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Climate Change and the Dung Beetle: Evaluation of Global Warming Impact on the Distribution of *Phyllognathus excavatus* (Forster, 1771) through the Mediterranean Region

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Featured Application: The featured application of this paper focuses on the impact of climate change on ecosystem services provided by the *Phyllognathus excavatus* beetle, specifically its role in recycling organic matter. The study highlights that dung beetles, including *Phyllognathus excavatus*, play a crucial ecological role in nutrient cycling, waste decomposition, and soil improvement. These beetles facilitate the breakdown of organic matter, such as dung, and contribute to the recycling of nutrients back into the ecosystem. However, climate change can disrupt the life cycles and habitat suitability of these beetles, affecting their ability to perform their recycling function effectively. Changes in temperature and precipitation patterns can alter the availability of fresh dung, which is essential for successful reproduction and larval development. Shifts in rainfall patterns and increased temperatures can also impact the timing of dung decomposition and alter the composition of microbial communities associated with dung, indirectly affecting the survival and fitness of dung beetles. Determining the resilience of ecosystem services, such as recycling, and creating effective conservation strategies to mitigate the negative effects of climate change on these significant ecological processes depend on our ability to understand the potential effects of climate change *on Phyllognathus excavatus* and other dung beetles.

Abstract: Climate change poses a significant threat to ecosystems, food security, and human well-being. This study focuses on the *Phyllognathus excavatus* beetle, an important insect species in the Mediterranean region with ecological importance in nature recycling of organic wastes. The aim of this study is to assess its current habitat suitability and predict its distribution under future climate scenarios. The beetle's occurrence records were gathered and climate information, including 19 bioclimatic variables, was retrieved from the Global Biodiversity Informatic Facility (GBIF) and WorldClim depository, respectively. The MaxEnt algorithm was used to calculate habitat appropriateness using geographic information systems (GISs) and species distribution modeling (SDM) with an accuracy of 0.907 using the AUC test. The findings show that the annual mean temperature is the most important factor, with the beetle flourishing in temperatures between 13.9 and 19.1 °C. The distribution is greatly impacted by the mean temperature of the warmest quarter. Future projections using different climate scenarios suggest potential changes in the beetle's distribution. By integrating climate data and occurrence records, this study provides insights into the vulnerability of *Phyllognathus excavatus* to climate change and identifies regions where its habitat may be at risk as 81% of its current habitat will be lost. The research helps to prioritize efforts to reduce the harmful effects of climate change on insect biodiversity and to design effective conservation strategies. Overall, this study advances our knowledge of the *Phyllognathus excavatus* beetle's present and projected distribution patterns in the Mediterranean region under the influence of climate change. It illustrates the significance of taking into account how climate change would affect insect populations and the use of SDM and GIS tools for researching and protecting insect biodiversity.

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1. Introduction

Due to the potential hazard climate change poses to mankind, food security, and ecosystem balance, global warming is becoming an urgent issue for communities all over the world. By absorbing heat emitted from the Earth's surface, greenhouse gases like carbon dioxide (CO_2) have increased in the atmosphere, raising global temperatures [1]. With a rise of more than 40% since the beginning of the industrial revolution and more than half of this increase occurring since 1970, human activities, notably the burning of fossil fuels, have considerably contributed to the increase in atmospheric CO_2 concentrations [2]. Different facets of our globe are showing the effects of climate change. The average surface temperature of the planet has risen by around 1 °C since 1900, along with other climate-related effects such as warming oceans, rising sea levels, a considerable loss of Arctic sea ice, and an increase in the frequency and severity of heatwaves [3]. One area that has been significantly impacted by climate change is insect biodiversity [2].

The *Phyllognathus excavatus*, also referred to as the dung beetle, is one of the insects that is particularly susceptible to the effects of climate change. Dung beetles are essential for seed distribution, ecological function, nutrient cycling, and environment preservation [4]. They contribute to waste decomposition, boost pasture production by returning nutrients to the soil, and improve soil structure by aerating it, allowing for improved moisture penetration [5]. They also interfere with the breeding cycles of flies and other parasites.

