BIODIVERSITAS
Volume 26, Number 3, March 2025
Pages: 1075-1084

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d260306

Present and future habitat suitability of *Mantheyus phuwuanensis* under climate change scenario

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Manuscript received: 16 January 2025. Revision accepted: 2 March 2025.

Abstract. *Chuaynkern C, Khajitmathee N, Phochayavanich R, Phommexay P, Chaiyes A, Maury N, Sudavanh S, Aowphol A, Rujirawan A, Pailoblee S, Suksavate W, Duengkae P, Chuaynkern Y. 2025. Present and future habitat suitability of* Mantheyus phuwuanensis *under climate change scenario. Biodiversitas 26: 1075-1084.* The Phu Wua Rock Agama, *Mantheyus phuwuanensis*, is a diurnal lizard endemic to northeastern Thailand and western Laos, first described in 1991 from Phu Wua Wildlife Sanctuary (northeastern Thailand). Despite being listed as Near Threatened by the IUCN, little is known about its ecological requirements, population dynamics, and the extent of its distribution. This study aims to provide an updated assessment of the species' range and evaluate its habitat suitability under current and future climate scenarios. Field surveys complemented by literature reviews documented 1,994 occurrences of *M. phuwuanensis* across its range. Using 28 environmental variables, Species Distribution Modeling (SDM) in MaxEnt achieved exceptional predictive accuracy (AUC: 0.993±0.005). Precipitation during the warmest quarter (average 1,519.58±339.04 mm³; range 825-1,855 mm³), distance to unconsolidated sediments (average 6.09±7.51 km; range 0-16.70 km), and slope (average 7.26±2.64 degrees; range 0.24-11.97°) were identified as the primary environmental factors influencing habitat suitability. Current suitable habitats were estimated at 2,715.90 km², primarily concentrated in Laos. Projections for 2050 and 2070 under SSP2-4.5 and SSP5-8.5 climate scenarios revealed alarming habitat reductions of 65.93-88.87%, highlighting the species' high sensitivity to climate change. Conservation measures are urgently needed to mitigate these impacts. We recommend designating *M. phuwuanensis* as a protected animal under Thai law and upgrading its CITES status to Appendix III to combat potential overexploitation. Future conservation strategies should prioritize habitat protection, ecological restoration, and cross-border collaboration between Thailand and Laos. These findings offer crucial insights into the vulnerability of *M. phuwuanensis* and underscore the importance of integrating habitat management with regional conservation efforts.

Keywords: Lao PDR, *Mantheyus phuwuanensis*, MaxEnt, Phu Wua Rock Agama, species distribution model, Thailand

INTRODUCTION

The ongoing global decline in biodiversity is one of our time's most critical environmental challenges, with species extinction rates accelerating to unprecedented levels in human history. Often referred to as the sixth mass extinction, it is largely driven by anthropogenic factors such as habitat destruction, overexploitation of resources, invasive species introductions, and climate change (Ceballos et al. 2015, et al. 2017; Ceballos and Ehrlich 2023). Habitat loss and fragmentation significantly disrupt ecosystems, forcing many species, particularly those with narrow ecological niches or limited distributions, toward extinction (Chuaynkern and Duengkae 2014; Prakash and Verma 2022; Phommexay et al. 2024a,b). Climate change further exacerbates these threats by altering temperature and precipitation patterns, reducing habitat suitability, and disrupting ecological dynamics (Tabari 2020). Current estimates indicate that species are disappearing at rates 100 to 1,000 times higher than natural background levels, with profound implications for ecological processes and the essential ecosystem services upon which human survival depends (Ceballos et al. 2015, et al. 2017; Ceballos and Ehrlich 2023). These alarming trends highlight the urgent need for effective global conservation initiatives to mitigate biodiversity loss and ensure ecological balance.

