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Modelling Distribution of an Endangered Longhorn Beetle, *Callipogon relictus* (Coleoptera: Cerambycidae), in Northeast Asia

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Abstract: Based on our own field data and using modeling of modern potential ranges (in the MaxEnt program), an assessment of the spatial distribution of the rare representative of the longhorn beetle family, *Callipogon* (*Eoxenus*) *relictus* Semenov 1899, was conducted in northeast Asia (220 geographic locations). The generated maps of the potential range of *C. relictus* demonstrate a high likelihood of the species' presence in the upland areas of southern far east Russia, the provinces of northeastern China, and the Korean Peninsula. Field data also indicate the extensive association of the species with undisturbed broadleaf and coniferous–broadleaf forests in northeast Asia. Maps of the potential distribution of *C. relictus* in northeast Asia have been compiled based on four climate change scenarios from the present time to 2070. Under all of the climate scenarios used, it is shown that suitable habitats for the species will persist in certain areas of Primorsky Krai, as well as neighboring provinces of the People's Republic of China and a small enclave on the Korean Peninsula in Gangwon-do province. Significant reduction in suitable conditions for the rare longhorn beetle will occur in the rest of its distribution range.

Keywords: forest ecosystems; *Callipogon relictus* Semenov 1899; Coleoptera; rare species; northeast Asia; distribution; climate change; spatial modeling; MaxEnt; potential area; climatic parameters

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Citation: Kuprin, A.; Shevchenko, N.; Baklanova, V. Modelling Distribution of an Endangered Longhorn Beetle, *Callipogon relictus* (Coleoptera: Cerambycidae), in Northeast Asia. *Forests* **2024**, *15*, 598. https://doi.org/10.3390/f15040598

Academic Editor: Christopher J. Fettig

Received: 11 January 2024
Revised: 20 February 2024
Accepted: 24 March 2024
Published: 26 March 2024

1. Introduction

The relic longhorn beetle (*Callipogon* (*Eoxenus*) *relictus* Semenov 1899) is rare, and it is the sole representative of the neotropical genus *Callipogon* Audinet-Serville 1832 in the fauna of northeast Asia. The species' range covers the territories of Russia, China, and Korea [1–5]. It is rare throughout its distribution range, and in Russia and Korea, it is classified as an endangered species and is included in protective lists of rare insects. Currently, thanks to extensive international cooperation, important data on the biology and ecology of this species have been gathered. The list of larval host trees has been expanded, the flight periods of adult beetles have been refined, and the peculiarities of the preimaginal biology have been studied under laboratory conditions. The genetic diversity of *C. relictus* in northeast Asia has also been investigated [6–15].

However, for the development of conservation and recovery programs for the species, detailed information about its distribution in northeast Asia is essential, including predictive assessments of the potential range of the beetle and its possible changes (transformations) due to the influence of climate and anthropogenic factors. Addressing these questions is made possible through species distribution modeling based solely on presence data, using the MaxEnt 3.3.3k software, which enables the construction of precise predictive models [16]. Based on the theory of maximum entropy, MaxEnt assesses the distribution probabilities of species detection according to environmental property value distributions similar to the habitats where species are found. Habitats determined with the highest probability of species detection are considered the most suitable. The effectiveness of this method in predicting the potential habitat of alien and rare insect species has been confirmed by the results of numerous studies, including *Anoplophora glabripennis* (Motschulsky 1853), *Rosalia alpina* (Linnaeus 1758) (Coleoptera: Cerambycidae), *Paracyphoderris erebeus* Storozhenko, 1980 (Orthoptera: Prophalangopsidae), and others [17–28].

The aim of this study is to summarize existing data on the distribution of the relic longhorn beetle and assess eco-geographical models of its distribution in northeast Asia constructed using machine modeling methods with the application of various climate scenarios.

2. Materials and Methods

2.1. Distribution Point Collection

This study utilized our own field research conducted in various parts of the species' range from 2008 to 2023 employing standard entomological methods for insect collection. All locations where *C. relictus* was found were mapped using a GPS navigator (Garmin 65S, Olathe, KS, USA). In addition, our data have been published in various studies [29,30], and we use collection data from leading scientific institutions in Russia, including the Zoological Institute of the Russian Academy of Sciences, St. Petersburg (ZIN RAS), the Zoological Museum of M. V. Lomonosov State University, Moscow (ZMMU), the Institute of Animal Systematics and Ecology, Siberian Branch of the Russian Academy of Sciences, Novosibirsk (IASE SB RAS), the Federal Scientific Center of the East Asia Terrestrial Biodiversity, the Far East Branch of the Russian Academy of Sciences, Vladivostok (FSCEATB FEB RAS, former IBSS FEB RAS), the Ussuri Nature Reserve, the Far East Branch of the Russian Academy of Sciences, Ussuriysk (UNR FEB RAS), in Korea, including Korea University, Seoul (KU), the Center for the Study of Insect Ecology, Yeongwol Insect Museum, Yeongwol-gun, Gangwon-do (CSIE), the Yangpyeong Insect Museum, Yangpyeong-gun, Gyeonggi-do (YIM), Paichai High School, Seoul (PHS), the Hampyeong Research Center of Insects, Hampyeong-gun, Jeollanam-do (HRCI), and China, including the Institute of Zoology, Chinese Academy of Sciences, Beijing (IZAS) were included in the analysis.

