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Research Article

Impact of Climate Change on the Distribution of *Oryctes rhinoceros* in Malaysia: Species Distribution Modelling and Future Projections

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ABSTRACT

Climate change is increasingly influencing the distribution and outbreak dynamics of insect pests, particularly in tropical agro-ecosystems. This study modelled the current and future potential distribution of *Oryctes rhinoceros* in Malaysia using MaxEnt based on bioclimatic variables and climate change scenarios. A total of seven uncorrelated bioclimatic variables were analyzed. Precipitation of the driest quarter (Bio17), mean temperature of the wettest quarter (Bio8), and annual temperature range (Bio7) were identified as the most influential predictors. Model performance was robust, with an AUC of 0.818 and a TSS of 0.65, indicating good predictive accuracy and reliability. Results from response curves indicated *O. rhinoceros* favors moderate dry-season rainfall (100-500 mm), warm and humid conditions (27-28°C), and intermediate thermal seasonality (8-12°C annual temperature range). The Jackknife test further confirmed Bio17 as the dominant variable, followed by Bio8 and Bio7. Current distribution mapping showed variable infestation levels across Malaysia, with higher habitat suitability in states such as Kedah, Perak, Selangor, Terengganu, and Negeri Sembilan. Future projections revealed relatively stable distribution under SSP126 and SSP245 scenarios up to 2050; however, under the high-emission SSP585 scenario, a marked expansion of suitable habitats was observed. By 2070, all scenarios indicated increased habitat suitability, with SSP585 projecting widespread high to very high suitability across most Malaysian states, including Sabah, Sarawak, Selangor, and Peninsular regions. In conclusion, climate change is expected to significantly enhance the potential distribution and establishment risk of *O. rhinoceros* in Malaysia, particularly under high-emission pathways, emphasizing the need for proactive pest management and climate-adaptive control strategies.

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Introduction

Oryctes rhinoceros, commonly known as the coconut rhinoceros beetle (CRB), is a highly destructive pest of oil palm and is native to tropical Asia (Bedford, 2012). Among palm species, including the economically important oil palm (*Elaeis guineensis*), *O. rhinoceros* is one

of the most damaging insect pests. Its larvae develop in decaying organic matter such as compost heaps and rotting palm logs, while adults directly damage palm plants by boring into the crown and feeding on sap. This feeding activity disrupts the meristematic tissues, often leading to reduced growth and, in severe cases, death of

young palms (Manjeri et al., 2011; Bedford, 2012; Latip, 2021). Consequently, *O. rhinoceros* represents a persistent and significant threat to plantation productivity and sustainability, particularly in Malaysia, a global center of oil palm production. Reported yield losses attributed to this pest range from 40% to 92% during the first year of harvest (Manjeri et al., 2013).

A more aggressive mitochondrial haplotype of *O. rhinoceros*, designated CRB-G, was identified in 2007 (Marshall et al., 2017). This haplotype exhibits reduced susceptibility to the well-established biological control agent *O. rhinoceros nudivir* (OrNV). Anggraini et al. (2023) further confirmed the presence of both CRB-G and CRB-S biotypes in populations collected from Johor, Malaysia. The emergence and spread of these novel haplotypes in Malaysian oil palm plantations pose a serious challenge to existing pest management strategies. Environmental and species distribution modelling play an important role in food security, pest management, and biodiversity conservation (Aidoo et al., 2021; Alvi et al., 2021; Roberts et al., 2022; Pereira et al., 2025). Such models also provide valuable insights into trophic interactions, population dynamics, and behavioral ecology (Estay et al., 2009; Frisman et al., 2021). Furthermore, habitat suitability assessments contribute to a better understanding of species ecology and support conservation and management strategies at both national and international scales (Obunga et al., 2022). Species distributions are largely shaped by interacting biotic and abiotic factors that regulate range expansion and contraction, thereby influencing invasion potential. In addition, climate change driven by increasing greenhouse gas emissions is altering ecosystems and reshaping the distribution of agricultural pests by affecting their fertility, population dynamics, dispersal ability, survival, nutrition, and behavior (Zheng et al., 2015; Zidon et al., 2016; Paudel et al., 2021).

The distribution and population dynamics of *O. rhinoceros* are strongly influenced by climatic conditions. Temperature regulates developmental rate, fertility, and adult activity, whereas humidity and rainfall are critical for larval survival in breeding habitats (De Almeida Costa et al., 2010). Several studies have demonstrated that climate change is altering insect pest distribution patterns by facilitating range expansion into previously unsuitable areas and enhancing reproductive potential (Gullino et al., 2021; Skendžić et al., 2021). In related studies, bioclimatic variables such

as precipitation seasonality, mean temperature, and extreme climatic events have been identified as key determinants of habitat suitability (Alqahtani et al., 2025; Tang et al., 2025). Despite its economic importance, limited research has been conducted on the current and potential distribution of *O. rhinoceros* in relation to climate change, particularly in Malaysia. Previous ecological niche and species distribution models for this pest have been limited in spatial scope and often conducted at regional or global scales, thereby constraining their applicability for national-level pest management programme (Lozier and Mills, 2011).

Species distribution modelling, also referred to as ecological niche modelling, is a cost-effective and widely used approach for predicting potential species distributions (Vasconcelos et al., 2024). These models are increasingly applied to assess the impacts of climate change on agricultural pests (Thomson et al., 2009). Understanding how anticipated climate change may alter habitat suitability under different climatic scenarios is essential for proactive pest surveillance, efficient resource allocation, and the development of adaptive integrated pest management (IPM) strategies.