The Phu Wua Rock Agama, *Mantheyus phuwuanensis* (Manthey & Nabhitabhata, 1991), was first described as a new species (*Ptyctomaemys phuwuanensis*) based on six specimens collected from Phu Wua Wildlife Sanctuary in Nong Khai Province, northeastern Thailand (now Bueng Kan Province) by Manthey and Nabhitabhata (1991). Subsequent specimens from Thailand and Laos revealed distinguishing characteristics that separate them from *P. gularis* (the type species of the *Ptyctolaemus*), including femoral pores and haired skin sense organs. These differences led Ananjeva and Stuart (2001) to establish a new genus, *Mantheyus*, with *P. phuwuanensis* designated as the type species. Currently, *Mantheyus* consists of only one species, *M. phuwuanensis*. This species inhabits areas near water sources, such as sandstone mountains and evergreen forests with extensive rock substrates and riverbanks. It is often observed on rock ledges along rivers, within large boulder piles in forest clearings, and inside small caves formed by these boulders (Manthey and Nabhitabhata 1991; Ananjeva and Stuart 2001; Manthey and Manthey 2017). Globally, *M. phuwuanensis* is classified as Near Threatened (NT) by the IUCN Red List (IUCN 2025). Without comprehensive research, the species remains at significant risk of population decline. Further studies are essential to understanding its population dynamics and identifying threats to its survival. Although not listed in the Convention on International Trade appendices in Endangered Species of Wild Fauna and Flora (CITES), the species occasionally appears in the Western pet trade (Manthey and Manthey 2005; IUCN 2025).

The distribution of *M. phuwuanensis* is currently limited. In Thailand, the species is known only from its type locality, Phu Wua Wildlife Sanctuary, Bueng Kan Province (Manthey and Nabhitabhata 1991). In Laos, it has been reported in the Phu Khao Khouay National Biodiversity Conservation Area (Ananjeva and Stuart 2001) and the Nam Kading National Biodiversity Conservation Area (Hallam et al. 2011). The global biodiversity crisis, marked by the rapid and alarming loss of species and ecosystems (Chuaynkern and Duengkae 2014; Kumar and Verma 2017; Prakash and Verma 2022), is exacerbated by environmental pressures such as habitat loss, unsustainable resource use, invasive species, and climate change (Chuaynkern and Duengkae 2014; Ramirez-Villegas et al. 2014; Phommexay et al. 2024a,b). Understanding species vulnerability to climate change requires comprehensive analyses of how ecosystems respond to environmental shifts (Pomoim et al. 2022; Phommexay et al. 2024a,b). For *M. phuwuanensis*, intensive field surveys are urgently needed to determine its distribution before populations face further declines. Equally important is identifying suitable habitats to predict their distribution and evaluating climate change's potential impacts by projecting habitat shifts under future scenarios. Such insights are crucial for developing effective conservation strategies to mitigate biodiversity loss in changing environments (Ramirez-Villegas et al. 2014). This study addresses these knowledge gaps by updating the distribution of *M. phuwuanensis* through field surveys and literature reviews while assessing its current and future habitat suitability using Species Distribution Modeling (SDM). The results are presented below.

MATERIALS AND METHODS

Mantheyus phuwuanensis data occurrence

Data on the occurrence of *M. phuwuanensis* were gathered from Thailand and Laos through a combination of field surveys and literature reviews (Manthey and Nabhitabhata 1991; Ananjeva and Stuart 2001; Manthey and Manthey 2017). In Thailand, surveys were conducted along the Mekong River, covering the provinces of Loei, Phetchabun, Udon Thani, Nong Khai, Bueng Kan, Sakon Nakhon, Mukdahan, Roi Et, Kalasin, Ubon Ratchathani, and Si Sa Ket. The surveys primarily focused on protected areas, including the Phu Khiao-Nam Nao Forest Complex, comprising Phu Khiao Wildlife Sanctuary (Chaiyaphum), Phu Luang Wildlife Sanctuary (Loei), Nam Nao National Park (Phetchabun), and Phu Kradueng National Park (Loei), the Phu Phan Forest Complex (Phu Phan National Park, Sakon Nakhon), and the Phanom Dong Rak-Pha Tam Forest Complex, which includes Phanom Dong Rak Wildlife Sanctuary (Si Sa Ket), Yoddom Wildlife Sanctuary (Ubon Ratchathani), and Phu Jong-Na Yoi National Park (Ubon Ratchathani). Additionally, surveys were conducted in Phu Wua Wildlife Sanctuary and non-protected areas in Bueng Kan Province. In Laos, surveys were carried out along the Nam Lik River and within the Phu Khao Khouay and Nam Kading National Biodiversity Conservation Areas (NBCA). Species identification was verified using descriptions and photographs from relevant publications (Manthey and Nabhitabhata 1991; Ananjeva and Stuart 2001; Manthey and Manthey 2017).