As a result, a database on the distribution of *C. relictus* in northeast Asia has been compiled and contains the most comprehensive data on the species' distribution in the region since 1899. The database includes information on the locations of adult and larval collections, as well as data on its biotopic distribution, flight periods, and the tree species on which the beetle was collected. In total, GPS coordinates for 220 locations of *C. relictus* habitats in northeast Asia were included in the initial analysis (Figure 1). All localities are listed in the Supplementary File.

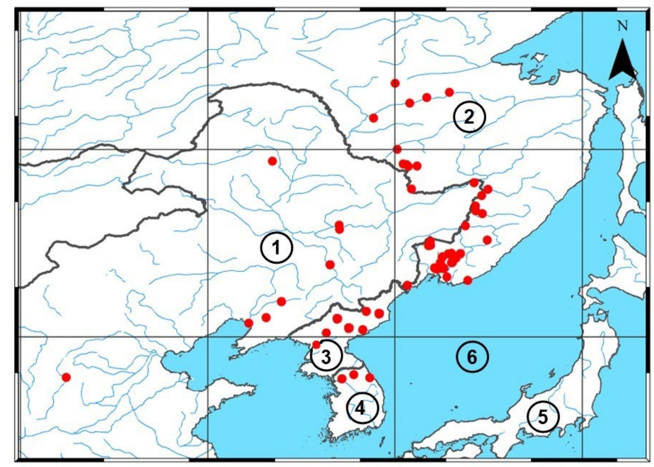


Figure 1. Known geographical distribution of *Callipogon relictus* in northeast Asia. Numbers indicate: 1—China; 2—Russia; 3—North Korea; 4—South Korea; 5—Japan; 6—Japanese (Eastern) Sea.

2.2. Climate Data Collection and Environmental Variables

The following layers from the WorldClim climate base (www.worldclim.org (accessed on 3 December 2023)) were used in the modeling (minimum resolution—5 arc-minutes or ~9 km per pixel), which allow for interpolation of the observed data from the years 1950 to 2023. Modeling to identify the ecological–climatic niche of *C. relictus* was carried out using 18 bioclimatic variables (BIOCLIM): BIO_1—Average annual temperature, °C; BIO_2—Average monthly temperature, °C; BIO_3—Iso-thermality (BIO_2/BIO_7) × 100); BIO_4—Temperature seasonality (standard deviation × 100); BIO_5—Maximal temperature in the warm month, °C; BIO_6—Minimal temperature in the cold month, °C; BIO_7—Annual amplitude temperature (b5-b6), °C; BIO_8—Average temperature in the wettest quarter, °C; BIO_9—Average temperature in the driest quarter, °C; BIO_10—Average temperature in the warmest quarter, °C; BIO_11—Average temperature in the coldest quarter, °C; BIO_12—Amount of precipitation per year, mm; BIO_13—Amount of precipitation in the wettest month, mm; BIO_14—Amount of precipitation in the driest month, mm; BIO_15—Precipitation seasonality (coefficient of variation), CV; BIO_16—Amount of precipitation in the most humid quarter, mm; BIO_17—Amount of precipitation in the driest quarter, mm; BIO_18—Amount of precipitation in the warmest quarter, mm; BIO_19—Amount of precipitation in the coldest quarter, mm) [31–33].

2.3. Species Distribution Model

The maps of the potential habitats of the *C.relictus* have been created with MaxEnt 3.3.3k software (http://www.cs.princeton.edu/~schapire/maxent/, accessed on 3 December 2023). With the help of the color gradations, the obtained maps indicate the level of probability of finding a species at a particular point and determine the degree of influence of the environmental parameters (in %) on the boundaries of their distribution, that is, the contribution of each factor to the model's construction. The maximum entropy method was used to determine the potential area of the model tree species. The quality of the models has been estimated using the AUC (area under the curve) values, with the area under the ROC curve representing the proportion of true and false positively classified cases (receiver operating characteristics) [34] and the omission rate characterizing false negative cases (error of the second kind). The model quality is rated as excellent with the AUC values of 0.9–1.0; good with the 0.8–0.9 values; and very bad if less than 0.6. The model's accuracy corresponds to a random choice at 0.5 [16]. The visualization of the obtained GIS maps was conducted with DIVA-GIS 7.5.0 software (www.diva-gis.org (accessed on 3 December 2023)) [35–37].

2.4. Change of Suitable Area under Different Climate Pathways

We used the IPCC concentration pathways (RCPs) as future climate change scenarios, namely RCP2.6, RCP4.5, and RCP8.5. RCP2.6 and RCP8.5 represented the minimum and maximum greenhouse gas emission scenarios, respectively, and RCP4.5 represented the medium greenhouse gas emission scenario, as it was superior to other medium greenhouse gas emission scenarios (RCP6.0) [38,39].