The main objective of this study is to map the current habitat suitability and spatial distribution of *O. rhinoceros* in Malaysia using occurrence records derived from published literature. The second objective is to identify the key environmental variables influencing its habitat suitability through MaxEnt modelling and variable contribution analysis. The third objective is to project future habitat suitability under Shared Socioeconomic Pathway (SSP) scenarios 126, 245, and 585 for the years 2050 and 2070. The findings of this study will provide an evidence-based framework to guide policymakers and agricultural stakeholders in strengthening surveillance systems and adopting climate-resilient pest management strategies, thereby supporting the long-term sustainability of the Malaysian oil palm industry.

Materials and Methods

Occurrence records of *O. rhinoceros*

Occurrence records of *O. rhinoceros* were compiled from published articles, reports, and theses (Kamarudin and Wahid, 2004; Ramle et al., 2005; Ahmad, 2006; Moslim et al., 2006; Ismail et al., 2009; Wan Zaki et al., 2009; Manjeri et al., 2011; Abidin et al., 2014; Nadia Zulkifli, 2015; Badrul Hisham, 2016; Mohama, 2016; Karim et al., 2019; Izaitul Aida et al., 2020; Pallanisamay et al., 2020; Razak and

Adam, 2020; Abdullah and Azmir, 2021; Idris et al., 2021; Anggraini et al., 2023; Bakeri et al., 2023; Syarif, 2024) and supplementary datasets provided by Xu (2021).

All records were georeferenced by assigning latitude and longitude coordinates using Google Maps (<https://www.google.com/maps>). The data were stored in comma-separated format in Microsoft Excel and subsequently imported into ArcGIS 10.8.2 for processing. Duplicate records and spatially redundant occurrences within a 5 km radius were removed using the SDM Toolbox to minimize spatial autocorrelation

and sampling bias. After data cleaning, 52 unique occurrence points were retained and used to model the current and future potential distribution of *O. rhinoceros* in Malaysia (Figure 1).

To further reduce sampling bias, a bias file was generated using a Minimum Convex Polygon (MCP) with a 50 km buffer around occurrence points in ArcGIS 10.8.2 using the SDM Toolbox, following recommendations by Duret et al. (2025) and Brown (2014). The resulting bias surface was used to weight background point selection, thereby reducing over-fitting in model calibration (Table 1).

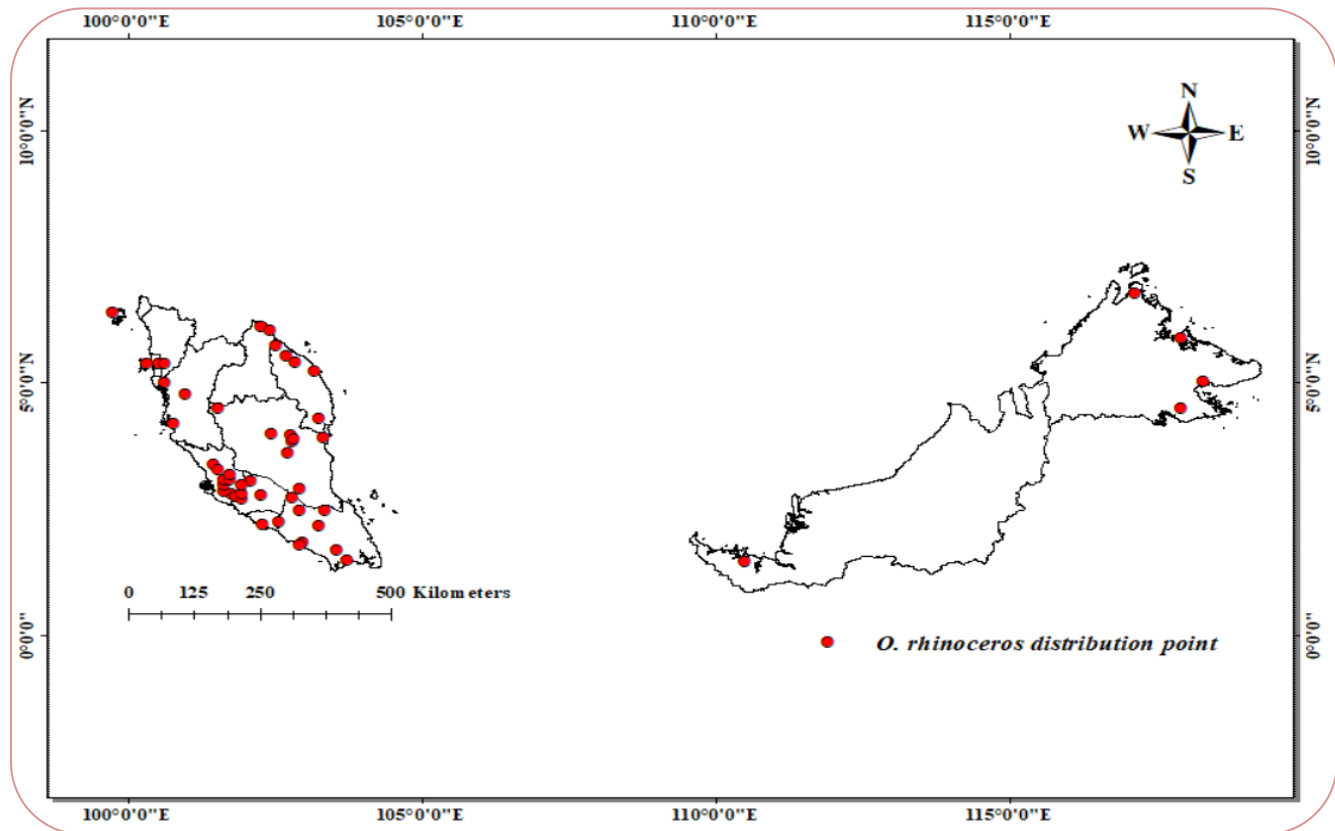


Figure 1. Occurrence records of *O. rhinoceros* after geographic rarefaction.