Environmental variables

To evaluate the factors influencing the distribution of *M. phuwuanensis*, 28 environmental variables at a spatial resolution of 30 arcseconds were analyzed, encompassing topography, vegetation indices, lithological data, and climate. Nineteen climatic variables, including temperature and precipitation, were retrieved from the WorldClim database (http://worldclim.org). Topographic data, such as the digital elevation model (DEM) and elevation, were also retrieved from WorldClim and processed to create aspect and slope layers using the 'terra' package in R version 4.4.1. Lithological characteristics were assessed by calculating distances to mixed sedimentary rocks, siliciclastic sedimentary rocks, and unconsolidated sediments, based on the data from Hartmann and Moosdorf (2012) and processed with the 'terra' package. Vegetation indices, including the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI), were calculated using Landsat 8 data (https://www.usgs.gov) with annual averages from 2018 to 2023 processed through Google Earth Engine. Additionally, Nighttime Light (NTL) data, with annual averages for 2000, 2005, 2010, and 2013, was obtained from the National Centers for Environmental Information (https://www.ncei.noaa.gov) and integrated into the analysis. The inclusion of these data layers (Table 1) is essential for accurately modeling the habitat suitability of *M. phuwuanensis*. Climatic variables, such as temperature and precipitation, influence the species' physiological and ecological needs. Topographic features like elevation, slope, and aspect shape microclimatic conditions, crucial for determining suitable refuges. Lithological data, including distances to sandstone and other rock types, helps identify appropriate geological habitats. Vegetation indices assess vegetation cover and water availability, both critical for habitat complexity and microclimate stability. Nighttime light data, as an indicator of human disturbance, helps refine habitat suitability by identifying areas affected by anthropogenic activity.

Species Distribution Modeling (SDM)

The study area was delineated based on biogeographical regions that encompass known species occurrences, including northeastern Thailand and western Laos. The Maximum Entropy (MaxEnt) approach was utilized in this study's Species Distribution Modeling (SDM) to map the habitat suitability of *M. phuwuanensis* in Thailand and Laos. MaxEnt, a widely used SDM tool, integrates environmental variables and occurrence data to predict species distributions (Phillips et al. 2006; Phommexay et al. 2024a,b). For this study, the potential distribution of *M. phuwuanensis* was modeled using MaxEnt version 3.4.4 (Steven et al. 2024). The model was configured with a random test percentage of 20% and employed a cross-validation method with 10 replicates to ensure robust predictions.

Table 1. The environmental variables utilized to develop the Species Distribution Model (SDM) for *Mantheyus phuwuanensis*

Environmental variables	Description
Bio1	Annual mean temperature
Bio2	Mean diurnal range
Bio3	Isothermality
Bio4	Temperature seasonality
Bio5	Maximum temperature of warmest month
Bio6	Minimum temperature of coldest month
Bio7	Temperature annual range
Bio8	Mean temperature of wettest quarter
Bio9	Mean temperature of driest quarter
Bio10	Mean temperature of warmest quarter
Bio11	Mean temperature of coldest quarter
Bio12	Annual precipitation
Bio13	Precipitation of wettest month
Bio14	Precipitation of driest month
Bio15	Precipitation seasonality
Bio16	Precipitation of wettest quarter
Bio17	Precipitation of driest quarter
Bio18	Precipitation of warmest quarter
Bio19	Precipitation of coldest quarter
aspect	Direction a slope face
elev	Elevation
ntl	Nighttime light
Slope	Degree of rise/run
NDVI	Normalized difference vegetation index
NDWI	Normalized difference water index
sm_dist	Distance to mixed sedimentary rocks
ss_dist	Distance to Siliciclastic sedimentary rocks
su_dist	Distance to unconsolidated sediments

The analysis focused on assessing habitat suitability for three periods: current, 2050 (2041-2060), and 2070 (2061-2080). The selection of environmental variables for modeling was guided by ecological insights and the availability of reliable datasets. For the current scenario, the model used present environmental conditions, while future climate data were derived from the ACCESS-CM2 model, obtained via the WorldClim database (http://worldclim.org), following the recommendation of McSweeney et al. (2015). Two key metrics were employed to evaluate the performance of the MaxEnt model: the Jackknife test and the Area Under the Receiver Operating Characteristic (ROC) Curve (AUC). The Jackknife test was used to assess the contribution of individual environmental variables to the model, while the AUC metric provided a measure of the model's predictive accuracy relative to random guesses (Phillips et al. 2006).

