verification was done using the Area Under the ROC Curve (AUC). AUC measures the model's ability to distinguish between presence and absence of species, ranging from 0 to 1.

To assess predictive capabilities, we set a prediction binarization threshold: areas were considered suitable for species existence if predictions were above the threshold, and unsuitable if below. In our modeling, we used a 10 percentile threshold to exclude individuals from atypical habitats, meaning 90% of presence points were included in the "potential area". The resulting AUC for our *C. exaratus* model was 0.960 ± 0.008, indicating high reliability. All simulations employed the CCSM 4 (Community Climate System Model, http://www.cesm.ucar.edu/models/ccsm4.0/) and considered the RCP 8.5 (https://www.climatewatchdata.org/pathways/scenarios/) climate change scenario (projecting a 4.1 °C increase). For layer manipulation and area calculations, we used the QGIS 3.18.0 software (Quantum GIS, 2020).

Result and discussion

The analysis of *Carabus exaratus* revealed several key factors influencing its distribution: average annual temperature (bio 1), precipitation of the warmest quarter (bio 18), precipitation of the coldest quarter (bio 19), seasonality of precipitation (bio 15), isothermal conditions (bio 3), and elevation above sea level (bio 20, see Table 1).

Our model yielded an average AUC value of 0.96, indicating the high efficiency of the *C. exaratus* distribution model obtained (Figs 2–3).

The simulation results revealed that suitable habitats for *Carabus exaratus* decrease when the average annual temperature falls below -10 °C or rises above +10 °C, and are non-existent above 15 °C (Fig. 3).

Table 1. Estimation of bioclimatic parameters affecting *C. exaratus* distribution

Variable	Percent contribution	Permutation importance
bio18b	78.4	49.7
bio19b	6.6	7.1
bio15b	3.5	5.3
bio8b	2.7	2.2
bio7b	2.4	3.1
bio20b	2.4	10.7
bio3b	2.1	5.8
bio11b	1.4	0.3
	0.5	15.8

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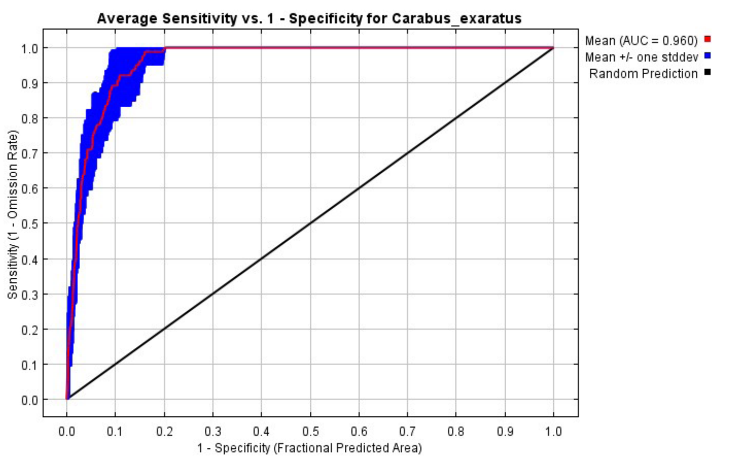

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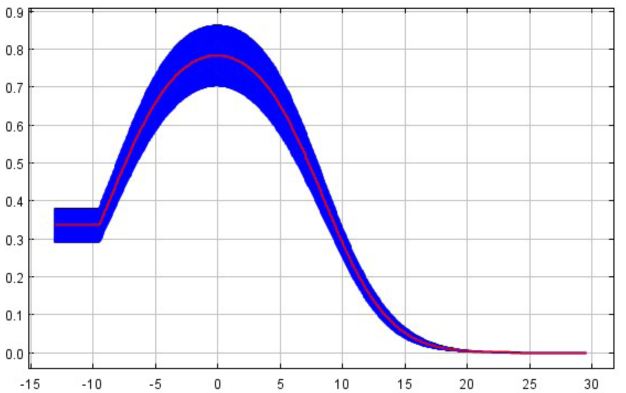

Figures 2–3. 2. Analysis of the prognostic distribution model accuracy: operational curve trend AUC (1 – test data, 2 – training data, 3 – random prediction). **3.** Model of *Carabus exaratus* preferences to environmental bioclimatic factors: bio 1 – average annual temperature indicators.

Furthermore, the ratio of average daily and annual temperature amplitudes ranging from -7 °C to +3 °C was observed (Fig. 4).

The simulation indicated that the most favorable elevation range for *Carabus exaratus* lies between 0 to 500 m above sea level. Although the comfort of living decreases with increasing elevation, it does not reach critical levels (Fig. 5). Notably, within the Chechen Republic, *C. exaratus* has been recorded at heights ranging from 25 to 2260 m above sea level, predominantly thriving in the floodplain forests of the Tersko-Kuma lowland.

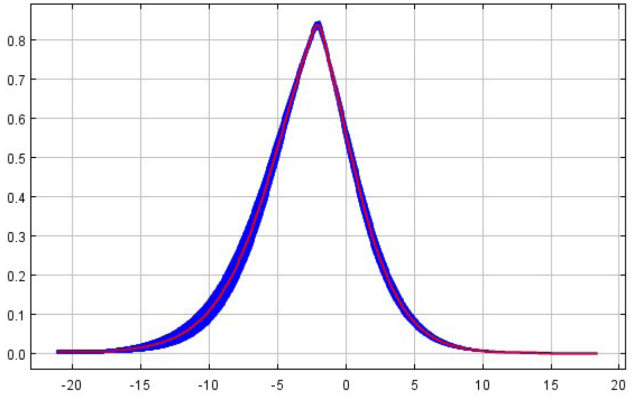

Figure 4. Model of *Carabus exaratus* preferences to environmental bioclimatic factors: bio 3.