Climatic variables

Nineteen bioclimatic variables were obtained for species distribution modelling from the WorldClim database (www.worldclim.org) at 30 arc-second spatial resolution. These variables are derived from long-term climatic observations (1970-2000) and represent key temperature and precipitation patterns.

The downloaded raster layers were converted into ASCII format using ArcGIS 10.8.2 for further analysis. To reduce multicollinearity among predictor variables, Pearson

correlation analysis was performed using the SDM Toolbox in ArcGIS. Variables with a correlation coefficient of $|r| > 0.8$ were excluded. Ultimately, seven non-collinear bioclimatic variables were selected for model development: Bio2 (Mean Diurnal Range), Bio3 (Isothermality), Bio7 (Temperature Annual Range), Bio8 (Mean Temperature of Wettest Quarter), Bio15 (Precipitation Seasonality), Bio16 (Precipitation of Wettest Quarter), and Bio17 (Precipitation of Driest Quarter).

For future climate projections, Shared Socioeconomic

Pathways (SSP126, SSP245, and SSP585) were used for the periods 2050 (2041-2060) and 2070 (2061-2080), based on the MIROC6 global climate model from CMIP6. Future climate datasets at 30 arc-second resolution were obtained

from WorldClim (www.worldclim.org) and used to project potential future distributions. These scenarios represent low (SSP126), intermediate (SSP245), and high greenhouse gas emission pathways (SSP585) (Zhang et al., 2024).

Table 1. Methodological framework for species distribution modelling of *O. rhinoceros*.

Step	Method	Tool	Key Settings	Purpose
Occurrence Data	Literature-based species records with georeferencing	Google Maps, Excel	Coordinates (lat/long); n = 52	Establish presence dataset
Data Cleaning	Remove duplicates and spatial autocorrelation	ArcGIS (SDMtoolbox)	5 km filtering	Reduce sampling bias
Bias Correction	Minimum Convex Polygon (MCP) buffer	ArcGIS	50 km buffer	Control background sampling bias
Climate Data	19 bioclimatic variables	WorldClim	30 arc-sec resolution	Environmental predictors
Variable Selection	Pearson correlation filtering	ArcGIS	r < 0.8; 7 variables retained	Avoid multicollinearity
Future Scenarios	SSP126, SSP245, SSP585 (2050, 2070)	WorldClim (MIROC6)	CMIP6 projections	Climate change assessment
Model Development	MaxEnt modelling	MaxEnt	10,000 background; RM=1; 10 runs	Habitat prediction
Validation	AUC and TSS metrics	MaxEnt	AUC > 0.8; TSS > 0.6	Model accuracy
Mapping	Suitability classification	ArcGIS	5 classes (0–1 scale)	Spatial visualization

Model calibration

Species occurrence data and environmental variables were analyzed using MaxEnt software (version 3.4.4). Prior to model calibration, all predictor variables were screened for multicollinearity, and only variables with $|r| < 0.8$ were included (Phillips et al., 2005; Gao et al., 2024). The model was run using cross-validation with 10 replicates. Background points were set to 10,000, and the regularization multiplier was set to 1 to reduce overfitting (Valavi et al., 2023). Feature interactions were limited to 500 iterations, and the convergence threshold was set to 0.00001. A 10th percentile training presence threshold was applied to distinguish suitable and unsuitable habitats (Singh et al., 2021).

Model validation and assessment

Model performance was evaluated using the Area under the Curve (AUC) of the Receiver Operating Characteristic (ROC) and the True Skill Statistic (TSS). AUC values range from 0 to 1, where values < 0.6 indicate poor performance, 0.6-0.7 fair, 0.7-0.8 moderate, 0.8-0.9 good, and > 0.9 excellent predictive performance (Jiménez-Valverde, 2011; Gao et al., 2024).

TSS values range from -1 to +1, where values > 0.6 indicate good model performance, 0.2-0.6 moderate performance, and < 0.2 poor performance (Allouche et al., 2006; Jones et al., 2010). Both AUC and TSS were calculated across 10 cross-validation runs to ensure robust evaluation of model predictive accuracy.

Visualization and mapping

Current and future habitat suitability maps for *O. rhinoceros* were generated in ArcGIS 10.8.2. Habitat suitability was classified into five categories: 0-0.2 (Very Low), 0.2-0.4 (Low), 0.4-0.6 (Moderate), 0.6-0.8 (High), and 0.8-1.0 (Very High) (Krishnan and Pimid, 2024).

Results

In this study, a total of seven bioclimatic variables were used for modelling. Among these, Bio17, Bio8, and Bio7 contributed most significantly to model performance (Table 2). Bio17 represents precipitation of the driest quarter (mm), Bio8 indicates the mean temperature of the wettest quarter, and Bio7 reflects the annual temperature range, which is important for assessing the influence of thermal variability on the distribution of *O. rhinoceros*.

Table 2. Bio-climatic variables and their contribution.