RESULTS AND DISCUSSION

***Mantheyus phuwuanensis* current distribution**

This study documented 1,994 occurrences of *M. phuwuanensis* across western Laos and northeastern Thailand (Figure 1). In Figure 1, closely clustered locations were consolidated into single solid circles to enhance clarity. In Laos (Figure 2), 1,989 occurrences were recorded within the Phu Khao Khouay and Nam Kading National Biodiversity Conservation Areas (NBCAs), spanning four provinces: Bolikhamxay, Vientiane, Xaisomboun, and Khammouane. Within Phu Khao Khouay NBCA, 1,305 occurrences were documented across three provinces, including nine in Bolikhamxay (one from Ananjeva and Stuart 2001, and eight from field surveys conducted in this study), 1,293 in Xaisomboun (field surveys), and two in Vientiane (field surveys). In Nam Kading NBCA, 684 occurrences were identified, with 683 in Khammouane (field surveys) and one in Bolikhamxay (field survey). In Thailand, *M. phuwuanensis* is restricted to Bueng Kan Province, with five documented localities. Two of these were in Phu Wua Wildlife Sanctuary, including the type locality (Manthey and Nabhitabhata 1991; Ananjeva and Stuart 2001), as well as one additional site identified during this study. The field surveys also revealed two new localities in Si Wilai District and one in Mueang District (Thum Rusi, Khok Khlong Sub-district).

The natural history of *M. phuwuanensis* remains poorly understood. In Laos, the species inhabits sandstone environments along the Phu Khao Khouay mountain range, where it deposits its eggs in rock crevices (this study). The eggs are oval-shaped with soft, leathery shells (Figure 2). In Thailand, existing information is limited to its morphology and a small number of distribution records (Manthey and Nabhitabhata 1991; Ananjeva and Stuart 2001; Poyarkov et al. 2023).

The distribution of *M. phuwuanensis* is restricted to the Indochinese region, specifically northeastern Thailand and western Laos. In Thailand, the species is restricted to Bueng Kan Province, with Phu Wua Wildlife Sanctuary in Bung Khla District serving as its type locality (Manthey and Nabhitabhata 1991). This sanctuary, recognized as a biodiversity hotspot, plays a crucial role in the conservation of *M. phuwuanensis* and supports several rare or narrowly distributed species (Poyarkov et al. 2023), including *Opisthotropis maculosa* (Stuart & Chuaynkern, 2007) (Colubridae), *Cyrtodactylus jarujini* (Ulber, 1993) (Gekkonidae), and *Tropidophorus latiscutatus* (Hikida, Orlov, Nabhitabhata & Ota, 2002) (Scincidae). Additional records from Si Wilai District and Khok Klong Sub-district (Mueang District) have expanded the known distribution of the species. In Laos, *M. phuwuanensis* is found in sandstone ecosystems along the Phu Khao Khouay mountain range, where it exhibits specific ecological adaptations, such as laying oval-shaped eggs with leathery shells in rock crevices. In contrast, ecological requirements of the species in Thailand remain poorly understood, with existing information primarily focused on morphology and a limited number of distribution records (Manthey and Nabhitabhata 1991; Ananjeva and Stuart 2001; Ananjeva et al. 2022). To better understand the relationship between Thai and Lao populations, specific tools, such as molecular analysis (e.g. DNA barcoding or microsatellite markers), landscape genetics, and spatial modeling, should be employed to determine whether the river acts as a dispersal corridor or a geographic barrier. Molecular tools can help clarify genetic differentiation between populations, while landscape genetics can assess how environmental features, like the river, influence gene flow. Additionally, spatial modeling techniques, such as Species Distribution Modeling (SDM), could provide insights into the potential habitats and corridors for the species. In our work, the analysis suggests that while some populations are situated near the river, others are isolated by its presence, indicating that the river may play a role in shaping the species' distribution patterns. However, limited surveys in northeastern Thailand, including those within protected areas that could harbor suitable habitats, likely underestimate the true distribution and population status of the species (Thongproh et al. 2019; Poyarkov et al. 2023). This underscores the necessity for extensive field studies to enhance our understanding of its range.