3. Results

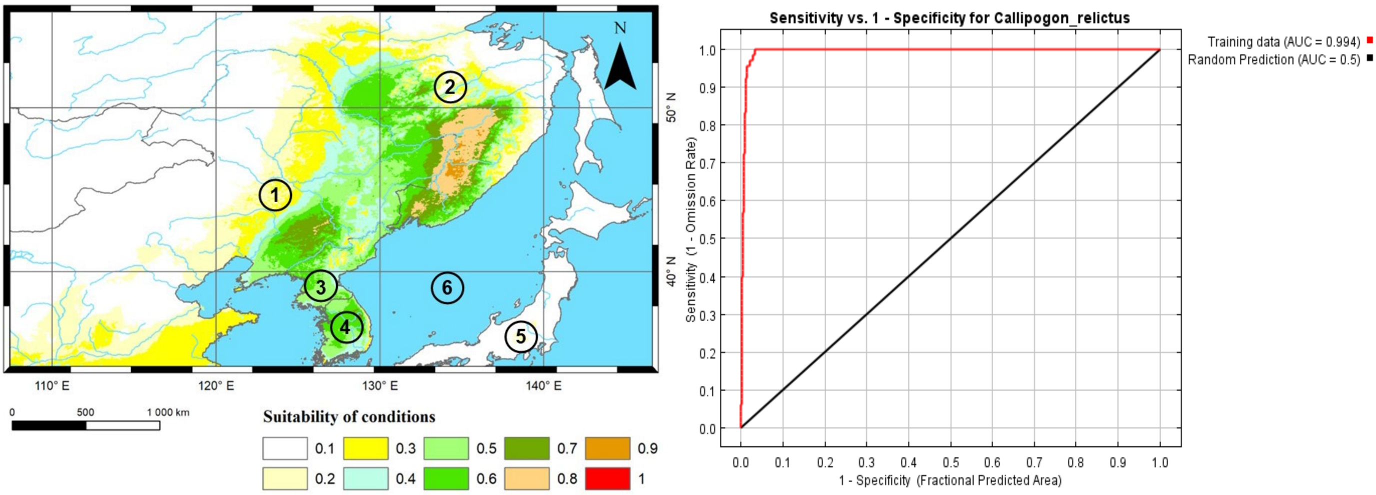
3.1. Reliability Analysis of Models Established for C. relictus

GIS modelling was used to analyze the ecological and climatic range of *C. relictus*. This study employed 19 environmental parameters (predictors BIO_1—BIO_19 and ALT) to reflect temperature and precipitation data from 1950 to the current time. The significance of all bioclimatic variables was assessed, and predictors correlating with each other were excluded for model building. This was achieved by calculating the Pearson correlation coefficient for all pairs of predictors using ENMTools v. 1.4.3 [40]. Variables with $|r| > 0.7$, which were considered less biologically important based on known preferences for *C. relictus* [41], were excluded from the correlated pair. The dataset comprised six bioclimatic predictors (Table 1). Using these data, the potential range of *C. relictus* in northeast

Asia was constructed (Figure 2). The response curves of the main bioclimatic parameters used in the modelling are shown in Figure 3. The AUC values, indicating the model's reliability level, are high, with values of 0.994 and 0.5, respectively. The potential contemporary range of the species obtained using the MaxEnt algorithm generally corresponds to the distribution of the beetle in northeast Asia and aligns well with previously published data on the beetle's distribution in the region [4,5,30].

Table 1. Significance of the involved bioclimatic parameters (%) in building models of *C. relictus* distribution in northeast Asia and ranges of their values.

Variable	Percent Contribution	Permutation Importance	Min	Max	Mean	SD	CV, %
BIO_1	3.8	73.7	−4.9	13.9	4.92	3.73	75.8
BIO_4	27.4	15.1	-	-	-	-	-
BIO_12	7.7	1.6	420	1480	836	253	30.2
BIO_13	2.2	0.9	108	439	187	83	44.4
BIO_18	42.3	0.9	257	890	456	167	35.9
BIO_15	16.6	7.8	-	-	-	-	-



(**a**) (**b**)

Figure 2. (**a**) Potential bioclimatic range of *C. relictus* in northeast Asia predicted using the MaxEnt model under the current climate conditions. Numbers indicate: 1—China; 2—Russia; 3—North Korea; 4—South Korea; 5—Japan; 6—Japanese (Eastern) Sea; (**b**) Analysis of the prognostic distribution model's accuracy for the operational curve trend AUC for current climate conditions.

The predicted range of the species extends from Shansi province (China) in the south northwards through the Korean Peninsula to the Amur region (Russia), and from Inner Mongolia (China) in the west to the coastal zone of the Russian far east, covering an area of 10.5×10^4 km^2.