Bio-Climatic Variables	Description	Percent Contribution
Bio 17	Precipitation of driest quarter (mm)	41.9
Bio 8	Mean temperature of wettest quarter (°C)	30.1
Bio 7	Temperature annual range (°C)	18.5
Bio 15	Precipitation seasonality	5.6
Bio 16	Precipitation of wettest quarter (mm)	2.2
Bio 3	Isothermality (%)	1.1
Bio 2	Mean diurnal range	0.7

The MaxEnt-generated response curves (Figure 2) illustrated the ecological preferences of *O. rhinoceros*. For Bio17, cloglog suitability values remained high (> 0.5) but declined sharply below 100 mm and above 500 mm, indicating that moderate dry-season rainfall provides optimal conditions for the species. For Bio8, habitat suitability increased steadily with rising temperatures, peaking at 27-28°C, suggesting adaptation to warm and humid conditions. For Bio7, maximum suitability occurred at intermediate annual temperature ranges (8-12°C), with a rapid decline below 5°C and above 15°C, indicating a preference for moderate thermal seasonality.

Model performance

The model yielded an AUC value of 0.818, indicating good discriminatory ability between presence locations and background points. This falls within the commonly accepted range for good species distribution models (0.8-0.9) and suggests reliable prediction of habitat suitability for *O. rhinoceros* (Figure 3) (Gao et al., 2024). The TSS value of 0.65 further confirms good model predictive performance and map reliability.

Analysis of bioclimatic variables

The Jackknife test (Figure 4) showed that Bio17 had the highest contribution (41.9%), followed by Bio8 (30.1%) and Bio7 (18.5%). In contrast, Bio2, Bio3, Bio15, and Bio16 contributed minimally to the model, indicating limited influence on the distribution of *O. rhinoceros*.

Current distribution of *O. rhinoceros*

Based on current occurrence data and historical climatic conditions, the species shows varying levels of distribution across Malaysia (Figure 5). States such as Kedah, Perak, Selangor, Kelantan, Terengganu, and Negeri Sembilan exhibit low to very high infestation levels. In contrast, Perlis, and Sarawak show rare to moderate distribution, while Sabah and Johor falls within the rare to moderate range.

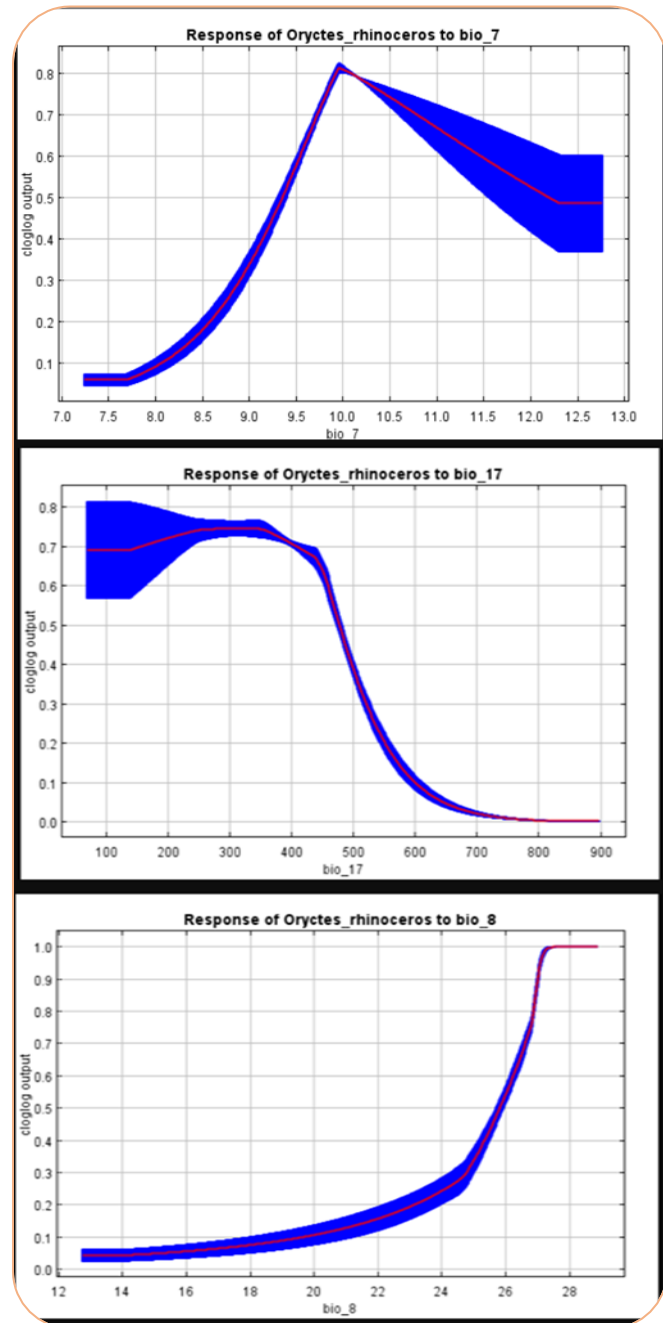


Figure 2. Response curves.