The *Phyllognathus excavatus* beetle has a wide distribution spanning from the Canary Islands across North Africa, the Mediterranean region, central Europe, the Middle East, and the Arabian Peninsula [6]. Its larval stage primarily resides in compost-rich soil, where it feeds on organic matter. The larva is often observed during the summer months, characterized by its slow-moving, relatively large, and white-bluish curved "C" shape [7]. The adult beetle exhibits a red-brown coloration and is easily distinguishable by the small horn on the male's head. It is predominantly nocturnal, and females lay their eggs in organic matter and fresh dung [8,9]. Although specific life cycles and dung preferences may vary among dung beetle species, they all reproduce through sexual reproduction, where males transfer sperm to females. Subsequently, the females lay eggs in dung, and upon hatching, the larvae emerge and feed on the surrounding feces. Eventually, the larvae enter the pupa stage, undergo complete metamorphosis, and emerge as adult beetles, actively searching for dung to feed on and other adults to mate with [10].

Climate change can directly and indirectly influence the distribution and abundance of *Phyllognathus excavatus* beetles. Changes in temperature and precipitation patterns can disrupt their life cycles, alter resource availability, and impact their reproductive success. For example, shifts in rainfall patterns may affect the availability of fresh dung, which is essential for successful reproduction and larval development. Increased temperatures can also affect the timing of dung decomposition and alter the composition of microbial communities associated with dung, which can indirectly impact the survival and fitness of dung beetles [11]. Furthermore, climate change can alter the phenology and geographic range of both the *Phyllognathus excavatus* beetles and their food resources. As temperatures warm, the timing of life cycle events, such as emergence, mating, and egg-laying, may shift, which can disrupt synchrony with their host resources. If the timing of dung availability does not match with the life cycle stages of the beetles, it can lead to reduced reproductive success and population declines [12]. In addition to direct effects on the beetles themselves, climate change can also influence their interactions with other species. For instance, changes in temperature and precipitation can affect the abundance and distribution of mammalian herbivores that produce dung, potentially altering the availability and quality of dung resources for the beetles. Disruptions in these intricate ecological interactions can have cascading effects on ecosystem processes, such as nutrient cycling and plant dynamics [13].

Geographical information systems (GISs) are one of the many cutting-edge scientific methods that researchers employ to assess the effects of global warming on a beetle species across its range [14]. By connecting climate change to bug dispersal, GISs offer useful insights. One such method is species distribution modeling (SDM), which forecasts the potential distribution of a species over a geographic area using environmental variables and species occurrence data [15]. Researchers can better understand how changes in temperature, precipitation, and other climatic conditions may affect insect populations and their distribution patterns by investigating the impacts of climate change on insects through SDM [16]. Scientists can determine which insect species are most vulnerable to climate change and pinpoint areas where their habitats may be in danger by combining temperature data with records of insect occurrence [15]. SDM can also be used to locate prospective refugia, or locations that may continue to be suitable for insect species in the face of a changing environment. To minimize the detrimental effects of climate change on insect biodiversity, it is essential to prioritize conservation efforts and establish effective conservation methods [17].

Therefore, the goal of this study is to evaluate the appropriateness of *Phyllognathus excavatus*'s existing habitat across the Mediterranean region and to identify any potential effects of climate change on its spread. This study seeks to offer important insights into the vulnerability of this beetle species and contribute to the development of well-informed conservation plans by the analysis of climate data, occurrence records, and using GIS techniques. For the Mediterranean region's ecosystems to continue functioning properly and to preserve insect biodiversity, it is crucial to understand the current and projected distribution patterns of *Phyllognathus excavatus*.

2. Materials and Methods

2.1. Occurrence Records

Almost all available records of *Phyllognathus excavatus* were collected from the literature and previous research [6,8], and the records of *Phyllognathus excavatus* in the digital database www.GBIF.com accessed on 18 June 2022. A total of 620 occurrence records were converted into a comma delimited format (CSV) and used to assess habitat suitability for *Phyllognathus excavatus* in the Middle East and Mediterranean region [18] (Figure 1).

Figure 1. Distribution of *Phyllognathus excavatus* in the Mediterranean region [18]; the records are distributed throughout the whole range of the species.