As seen in Figure 2a, the climatic conditions of the southern Russian far east, including the territories of Primorsky Krai, the southern part of Khabarovsk Krai, and parts of the Amur region, are the most favorable for the beetle. The largest area suitable for the species is located in Primorsky Krai, with a probability of over 70%. Extensive territories with optimal habitats for *C. relictus* with a probability of over 90% cover the southern Primorsky Krai, bordering the Eastern Manchurian and North Korean mountains, which form a single mountain system. High population numbers of the species have been recorded in the Ussuri Nature Reserve and the "Kedrovaya Pad" Reserve, which are currently part of the vast Land of the Leopard National Park system. In these areas, relatively undisturbed coniferous and broad-leaved forests, necessary for the habitat and development of *C. relictus* larvae, have been preserved.

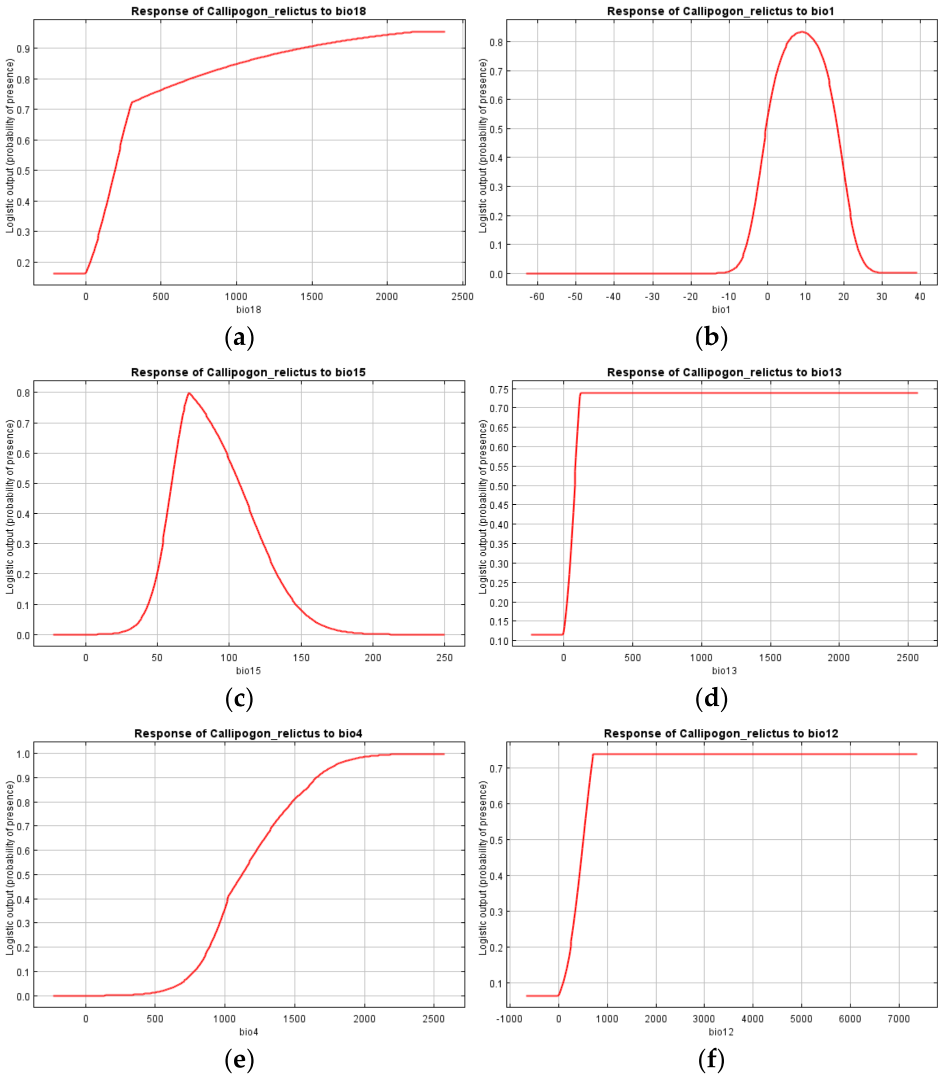


Figure 3. Response of *C. relictus* preferences to environmental bioclimatic factors. (**a**) BIO_18; (**b**) BIO_1; (**c**) BIO_15; (**d**) BIO_13; (**e**) BIO_4; (**f**) BIO_12.

However, the area of these territories is decreasing from west to east towards the coast of the Sea of Japan (East Sea), with a low probability of species detection ranging from 20% to 40%, due to deforestation and pyrogenic factors [13,42].

Within the northern Korean Peninsula, the most suitable territories (probability exceeding 60% and higher) are located in the provinces of Pyeonganbuk-do, Hamgyeongbuk-do, Jagang-do, and Yanggang-do, which is consistent with the literature and our data [10,12]. Further south, in the Republic of Korea, provinces with high climatic suitability (probability exceeding 80%) for *C. relictus* habitats include Gyeonggi-do and Gangwon-do, with occasional findings of adults since 2007 [13]. Moving further south on the Korean Peninsula, the likelihood of species detection is projected to be minimal (10%–40%).