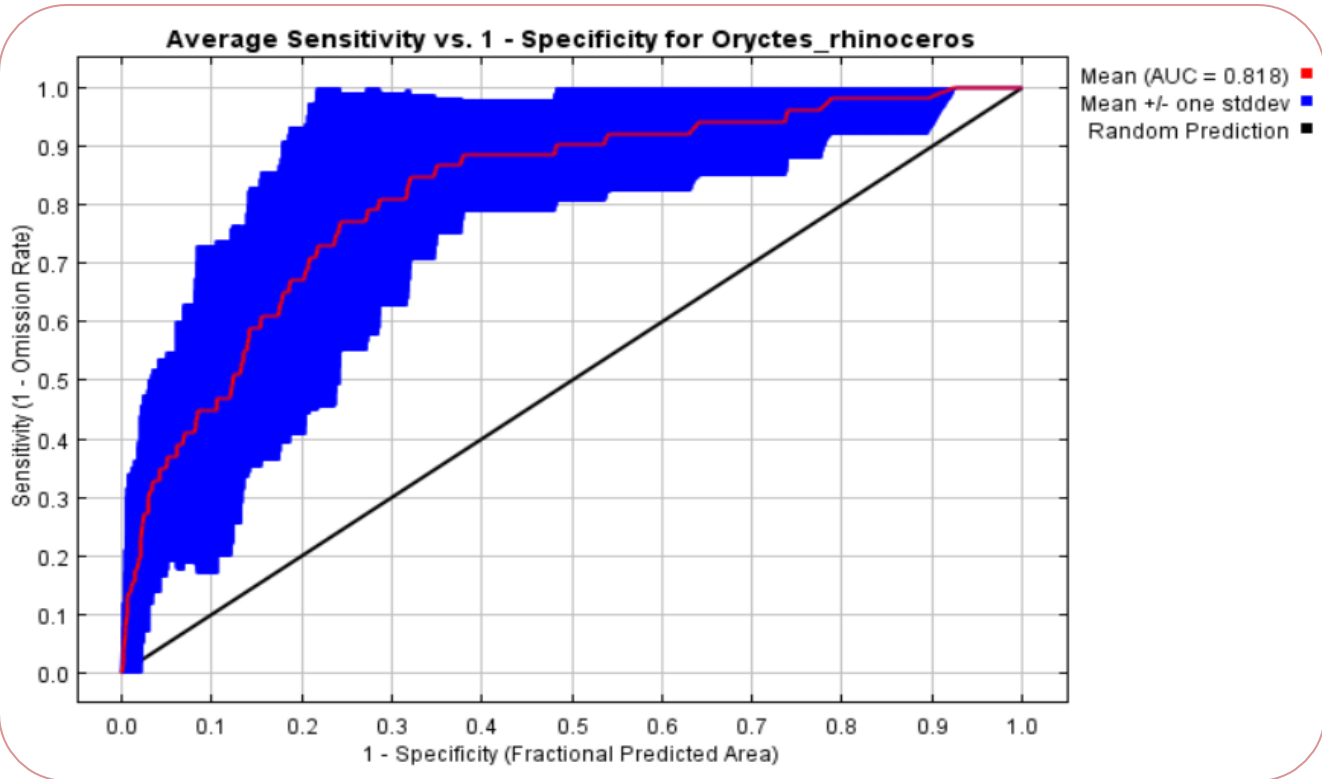


Figure 3. ROC curve for the training and test datasets.

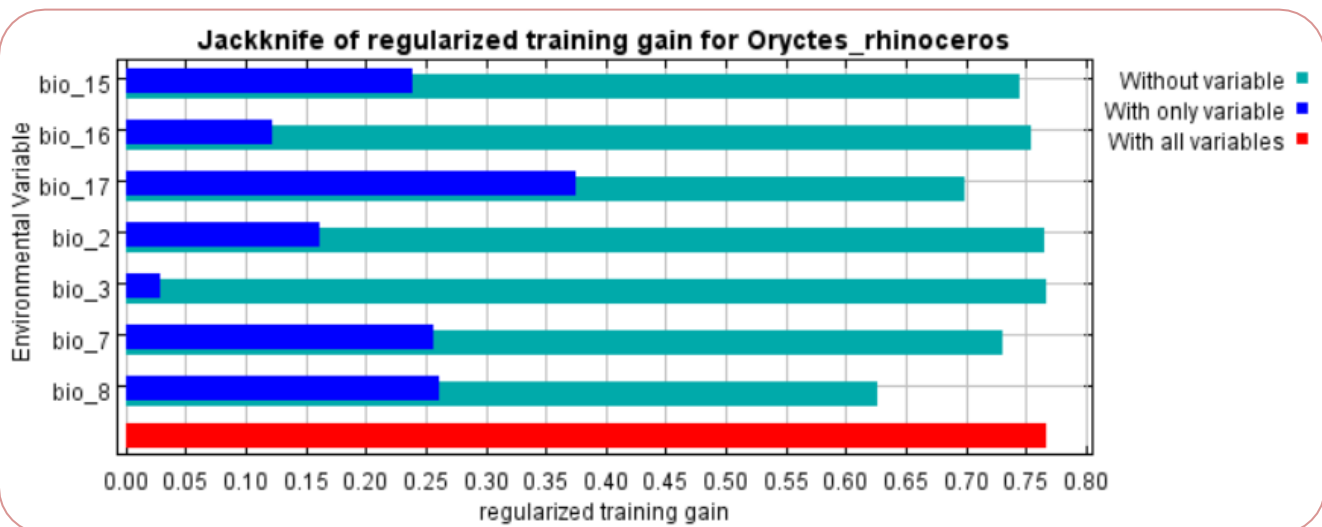


Figure 4. Jackknife test of key environmental variables influencing the habitat suitability of *O. rhinoceros*.

Future distribution of *O. rhinoceros* (2050)

Under future climate scenarios, *O. rhinoceros* distribution shows differential responses. Under SSP126 and SSP245 for 2050 (Figure 6A, B), no major contraction or expansion is observed compared with current conditions. However, under the high-emission scenario SSP585, a clear expansion of suitable habitat is

projected (Figure 6C). States such as Sabah, Pulau Pinang, and Sarawak are projected to shift from rare to moderate suitability toward moderate to very high suitability. Similarly, Selangor, Kedah, Melaka, Perlis and Negeri Sembilan are projected to experience very high suitability, while Pahang, Johor, Perak, and Kelantan also show notable expansion in predicted distribution.