2.2. Current and Future Climatic Data

With a spatial resolution of about 5 km^2, the known 19 bioclimatic variables were obtained from www.worldclim.org (accessed on 12 December 2022). The 19 bioclimatic variables were clipped using the shapefile of the study area as a template, and the final set was then converted to (ASCII) format using (ArcGIS v10.3, Special analyst tool, Extract by

Mask), Table S1. The generated climatological data were used to make a primary screening model to illustrate the most effective variables in the distribution of *Phyllognathus excavatus*. Six bioclimatic variables were found to contribute more to the model with less correlation effect: (Bio 1) Annual mean temperature, (Bio 2) mean diurnal range, (Bio 4) temperature seasonality, (Bio 5) maximum temperature of warmest month (Bio 10) mean temperature of warmest quarter, (Bio 17) precipitation of driest quarter. The final set of bioclimatic variables was used to generate the final current model of the insect. For future data, parallel datasets of temperature variables were used from www.worldclim.org (accessed on 18 June 2022) covering four GCMs scenarios (BCC-CSM1-1 (BC), CCSM4 (CC), MRI-CGCM3 (MG) and NorESM1-M (NO)) for two representative concentration pathways (RCPs) 26 and 85 representing 2050 and 2070. These data have been developed by climate centers to predict future temperatures by considering two levels of carbon concentration [19].

2.3. Species Distribution Modeling

The habitat appropriateness of *Phyllognathus excavatus* was estimated using the maximum entropy approach implemented in maxent v3.3.3e. This technique produces a superb prediction model that simply depends on the availability of data [20]. Additionally, the link between habitat appropriateness for a species that varies from low to high suitability and bioclimatic variables was estimated using the response curve for each bioclimatic variable [19]. 25% of the occurrence records in our model were utilized for testing, and 75% were used for training. The model performance was improved by repeating this procedure five times [21]. First, all 19 bioclimatic factors were included in this process. Then, using the jackknife test of Maxent, the most significant collection of variables was determined by excluding the variables that contributed less than 70% [9]. Also, for the 19 bioclimatic data, a Pearson correlation function with a value of (|r| 0.8) was employed to reduce multicollinearity. Finally, six biologically significant bioclimatic variables were selected to create the final model based on numerous statistical analyses [20]. The raster calculator of a special analyst tool in ARC-GIS was used to generate the calibration maps and calculate the percentage loss [21].

2.4. Two-Dimensional Niche Methodology

The enveloped test of two-dimensional niche analysis was carried out using DIVA-GIS software v7.5 using the annual mean temperature (Bio 1) and annual perception (Bio 12). The test used recorded points to draw the niche range of the species throughout the study range [22].

2.5. Model Evaluation

The model performance was estimated using the area under the curve (AUC) of the receiver operating characteristics (ROCs), and its value ranged from (0) random discrimination to (1) perfect discrimination higher. AUC values more than (0.75) indicated strong fitting of the models, whereas AUC values less than (0.5) indicated poor fitting of the models for the ecology of the species under consideration [23,24].

3. Results

3.1. Model Evaluation and Bioclimatic Factor Contributions

A high value of the area under the curve, equal to 0.907, was obtained from the AUC test of the maximum model for *Phyllognathus excavatus*. This demonstrates the excellent validity of the distribution maps and models that were developed. The bioclimatic variable (Bio 1) in the created model was the most effective one. Table 1 and Figure 2a show that the annual mean temperature (Bio_1) with the percentage contribution is 40.4 degrees. The study of the Bio_1 data shows that the best mean range was (13.9–19.1 °C), which is a reasonably high temperature that is beneficial to some limits, Figure 2b. The Jackknife test of the chosen variable demonstrates that the variables related to temperature have a greater impact than the variables related to humidity Bio 17, Figure 2c. With a contribution of 25.8%, the mean diurnal range (Bio 2) is the second most important bioclimatic element, followed by the precipitation of the driest quarter (Bio 17), with contributions of 22.5% and 7.9%, respectively. With just a 2.1% and 1.2% impact, respectively, the remaining variables of temperature seasonality (Bio 4) and maximum temperature of warmest month (Bio 5) were insignificant.

Table 1. The permutation importance of the bioclimatic variables used to generate the final model of *Phyllognathus excavatus*.

Variables	Bio_2	Bio_1	Bio_17	Bio_10	Bio_4	Bio_5
Permutation importance	22.5	40.4	7.9	25.8	2.1	1.2