In China, the potential range with a high probability of species detection (ranging from 60 to 80%) covers eastern Manchuria within the Amur River basin, extending to the east of Heilongjiang and Jilin provinces. Further south, the distribution extends to the preserved mountainous forest ecosystems in Liaoning, Hebei, Shanxi, and Shaanxi provinces [15,30]. Literature reports indicate that *C. relictus* larvae were accidentally introduced beyond their natural range during the export of commercial timber to Canada, Japan, and the far east of Russia [30]. They successfully completed their development to the adult stage in these regions; however, naturalization into natural ecosystems did not occur. Data obtained from MaxEnt modeling also do not identify suitable eco-climatic conditions for the species' distribution in these territories. For example, in Japan, the probability of species detection ranges from 10 to 30%, while in the Magadan Region (Russia), it is no more than 10% (Figure 2a).

3.2. Potential Suitable Areas for C. relictus under Future Climate Conditions

Based on four climate change scenarios, RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, maps of potential distribution of *C. relictus* in northeast Asia from the present to 2070 have been compiled (Figure 4). The AUC values, indicating the model's reliability level, are high, with values of 0.994 and 0.5, respectively (Figure 5). In the Russian Primorsky Krai, valley broad-leaved and cedar-broad-leaved forests remain the primary bioclimatic zones suitable for the distribution of this species, with a probability ranging from 80% to 90%.

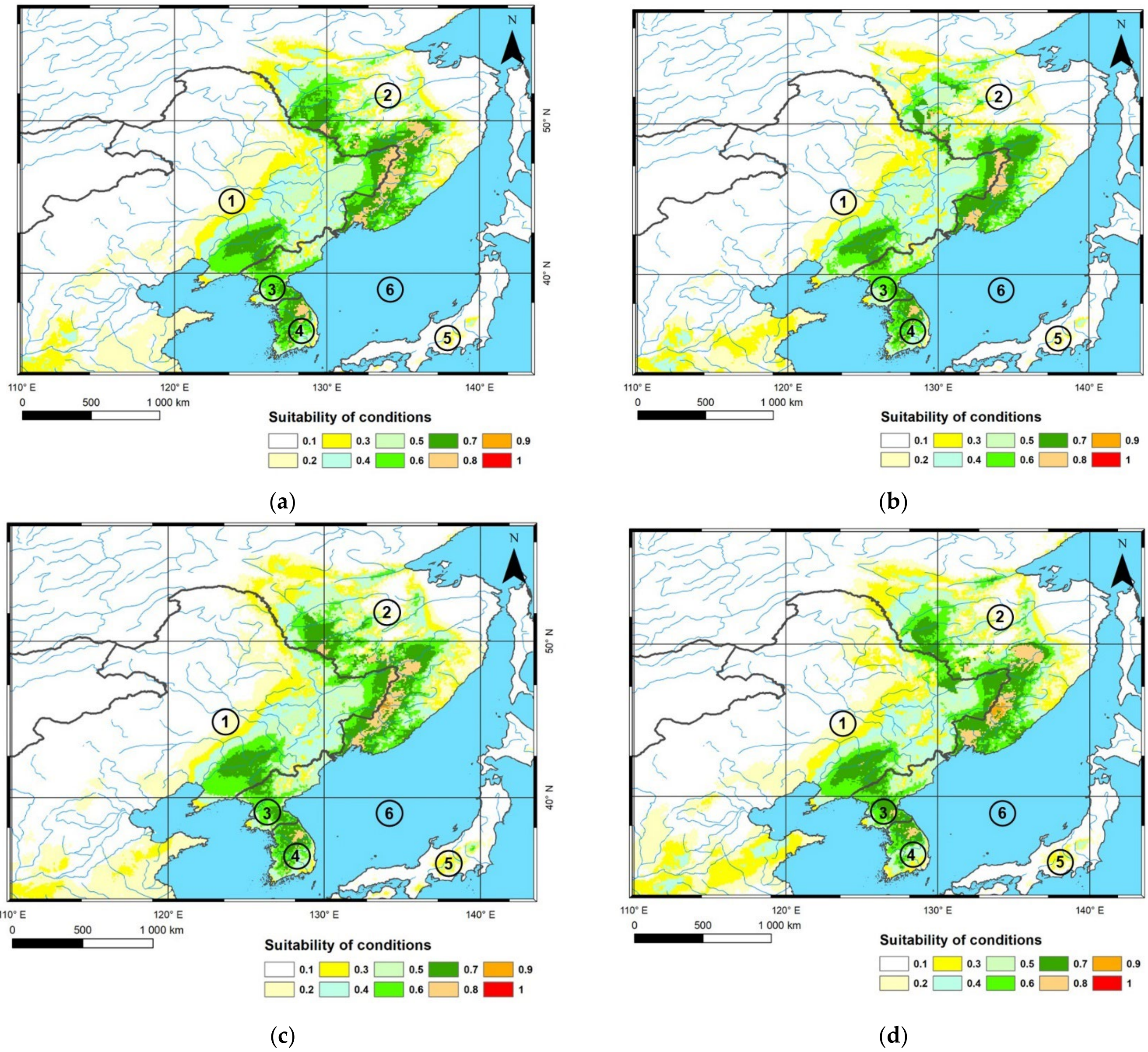


Figure 4. Bioclimatic range of *Callipogon relictus* until 2070 according to different climatic scenarios: (**a**) RCP 2.6; (**b**) RCP 4.5; (**c**) RCP 6.0; (**d**) RCP 8.5. Numbers indicate: 1—China; 2—Russia; 3—North Korea; 4—South Korea; 5—Japan; 6—Japanese (Eastern) Sea.