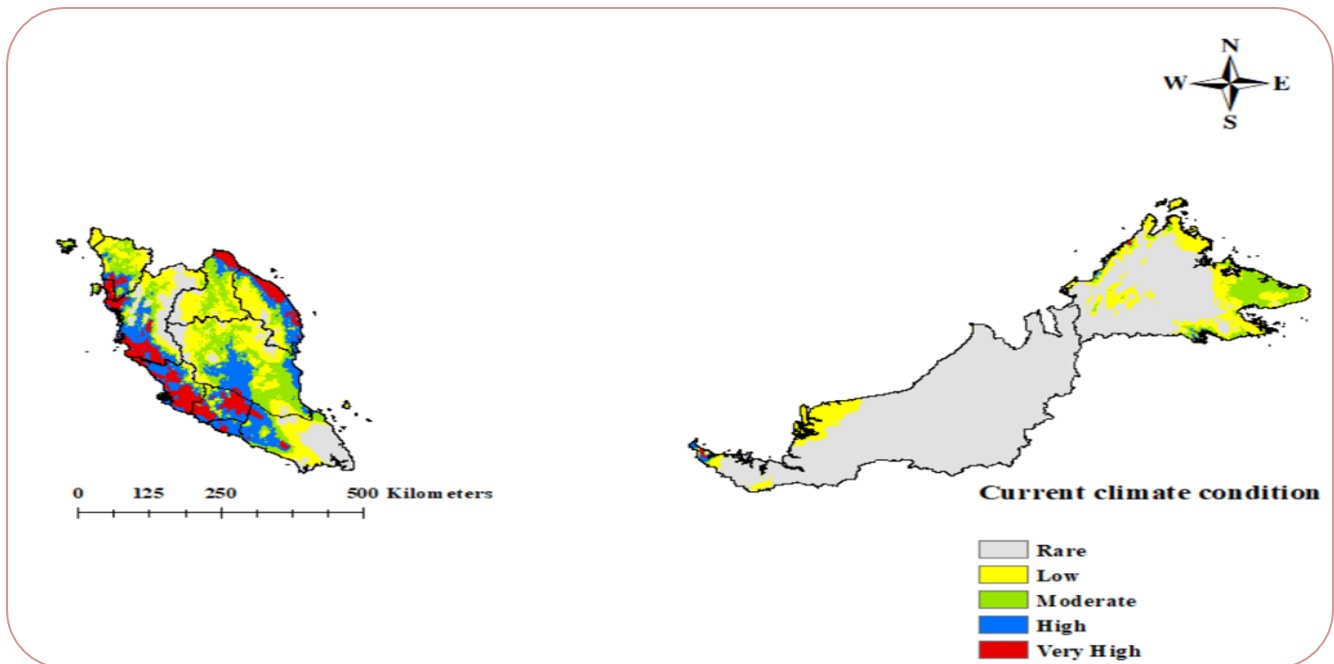


Figure 5. Current distribution of *O. rhinoceros* under climate conditions.