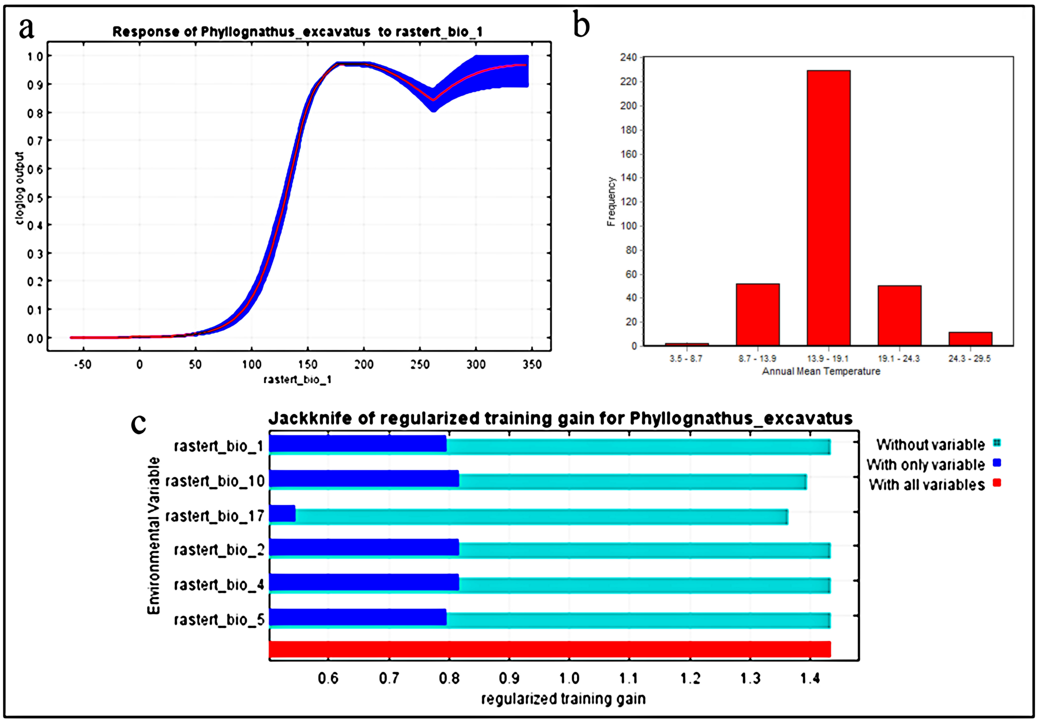

Figure 2. (**a**) Response curve of Bio_1 of the *Phyllognathus excavates* model. (**b**) represents the optimum temperature for the species, and (**c**) represents the most effective bioclimatic variables on the habitat suitability of the *Phyllognathus excavates* beetle.

3.2. Two-Dimensional Niche Analysis

The temperature and precipitation form the basic component of any species climatological niche, so Bio 1 and Bio 12 were used to envelop the test to show the limitation range of *Phyllognathus excavates*. The results indicated that this species has high adaptability with all humidity conditions as it can be found in desert areas with very low rains and in high humidity areas with high precipitations, while it has a somewhat narrow range of temperature adaptability that ranges from 11 °C to 26 °C. In the generated graph in Figure 3, the green points indicate the records that have all the 19 bioclimatic variables within the enveloped niche of the species, while the red points are divided into two groups that occur inside the enveloped niche; these occur under the limitation of the tested variables (Bio 1 and Bio 12), but have one or more other variables that occur outside the species range limitation, while that occurs outside the enveloped already occurs out the limitation of the tested variables.