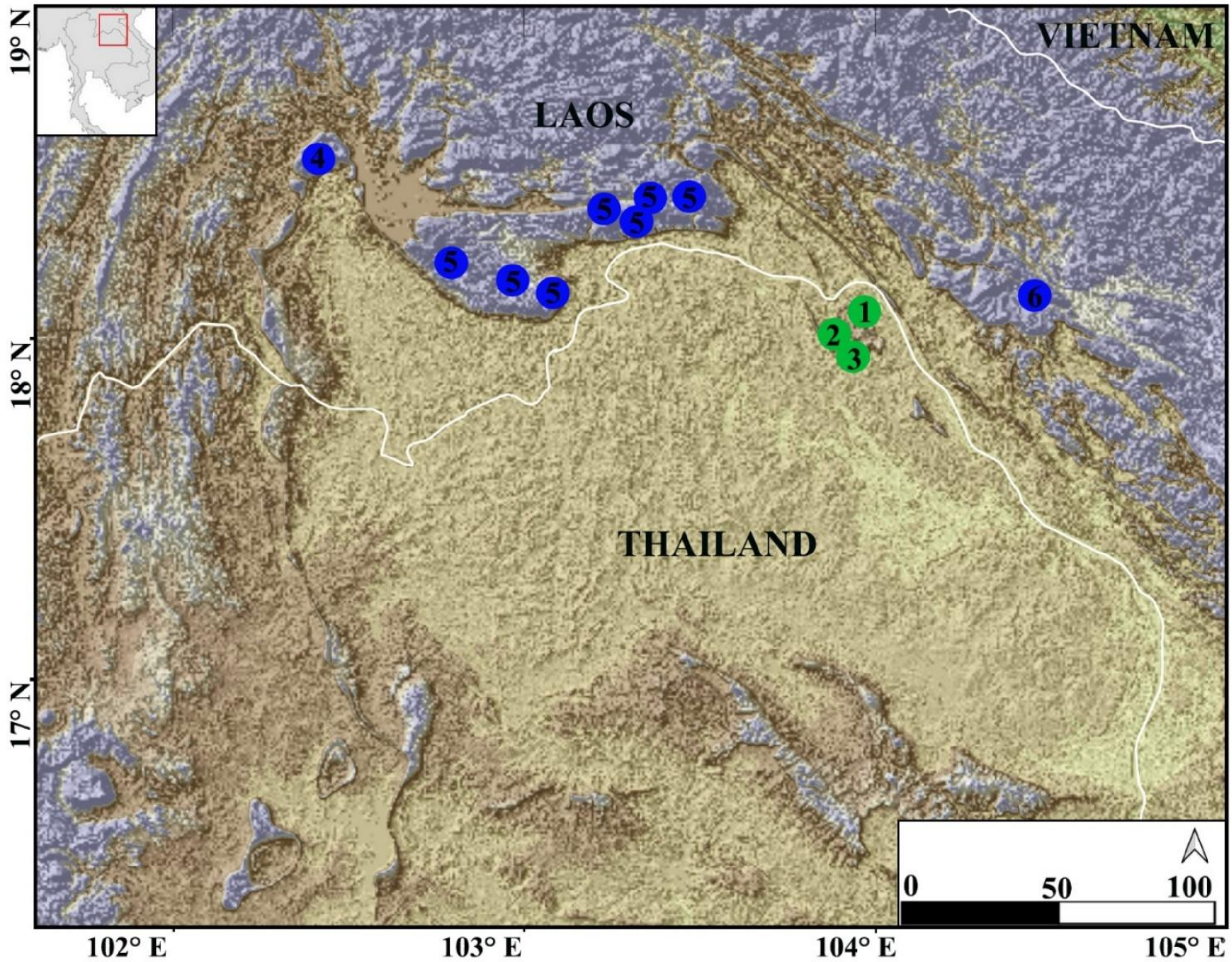

Figure 1. Map showing the distribution of *Mantheyus phuwuanensis* across northeastern Thailand (green circles) and western Laos (blue circles). Location symbols: 1. Phu Wua Wildlife Sanctuary (type locality, Manthey and Nabhitabhata 1991), Bueng Kan; 2. Thum Rusi, Khok Khong Sub-district, Mueang District, Bueng Kan; 3. Si Wilai District, Bueng Kan; 4. Nam Lik River; 5. Phu Khao Khouay NBCA; 6. Nam Kading NBCA. Notably, closely clustered localities were consolidated into single solid circles to enhance map clarity, resulting in a total of 1,994 occurrence points