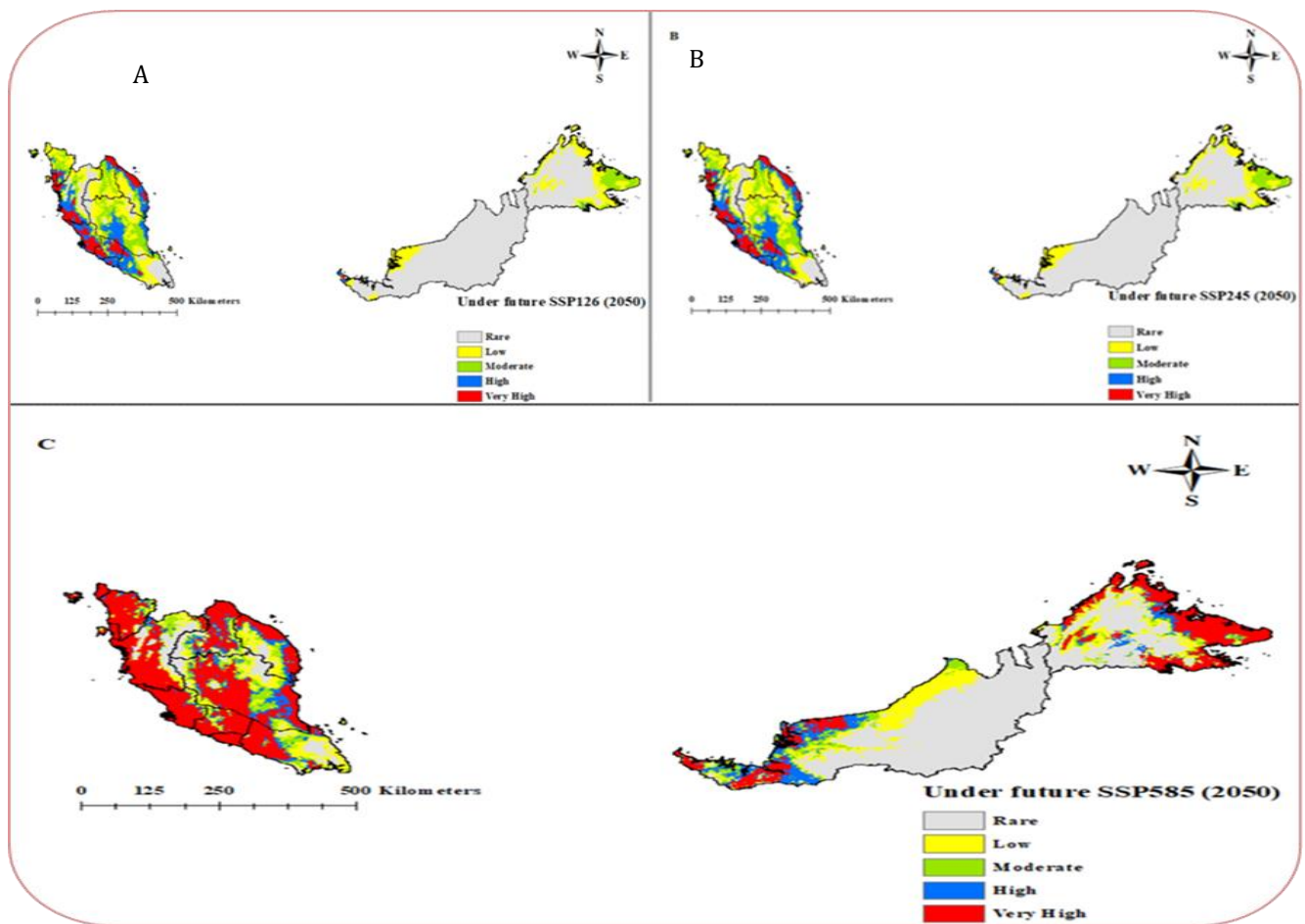


Figure 6: Projected distribution under A (SSP126), B (SSP245), and C (SSP585) scenarios for the year 2050.

Future distribution of *O. rhinoceros* (2070)

By 2070, the distribution of the coconut rhinoceros beetle is projected to expand further compared with both current and 2050 projections under SSP126 and SSP245 (Figure 7D, E). Under SSP126, Sarawak shows a shift from rare to very high suitability. Under SSP245, expansion is projected along the western coastline of Sarawak, while other states also show increasing suitability, with Melaka reaching very high levels. Under the SSP585 scenario (Figure 7F), a pronounced expansion is observed, with high to very high suitability across most states in Malaysia, indicating widespread establishment potential under high-emission climate conditions.

Discussion

Climate change is increasingly recognized as a major driver of the emergence, spread, and intensification of agricultural pests (Das et al., 2011). Climate projections indicate that the global mean surface temperature is expected to increase by approximately 1°C by 2025 and may rise by as much as 3°C by the end of this century (Porter et al., 1991). Such anthropogenic climate change, primarily driven by elevated greenhouse gas concentrations, is expected to substantially alter the distribution, population dynamics, and outbreak potential of insect pests worldwide (Trenberth, 2018).

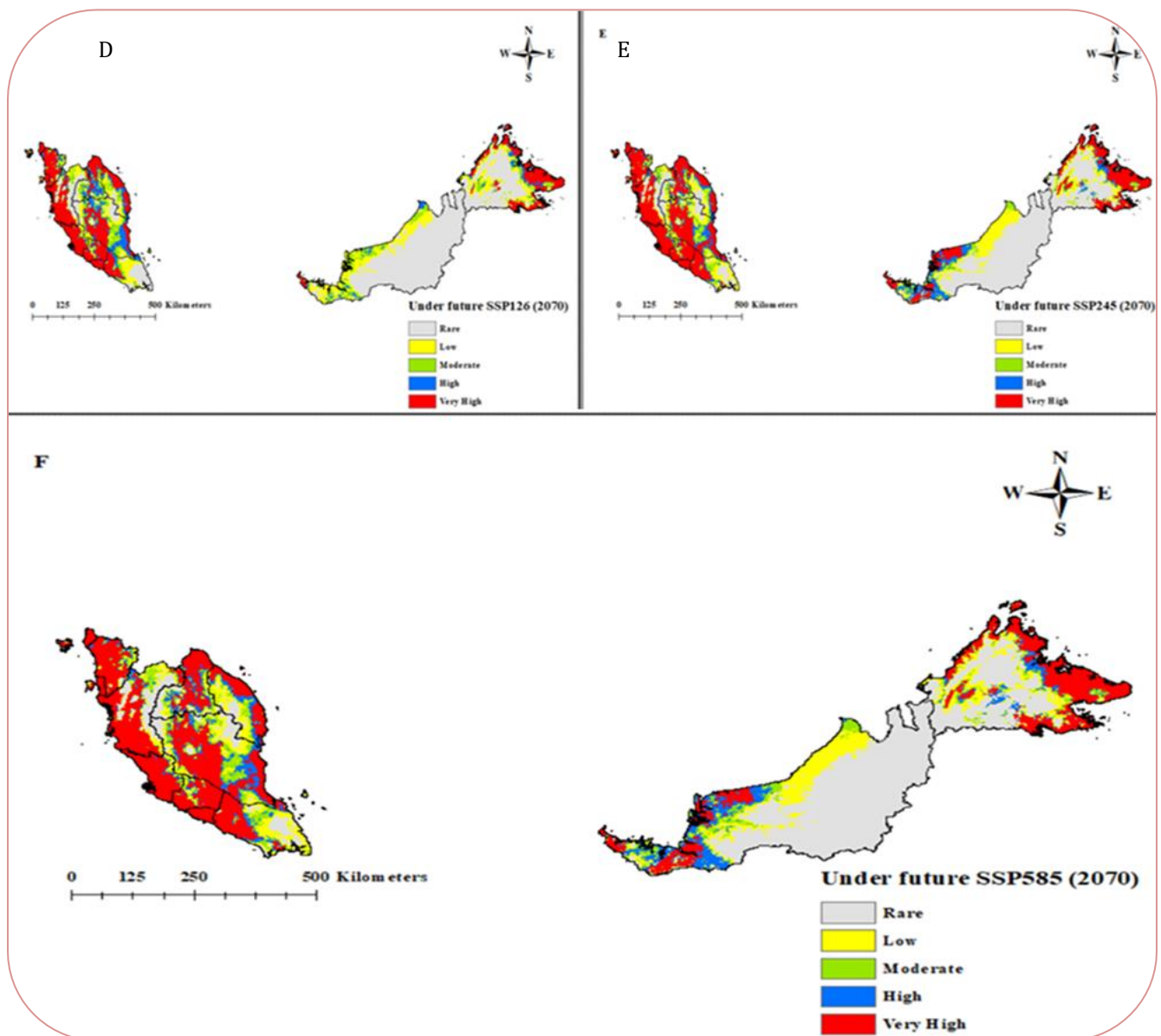


Figure 7: Habitat suitability projections under D (SSP126), E (SSP245), and F (SSP585) scenarios for the year 2070.