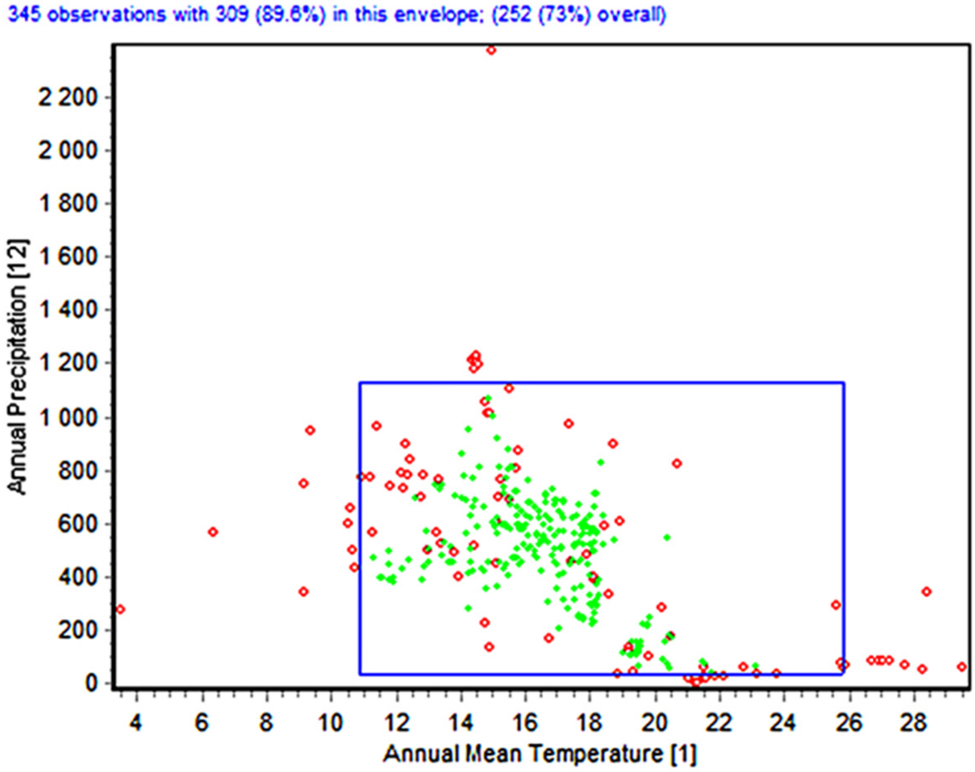

Figure 3. Environmental envelope model of recorded points of *Phyllognathus excavates*.

3.3. Predicted Current Potential Distribution

The predicted current map shows regions highly suitable for *Phyllognathus excavates*, Figure 4. The species is mainly distributed through the Mediterranean region, especially on sea coasts.

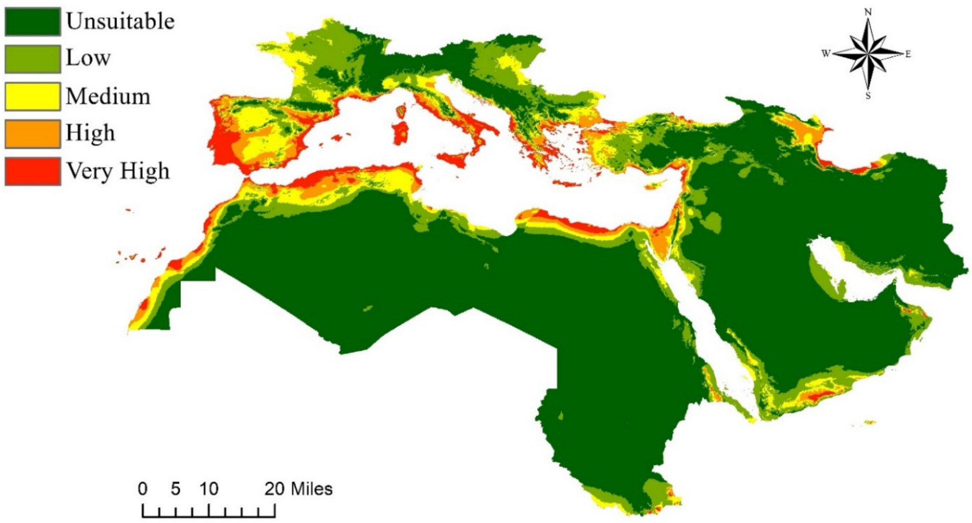

Figure 4. *Phyllognathus excavates*' current predicted range. The species appears to have a very good habitat suitability through the costal area of Mediterranean Sea through out North Africa, but it dominate the lands in countries of south Europe such as Greece, Italy, Spain, and Portugal.

Our predictive model is consistent with the species' actual geographic distribution; it indicates a high likelihood of occurrence in southern Europe, particularly the Iberian Peninsula (Portugal and Spain), as well as the Italian peninsula and the Greek Archipelago.

Insects exhibit high to extremely high habitat suitability in the northern portions of Algeria, Morocco, and Tunisia, as well as along the eastern coast of the Atlantic Ocean close to Morocco and Mauretania on the western and southern beaches of the Mediterranean Sea. In Sainai and the North Coast of Egypt, the environmental adaptability is quite good. Iran and the Arabian Peninsula, on the other hand, are the low-suitability regions.

3.4. The Estimated Potential Future Distribution in 2050 and 2070

Four climatological change GCMs scenarios (BCC-CSM1-1 (BC), CCSM4 (CC), MRI-CGCM3 (MG) and NorESM1-M (NO)) were used to generate mean predictive maps for the future in 2050 and 2070. The generated maps for the future models of 2050 and 2070 under two (RCPs) 2.6 and 8.5 demonstrate significant habitat suitability loss across the majority of their range. The extinction of regions like North Africa, Turkey, and Greece is a serious concern. The Arabian Peninsula is obviously unfavorable for the species, and some pocket habitats in the Gulf and Sudan will completely vanish. Northern France is the only new location that will become better suited for *Phyllognathus excavations*, Figure 5. The Calibration maps that were generated from comparing the current situation with the future one ensures the extinction of this species on southern and eastern Mediterranean to Greece. Italy, France, and part of Spain and Portugal will be the only range of this species through the next 50 years, Figure 6. The percentage of complete loss of its habitat represented in the worst scenario about 81% of its current range.