The Mekong River serves as a significant geographic barrier, isolating Thai populations of *M. phuwuanensis* from those in Laos, a phenomenon observed in various flora and fauna species across the region. Studies suggest that large rivers like the Mekong play a crucial role in limiting gene flow and shaping species distribution, acting as both physical and ecological barriers (de Brito Martins and de Aguiar 2016; Weston et al. 2022). The river's extensive width, strong currents, and seasonal flooding contribute to these isolation effects, often resulting in pronounced differences between populations on each side (Sun et al. 2024). Similar patterns have been observed in amphibians and reptiles, where natural barriers like the Mekong split populations, leading to distinct regional adaptations (Lukoschek et al. 2011; Geissler et al. 2015). These patterns highlight the Mekong River's role in driving genetic divergence and fostering localized adaptations, underscoring the need for research into the genetic diversity and population structure of *M. phuwuanensis* to inform effective conservation strategies.

As the sole representative of the monotypic genus *Mantheyus* (Ananjeva and Stuart 2001), reclassified from the agamid genus *Ptyctolaemus* based on distinctive features such as femoral pores and specialized sensory organs, this diurnal lizard occupies specific niches in the Dry evergreen forest of northeastern Thailand and western Laos. Molecular phylogenetic analyses affirm its evolutionary distinctiveness as a sister clade to other members of the subfamily Draconinae (Grismer et al. 2016; Ananjeva et al. 2022). Despite its evolutionary significance, *M. phuwuanensis* faces threats from habitat loss and fragmentation in Thailand, while its dependence on sandstone ecosystems in Laos makes it vulnerable to environmental disturbances. Conservation efforts should prioritize on habitat protection, population monitoring, and addressing human-induced threats. Cross-border collaboration between Thailand and Laos is essential for managing this transboundary species, with future research needed to map its range, assess habitat quality, and investigate its ecological and genetic characteristics to ensure its long-term survival.