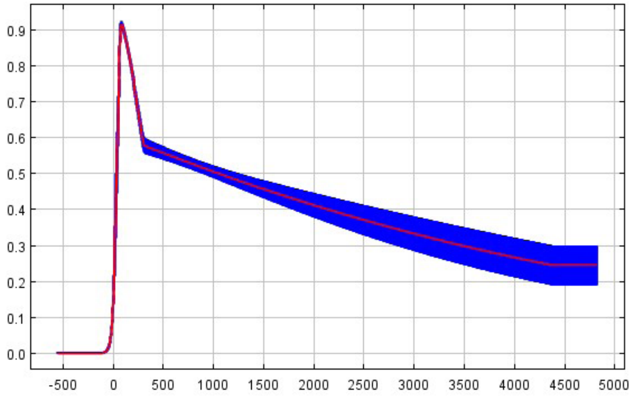

Figure 5. Model of *Carabus exaratus* preferences to environmental bioclimatic factors: bio 20 altitude.

The distribution of *Carabus exaratus* is also influenced by precipitation, particularly during the warmest (bio 18) and coldest quarters (bio 19). The optimal precipitation range for the species falls between 150–350 mm, with discomfort noted below 100 mm and above 500 mm (Fig. 6).

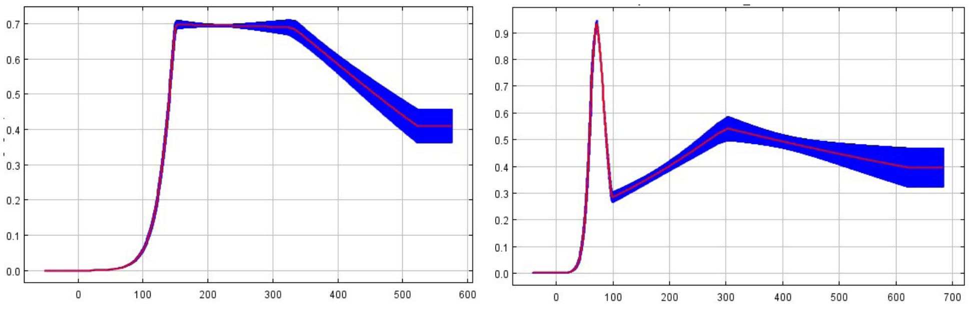

Figure 6. Model of *Carabus exaratus* preferences to environmental bioclimatic factors: bio 18 – precipitation of the warmest quarter; bio 19 – precipitation of the coldest quarter.

Our modeling process produced predictive maps of *Carabus exaratus* ranges under changing climate conditions, following the RCP 8.5 climate scenario. Notably, the ground layer of biogeocenoses appears to be the most sensitive to climate change due to its inability to shield the soil surface from atmospheric effects. This shift in species ranges may be a result of ongoing climate change. Additionally, climatic variables significantly impact the life cycle and seasonal dynamics of *C. exaratus*, a species exhibiting a recyclic autumnal type of reproduction (Fig. 7).

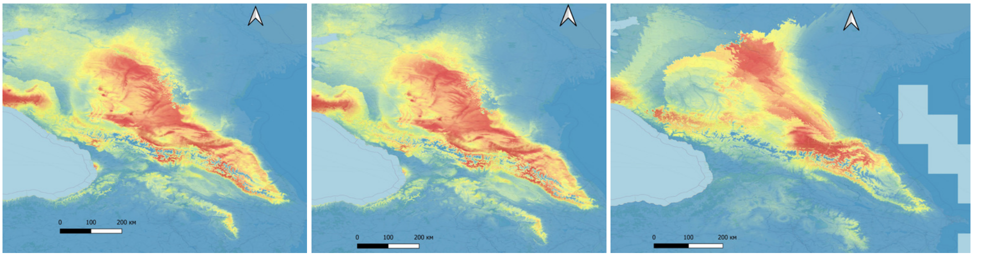

Figure 7. Bioclimatic area in *Carabus exaratus*: a – modern area; b – area of 2050 according to the RCP 8.5 scenario; c – area of 2070 according to RCP 8.5 scenario.

Using the QGIS field calculator, we calculated the sizes of the modern range and the predicted ranges for *C. exaratus* according to the RCP 8.5 scenario for 2050 and 2070 (Table 2).

Table 2. Size of the bioclimatic area (sq km) in *C. exaratus* according to the RCP 8.5 scenario

RCP 8.5	0.4–0.6	0.6–0.7	0.7–0.8	0.8–1.0
2020	53613.4	47157.4	50015.4	41261.9
2050	41746.2	42386.8	35903.3	12938.1
2070	42212.9	29374.5	23105.2	12845.5

Conclusion

Our findings reveal a reduction in the predicted ranges compared to the current distribution area of *Carabus exaratus*. Notably, there is a significant decrease in the most favorable areas, characterized by a comfort index of 0.8–1.0 and 0.7–0.8. The predictive maps, generated using the MaxEnt algorithm and based on identified ecological and climatic niches, generally align with the species' known distribution within the Caucasus region. In essence, our results indicate that global warming is causing a shift and substantial reduction in the bioclimatic range of *Carabus exaratus*.

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