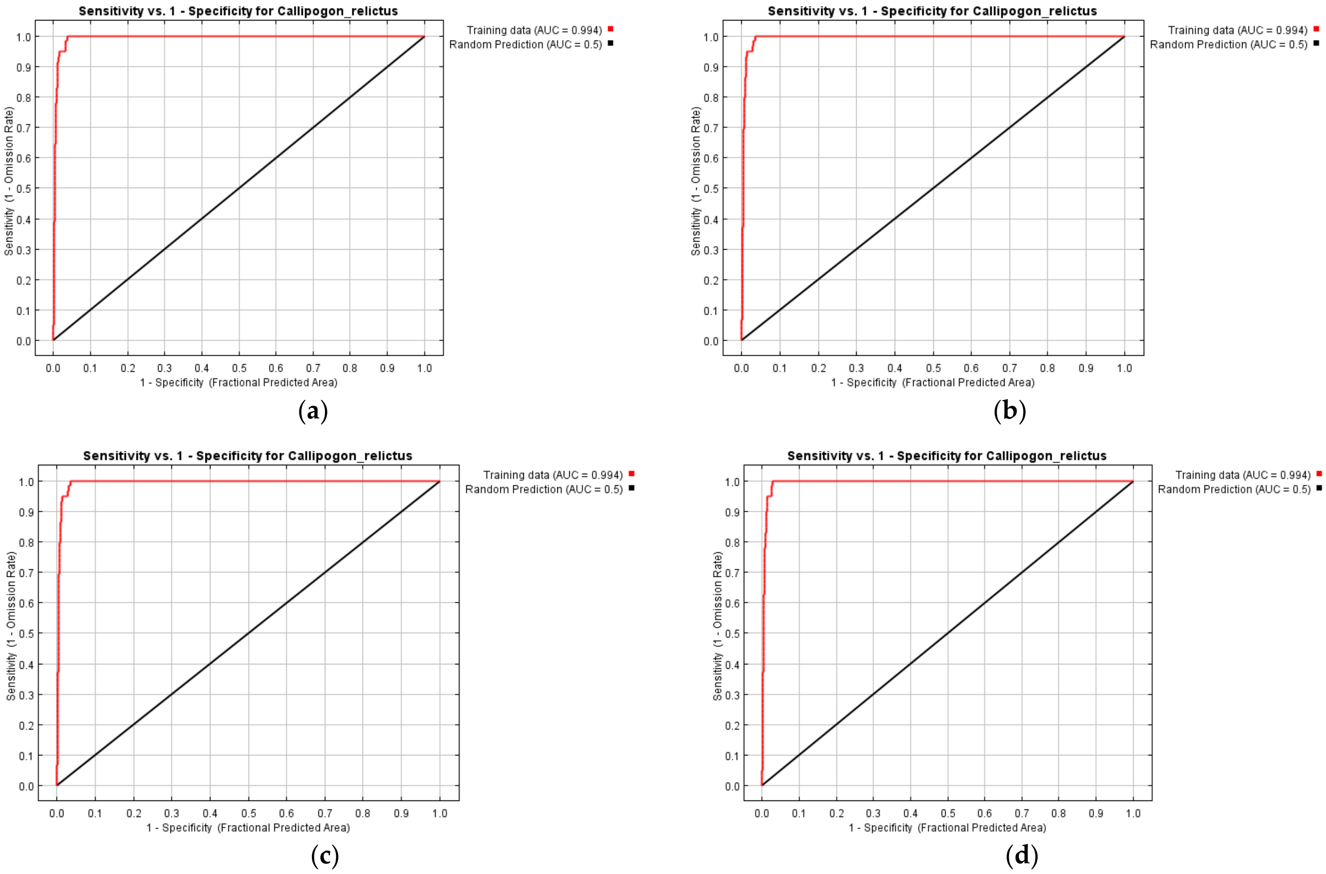


Figure 5. Analysis of the prognostic distribution model's accuracy for the operational curve trend AUC for different climatic scenarios: (**a**) RCP 2.6; (**b**) RCP 4.5; (**c**) RCP 6.0; (**d**) RCP 8.5.

In China and on the northern Korean Peninsula, from the present to 2070, there will be a significant reduction in suitable habitats for the species, with a low likelihood of occurrence ranging from 20 to 50% and, in some high-mountain areas, up to 70% (Figure 4). On the southern Korean Peninsula, under all climate scenarios, the main zone suitable for species distribution will remain the forest ecosystems located in Gangwon-do province (80%–90%).