The present study identified key climatic variables governing the potential distribution of *O. rhinoceros* in Malaysia. Precipitation of the driest quarter (Bio17) emerged as the most influential predictor, highlighting the critical role of moisture availability in larval development and survival. Mean temperature of the wettest quarter (Bio8) was the second most important variable, contributing 30.1% to habitat suitability. This variable represents thermal conditions during the rainy season, when host plants are actively growing and breeding resources are abundant. As *O. rhinoceros* is a poikilothermic insect (Neelaboina et al., 2018), warm and humid conditions accelerate its development, survival, and reproductive success. Previous studies have demonstrated that tropical rhinoceros beetles achieve optimal development within a temperature range of approximately 26-28.5°C (Hao et al., 2022; Fu et al., 2024). However, exposure to extreme temperatures and excessive rainfall can negatively affect survival and population establishment.

Temperature annual range (Bio7), which reflects the difference between the maximum temperature of the warmest month and the minimum temperature of the coldest month, also substantially influenced habitat suitability. Similar findings have been reported in previous ecological niche modelling studies of *O. rhinoceros*, emphasizing the importance of annual thermal variability in determining species distribution. Temperature is widely recognized as one of the primary environmental factors regulating insect growth, development, reproduction, survival, and geographic distribution (Ju et al., 2011; Leonard et al., 2020). Large annual temperature fluctuations generally reduce habitat suitability by imposing physiological stress and limiting successful population establishment. Likewise, global distribution models of *O. rhinoceros* and other scarab beetles consistently identify regions characterized by moderate annual temperature variation, high humidity, and abundant host plants as highly suitable habitats (Hao et al., 2022; Shen et al., 2024).

The species distribution model demonstrated good predictive performance, with an AUC of 0.818 and a TSS of 0.65, indicating good discriminatory ability and reliable spatial prediction. These values exceed the commonly accepted thresholds for robust ecological niche models (AUC > 0.80; TSS > 0.60) (Allouche et al., 2006). The results suggest that the selected bioclimatic variables adequately captured the major climatic constraints

governing the distribution of *O. rhinoceros* in Malaysia. Nevertheless, the model predicts climatic suitability rather than realized species distribution. Several non-climatic factors, including land-use patterns, plantation management practices, host plant availability, natural enemies, and human-mediated dispersal, were not incorporated into the model but are known to influence the establishment and spread of *O. rhinoceros* populations (Kamarudin and Wahid, 2006; Hao et al., 2022).

Limitations

Despite its satisfactory predictive performance, the present study has several limitations. First, the model relied exclusively on climatic variables and did not incorporate other ecologically relevant predictors, such as land cover, elevation, soil characteristics, plantation age, and host plant distribution, all of which may substantially influence the abundance and distribution of *O. rhinoceros*. Integrating these environmental variables into future models would likely improve prediction accuracy, particularly at finer spatial scales. Second, occurrence records may be spatially biased towards well-surveyed or highly productive plantation areas, potentially affecting model performance despite data filtering procedures. Finally, climatic suitability does not necessarily imply species occurrence, as biological interactions, pest management interventions, dispersal barriers, and landscape connectivity may restrict colonization of climatically suitable habitats (Aidoo et al., 2022; Hao et al., 2022).

Conclusion

The present study demonstrates that climate change is likely to expand the potential distribution of *O. rhinoceros* across Malaysia. Model projections indicate that under the low- and intermediate-emission scenarios (SSP126 and SSP245); the potential distribution remains largely comparable to current conditions by 2050. In contrast, the high-emission scenario (SSP585) predicts substantial expansion of suitable habitats, particularly in Pahang, Johor, Perak, and Kelantan by 2050. By 2070, under SSP585, nearly all Malaysian states are projected to exhibit high to very high climatic suitability for *O. rhinoceros*. These findings provide valuable insights for oil palm producers, pest management practitioners, and policymakers by identifying regions at increased future risk of infestation. The predicted distribution maps can support climate-informed surveillance, early warning systems, and proactive integrated pest management

strategies, thereby enhancing the long-term sustainability, productivity, and resilience of Malaysia's oil palm industry under changing climatic conditions.

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Author Contributions

MAH and KTK conceived and designed the study. MAH conducted the literature review and carried out the experimental work. KTK provided overall supervision and ensured methodological rigor and analytical consistency throughout the study. MMMM served as co-supervisors, providing critical guidance on the experimental design, data interpretation, and refinement of the research at various stages of the project. MAH and KTK prepared the initial draft of the manuscript, including organizing the content, compiling the results, and developing the preliminary interpretations. All authors subsequently critically reviewed and revised the manuscript, contributed to its intellectual content, verified the data and analyses, and approved the final version for publication.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger

SDG 13: Climate Action

SDG 15: Life on Land

Policy Addressed

This study supports policies promoting climate change adaptation, climate-smart agriculture, integrated pest management (IPM), national plant biosecurity and pest surveillance, sustainable oil palm production, climate risk assessment, early warning systems, and evidence-based agricultural decision-making through the application of species distribution modeling.

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