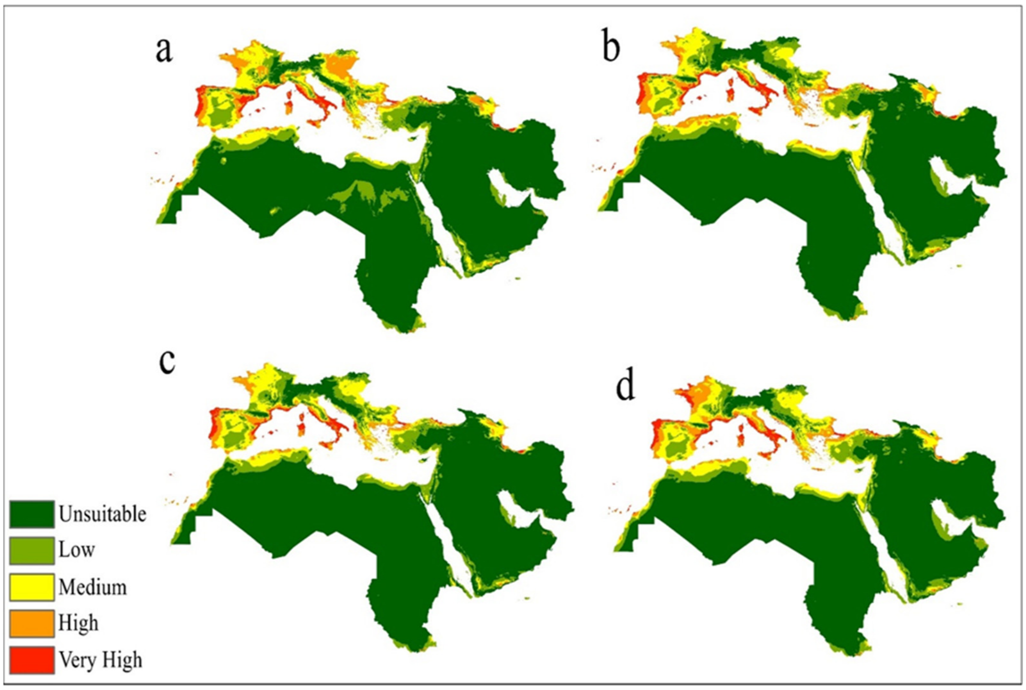

Figure 5. Under two representative concentration pathways (RCPs 2.6, 8.5) of climate conditions in 2050 and 2070, the mean estimated future distribution maps of the *Phyllognathus excavatus* beetle was calculated. (**a**) RCP of 2.6 for 2050, (**b**) RCP of 8.5 for 2050, (**c**) RCP of 2.6 for 2070, and (**d**) RCP of 8.5 for 2070 are all possible scenarios. The future maps show how the species habitat suitability degradation through most of its range especially in the Mediterranean coasts of North Africa.