By 2070, the greatest reduction in areas with medium and high suitability for the species' habitats, compared to the current suitable distribution area, is projected by the model under the RPC 4.5 climate scenario, amounting to 0.87×10^4 km^2 or 2.04% of the entire potential range. For the other applied scenarios, the area of bioclimatically suitable territory is also low, ranging from 1.22×10^4 km^2 to 1.42×10^4 km^2 or 2.43% to 2.97% (Table 2). However, under the most "stringent" scenario, PCP 8.5, the area of suitable territory for the species is higher than that of the RPC 4.5 scenario by 0.35×10^4 km^2. Under the "softer" scenarios (RPC 2.6, RPC 4.5, and RPC 6.0), areas with favorable conditions decrease, and the species distribution shifts towards increased unsuitability. Territories with medium suitability become the least stable, with deteriorating properties for beetle viability with changing bioclimatic parameters (Figure 4).

As a result, by 2070, the potential range area of the species under different climatic conditions may decrease by approximately four to seven times from 6.35×10^4 km^2 to 0.87×10^4 km^2.

The most significant predictors for forecasting the range of *C. relictus* in northeast Asia were the average annual temperature (BIO_1, contributing 3.8%), the amount of precipitation per year (BIO_12, 7.7%), the amount of precipitation in the wettest month (BIO_13, 2.2%) and the amount of precipitation in the warmest quarter (BIO_18, 42.3%) (Table 1).

Table 2. Proportion of suitable area for *C. relictus* in northeast Asia, from the current time to 2070.

	Suitable Area		Unsuitable Area	
	Area ($\times 10^4$ km^2)	Proportion (%)	Area ($\times 10^4$ km^2)	Proportion (%)
Current	6.35	5.89	101.57	94.11
RPC 2.6	1.42	2.97	46.39	97.03
RPC 4.5	0.87	2.04	41.78	97.96
RPC 6.0	1.32	2.73	47.06	97.27
RPC 8.5	1.22	2.43	49.25	97.57

4. Discussion

The application of MaxEnt algorithms with different climate scenarios allowed us to construct, for the first time, the potential range of the rare beetle *C. relictus* in northeast Asia and to forecast its changes by 2070 due to climate change. High AUC indices confirmed the validity of our models in potential distribution, and the resulting maps accurately characterized the features of the beetle's range transformation in northeast Asia (Figure 4).

Under all of the applied scenario conditions, it is shown that some areas of Primorsky Krai, as well as adjacent provinces of the People's Republic of China and a small enclave on the Korean Peninsula in Gangwon-do province, will remain suitable for the species. In the rest of the distribution area, there will be a significant reduction in conditions suitable for the habitat of the rare longhorn beetle.

The average annual temperature, amount of precipitation per year, amount of precipitation in the wettest month, and amount of precipitation in the warmest quarter made significant contributions to the models. The impact of isothermality on the potential distribution and future suitable areas for *C. relictus* may indicate the high vulnerability of species inhabiting high altitudes and their dependence on significant temperature fluctuations and extreme weather events [43,44]. These bioclimatic factors may also influence the population life of *C. relictus* in northeast Asia by affecting the life cycle of beetles, especially the activity periods of adults. Unfortunately, to date, we lack reliable and precise data on the duration of the beetle's development in natural conditions due to methodological complexities arising during the study of the biology of saproxylic larvae [8]. According to laboratory research data, for the normal maturation of gonads in *C. relictus*, a temperature of +22 °C and humidity of 80% are required for a minimum of three weeks. Therefore, increased precipitation during breeding periods, especially the frequent extreme weather events in recent years, may have a detrimental impact on the activity periods of adults, particularly females, which require additional nourishment before mating [7,29].

The contribution of temperature indicators proved to be less significant (Table 1), likely due to the fact that *C. relictus* larvae, as saproxylic insects, inhabit the depths of wood in its three to four stage of decomposition. They create a system of vertical tunnels and manage to avoid critical deviations in bioclimatic factors both in the winter and summer seasons thanks to the unique microclimatic conditions created by the wood itself. The transformational activities of the larvae enable them to alter moisture parameters within the tree trunk, promoting the development of xylophagous fungi mycelium and other microorganisms, which contribute to enhancing the nutritive properties of low-carbohydrate wood [6–8,45]. Low temperatures during the winter period in the conditions of the monsoonal climate of southern Primorye result in the beetle larvae entering diapause (personal field observations of the authors). Extended diapause periods ranging from 1 to 16 years are also known for saproxylic insect larvae, allowing them to survive unfavorable environmental conditions [46].

Altitude above sea level remains a crucial factor restraining the distribution of certain endemic and rare insect species [42]. Therefore, the contribution of this factor will remain significant for *C. relictus*. Currently, there is information about local findings of the beetle in the Eastern Manchurian and North Korean mountains, with the highest population density in the area of Mt. Paektu, on the border between North Korea and China [3,30].