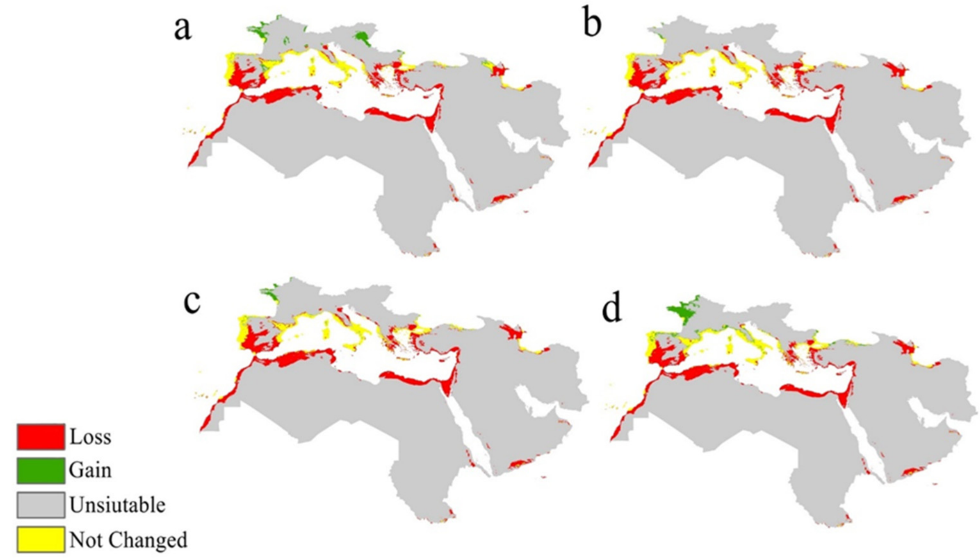

Figure 6. By comparing the four future scenarios to the current situation, calibration maps reveal gains and losses in the appropriateness of the *Phyllognathus excavatus* beetle's habitat (2050 and 2070). (**a**) RCP (2.6) for 2050, (**b**) RCP (8.5) for 2050, (**c**) RCP (2.6) of 2070, and (**d**) RCP (8.5) for 2070. The calibration maps of the future situation of this species indicates the threat that this species will face due to climate change.

4. Discussion

Global warming and climate change, driven by escalating greenhouse gas emissions, are critical concerns due to their profound implications for biodiversity, ecosystems, and human well-being [25]. The rising concentrations of CO_2 result in heat absorption and consequent warming of the Earth's surface. Since 1900, the average global surface temperature has risen by 1 °C as a result of human activity, primarily the use of fossil fuels, which has increased atmospheric CO_2 levels by almost 40%. These changes have induced ocean warming, sea level rise, and intensified heat waves, signifying far-reaching climate consequences [26]. Amidst these shifts, the *Phyllognathus excavatus* beetle, renowned for its role in nutrient cycling, ecosystem function, and soil improvement, is vulnerable to climate-induced alterations [5].

We created maps of the possible global distribution of the *Phyllognathus excavatus* using MaxEnt modeling. The model's prediction accuracy is quite very good, as shown by the AUC of 0.907, which is a very good indicator. This shows that the measurement of *Phyllognathus excavatus*'s global spread is accurate and can offer helpful direction for decision-makers and mitigation efforts, particularly in areas where it has not yet emerged. We also created forecasted global distribution maps for it using a geographic information system (GIS). Other insect species, including *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) in central Asia, *Bactrocera dorsalis* Hendel (Diptera: Tephrididae) in China, and *Episimus utilis* Zimmerman (Lepidoptera: Tortricidae) in Brazil, have also had their geographic distributions mapped using this tool [27–29].

The current study addresses the significant impact of climate change on the distribution and habitat suitability of the *Phyllognathus excavatus* beetle through the Mediterranean region and the Middle East. The research employs SDM to assess the beetle's current and potential future distribution in response to changing climatic conditions. The results provide insights into the species' habitat preferences and vulnerability to climate change, contributing to our understanding of how climate-induced shifts may affect ecosystems and agriculture in the Mediterranean area. The research reveals bioclimatic variables that influence the spread of the *Phyllognathus excavatus* beetle. The annual mean temperature (Bio 1) emerges as the most important element, considerably contributing to the habitat appropriateness model. This emphasizes the beetle's affinity for specific temperature ranges, with 13.9 °C to 19.1 °C being the ideal range. The study also emphasizes the significance of other variables such as mean diurnal range (Bio 2), mean temperature of the warmest quarter (Bio 10), and precipitation of the driest quarter (Bio 17), all of which contribute to the spread of this beetle. These findings are consistent with previous research indicating that temperature and moisture availability are crucial in determining species distributions [4,5]. The higher temperature limits *Phyllognathus excavatus* in contrast to its tropical cousin *Oryctes rhinoceros*, whose annual temperature ranges were 27 °C to 29 °C [30]. The study's focus on specific bioclimatic variables allows for a deeper understanding of the ecological niche of *Phyllognathus excavatus* and how it may respond to changing climatic conditions.

The predicted current distribution map aligns well with observed occurrence records, with regions of high habitat suitability predominantly concentrated along the Mediterranean coastlines. When projecting into the future, the study's results indicate potential shifts in the distribution of *Phyllognathus excavatus* under different climate scenarios (RCP 2.6 and 8.5) for 2050 and 2070. Particularly, areas in North Africa, Turkey, and Greece face potential habitat loss, suggesting increased vulnerability to extinction. The Arabian Peninsula appears to become unsuitable for the species, indicating a considerable reduction in suitable habitats. These projected changes align with broader ecological predictions of climate-driven shifts in species distributions, emphasizing the urgent need for conservation efforts at risk regions [31,32]. The envelope (two-dimensional niche) analysis further supports the adaptability of *Phyllognathus excavatus* to varying humidity conditions, while its temperature range appears relatively narrow (11–26 °C). This highlights the species' sensitivity to temperature fluctuations, which is consistent with the well-known temperature-dependent nature of insect physiology and behavior [33].