According to MaxEnt models, under all climate scenarios, these territories will become less suitable, and the probability of encountering adults will be low, ranging from 20% to 70% (Figure 4). It can be assumed that a global temperature change of 2 to 4 °C and an increase in CO_2 emissions in the implementation of RCP4.5 and RCP8.5 scenarios will lead to a reduction in deciduous tree species. Consequently, the areas of undisturbed broad-leaved forests, which serve as the feeding base for the larvae of the relict longhorned beetle, will decrease [4,10,29]. Furthermore, the reproductive *k*-strategy of this large representative of the Prioninae family, striving to maintain equilibrium between microclimatic conditions and trophic resources, renders it increasingly vulnerable to anthropogenic factors [4,30].

The reduction in the modern potential habitat of the species in the Russian far east can be attributed to the development of natural resource utilization and economic activities in the region. In the mid-19th century, intensive settlement and agricultural development of the Russian Empire's far east territory commenced. Settlement occurred not only in the Zeya-Bureya and Prihankayskaya plains but also in the foothills of mountain ranges and intermountain valleys of major tributaries of the Amur and Ussuri rivers (Zeya, Bolshaya Ussurka, Arsenyevka). From 1900 to 1917, agricultural development of cleared forest areas began using a slash-and-burn farming system [47]. Intensive logging led to changes in its tree species composition. Species, such as Mongolian oak (*Quercus mongolica*), Manchurian ash (*Fraxinus mandshurica*), Japanese elm (*Ulmus japonica*), Amur linden (*Tilia amurensis*), and Manchurian walnut (*Juglans mandshurica*), were felled, with a preference for large trees, from which no more than 40% of commercial timber was extracted. This method of forest use altered the health of the forests. The complete absence of clearing in the felling areas created a high fire hazard. In many cases, these felling areas became sites of significant forest fires, often compounded by fires resulting from agricultural slash-and-burn practices. Extensive burnt areas emerged in the territories of modern Khabarovsk Krai and the southern Amur Region, particularly in the basins of the Bureya and Amgun rivers [29,48]. Over the century of far east settlement, forest development and utilization occurred at an accelerated pace, using methods and approaches that did not contribute to increasing forest productivity. Even a brief analysis of the history of natural resource utilization and development in the Russian sector of the species' range (Russian far east) explains the decline in the population size and habitat area suitable for *C. relictus*, as depicted using MaxEnt algorithms (Figure 2).

The survival of *C. relictus* depends on the preservation of undisturbed valley broad-leaved and coniferous-broad-leaved forests in northeast Asia, which are characterized by high biological diversity and play crucial roles in climate regulation and carbon sequestration. The development of programs for the conservation of populations of rare and endangered saproxylic insects will be facilitated not only by detailed knowledge of their biology and ecology but also information about the history of land use in the areas where the species currently resides or has lived in the past.

5. Conclusions

The application of modeling methods using the MaxEnt program has enabled the construction of the current potential habitat of the rare representative of neotropical fauna, the *C. relictus* beetle in northeast Asia. It has also allowed us to monitor its changes under the development of four climate scenarios. The modeling results of the potential habitat indicate a high likelihood of the species inhabiting the foothill areas of the southern Russian far east, the provinces of northeastern China, and the Korean Peninsula. Field data also indicate the extensive association of the species with undisturbed broadleaf and coniferous–broadleaf forests in northeast Asia. Maps of the potential distribution of *C. relictus* in northeast Asia have been compiled based on four climate change scenarios from the present time to 2070. The most influential predictors in forecasting the beetle's habitat have proven to be altitude above sea level, precipitation levels during the driest quarter of the year, and temperature factors.

The combination of field data and modeling using various climate scenarios will enable the development of scientifically grounded models to analyze the distribution of saproxylic beetles. It will also contribute to the creation of a comprehensive biodiversity monitoring system and enhance our understanding of the risks associated with the loss of taxa within various groups of invertebrate animals in the context of global climate change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15040598/s1, Table S1: Geographic coordinates of known records of *Callipogon relictus* in its range.

Author Contributions: Conceptualization, A.K. and N.S.; methodology, A.K. and N.S.; software, N.S.; investigation, V.B. and A.K.; writing—original draft preparation, A.K.; writing—review and editing, A.K.; visualization, V.B. and N.S. supervision, A.K.; project administration, A.K.; funding acquisition, A.K. All authors have read and agreed to the published version of the manuscript.

Funding: The research were carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (registration number: 124012400285-7 and 124013000750-1) and as part of the most important innovative project of national importance “Development of a system for ground-based and remote monitoring of carbon pools and greenhouse gas fluxes in the territory of the Russian Federation, ensuring the creation of recording data systems on the fluxes of climate-active substances and the carbon budget in forests and other terrestrial ecological systems” (Registration number: 123030300031-6).

Data Availability Statement: Data are contained within the article.

Acknowledgments: We acknowledge the support provided from the members of the Research Center of Natural Monument Insects and Federal Scientific Center of the East Asia Terrestrial Biodiversity for acquisition of valuable specimens. We also acknowledge the World Climate Research Programme, which coordinated and promoted CMIP6. We thank the climate modelling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF. We thank the three reviewers for their valuable comments and proposals.

Conflicts of Interest: The authors declare no conflict of interest.

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