The decline in habitat suitability in North Africa could have broader implications for ecosystem functioning and nutrient cycling, as *Phyllognathus excavatus* plays a crucial role in these processes. Reduced dung beetle populations could disrupt dung decomposition and nutrient recycling processes, impacting soil quality and ecosystem health. When taking a large view some other species of dung beetles could replace *Phyllognathus excavates* through this area. Recently, a modeling study of *Oplostomus fuligineus* indicated that this species of dung beetle will shift its range from tropical Africa to north Africa and it is already collected from Tunisia [34]. Furthermore, the study's findings have implications for agricultural systems. Changes in the distribution of dung beetles can influence dung decomposition rates and fly population dynamics, which could affect livestock health and disease transmission [35]. Moreover, alterations in the beetle's distribution could impact animal waste management practices, potentially leading to shifts in waste degradation rates and nutrient recycling in agricultural landscapes [36].

This study's findings are consistent with earlier research on the effects of climate change on species ranges and ecological interactions. For example, Parmesan and Yohe [35] highlight the significance of temperature in shaping species' reactions to climate change, whereas Thuiller and others [36] investigate the possibility for range changes under different climate scenarios, such as the one that exists here in northern France. The study's focus on a single insect species and its ecological activities gives useful insights into the potential effects of distributional changes on nutrient cycling and agricultural systems, complementing larger research on biodiversity shifts [37–41].

However, it is important to acknowledge the potential limitations of the study. The model assumes that species' distribution is solely determined by climatic factors, neglecting other ecological, biological, and anthropogenic factors that can influence distribution patterns. Additionally, the accuracy of the predictions heavily relies on the accuracy of input occurrence data and climate projections. This limitation is due to the relay of the future models on climate only and we cannot easily know how other factors will be in the future.

5. Conclusions

This study provides valuable insights into the distribution of the *Phyllognathus excavatus* beetle in the Mediterranean region in relation to climate change. The researchers employed species distribution modeling (SDM) and geographical information systems (GISs) to assess the beetle's habitat suitability and vulnerability to climate change. The study highlights the significance of climate variables, particularly temperature, in understanding the distribution patterns of *Phyllognathus excavatus*. The annual mean temperature was identified as the most relevant variable, with temperatures ranging from 13.9 °C to 19.1 °C being optimal for the beetle's survival. By understanding the temperature preferences of the beetle, conservation efforts can focus on preserving and restoring habitats that are favorable for its survival. Future projections based on different climate scenarios provide valuable information for predicting potential changes in the beetle's distribution. This enables targeted conservation actions to counteract the negative impacts of climate change. Proactive interventions such as habitat restoration and the establishment of protected areas can be implemented in regions where the beetle is expected to become less suitable. The study emphasizes the importance of SDM and GIS technologies in studying and safeguarding insect biodiversity in the face of climate change. The researchers developed a comprehensive model that integrates climate data and occurrence records to assess the vulnerability of *Phyllognathus excavatus*. This approach can be extended to other insect species, enhancing our understanding of their distribution patterns and aiding the development of effective conservation strategies. While the study provides valuable information, it acknowledges certain limitations. The accuracy of the model predictions depends on the quality and quantity of the data used. Future studies should aim to improve data collection and incorporate additional factors that may influence the beetle's dispersion. Additionally, the study's findings are specific to the Mediterranean region, and caution should be exercised when extrapolating them to other geographic areas. Overall, this research enhances our understanding of the habitat preferences and vulnerability of the *Phyllognathus excavatus* beetle to climate change in the Mediterranean region. The findings underscore the importance of integrating climate change considerations into insect conservation efforts and highlight the effectiveness of SDM and GIS techniques in addressing the threats posed by climate change to insect biodiversity. By focusing on protecting suitable habitats and implementing targeted conservation measures, we can work towards mitigating the potential adverse effects of climate change on this species and contribute to the overall conservation of insect populations in a changing environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app132212107/s1, Table S1: Bioclimatic variables.

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