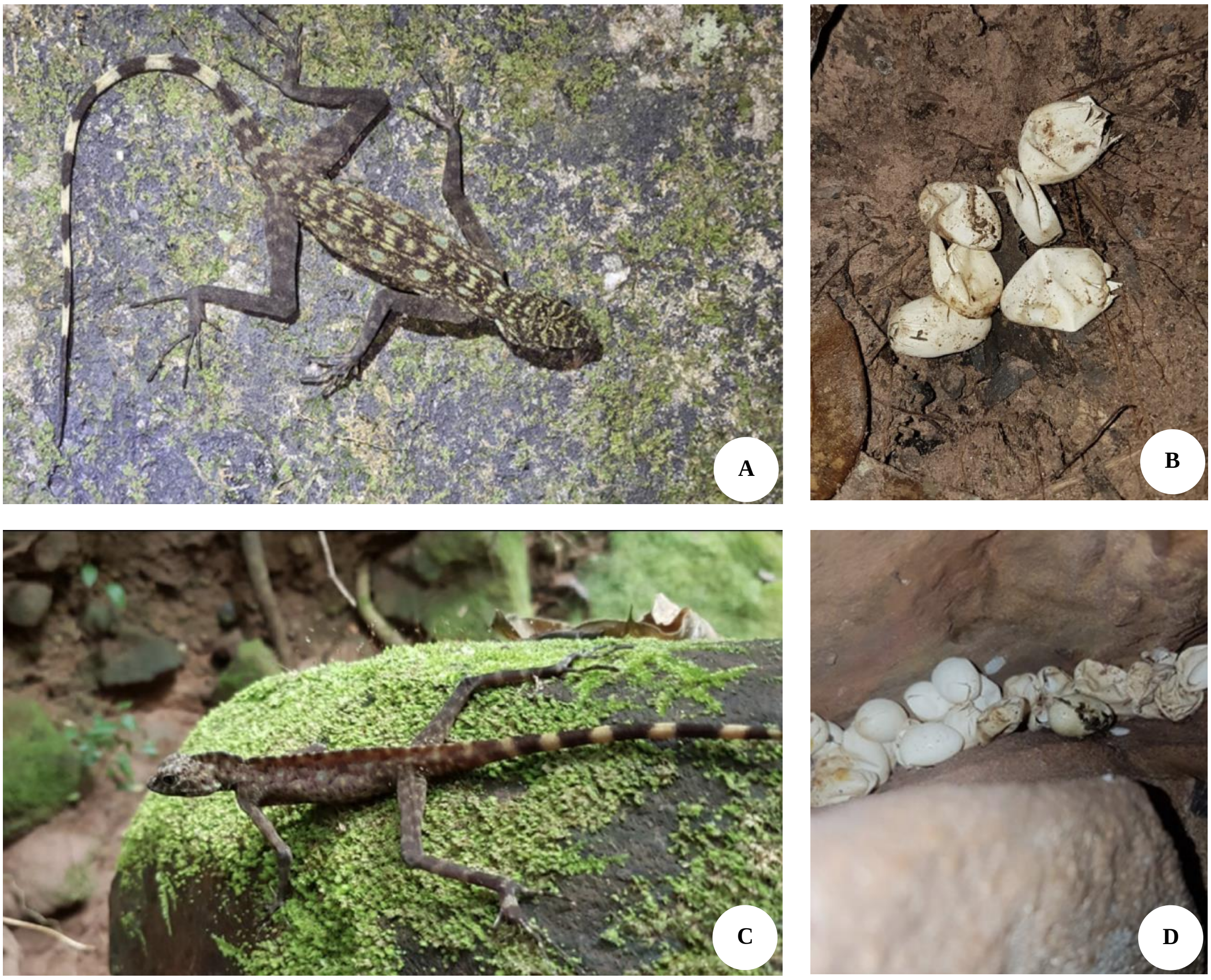

Figure 2. Life photographs of *Mantheyus phuwuanensis* from Laos. A. Dorsal view of *M. phuwuanensis* from Na Hin, central Laos; B. Hatched eggs of *M. phuwuanensis*; C. Dorsolateral view of *M. phuwuanensis* from Nam Lik; D. Eggs and their oviposition site in a rock crevice

Mantheyus phuwuanensis **habitat suitability**

The habitat suitability model for *M. phuwuanensis* was conducted with 10 replicates, yielding an average AUC value of 0.993±0.005 (Figure 3). This exceptionally high AUC score demonstrates outstanding model performance and strong discriminatory power (Phillips et al. 2006).

The primary environmental variables influencing the habitat suitability of *M. phuwuanensis* were identified as Precipitation of the Warmest Quarter (Bio18), Distance to Unconsolidated Sediments, and Slope. Bio18 emerged as the most significant factor, contributing 48.5% to habitat suitability, with an average precipitation of 1,519.58±339.04 mm³ (ranging from 825 to 1,855 mm³). Distance to Unconsolidated Sediments contributed 27.1%, with an average distance of 6.09±7.51 km (ranging from 0 to 16.70 km), while Slope accounted for 8.2%, with an average of 7.26±2.64° (ranging from 0.24-11.97°). Among these, Bio18 showed the strongest influence, exhibiting a positive association with habitat suitability, suggesting that *M. phuwuanensis* relies heavily on areas with high precipitation during the warmest quarter. Similarly, the relationship between Bio18 and Slope was positive, indicating that steeper slopes also enhance habitat suitability. Conversely, Distance to Unconsolidated Sediments demonstrated a negative relationship, implying that habitats closer to unconsolidated sediments are more favorable for the species, while suitability decline as distance increases.

Jackknife analysis further highlighted the critical role of Bio18 in the model. When evaluated independently, Bio18 provided the highest gain, highlighting its predictive significance. Conversely, excluding Bio18 resulted in the most significant reduction in model gain, emphasizing its irreplaceable importance in predicting habitat suitability for *M. phuwuanensis* (Figure 4).

To define habitat suitability, the 10th percentile training presence cloglog threshold of 0.46 was applied, identifying priority areas for species surveys (Tran et al. 2023). Using this threshold, habitats were categorized into three suitability levels: low (0.46-0.60), medium (0.6-0.80), and high (>0.80). The total habitat suitability area was estimated at 2,715.90 km² within the study region (Thailand 131.02 km^2 (4.82%); Laos 2,584.89 km^2 (95.18%), distributed as follows: low suitability (1,025.88 km²), medium suitability (927.82 km²), and high suitability (762.20 km²) (Figure 5, Table 2).

The SMD model used in this study provided valuable insights into the environmental factors influencing the distribution of *M. phuwuanensis*. It demonstrated excellent performance, with a high AUC value of 0.993±0.005, indicating strong predictive reliability. Key variables shaping habitat suitability included Precipitation of the Warmest Quarter (Bio18), Distance to unconsolidated sediments, and slope. Among these, Bio18 was the most influential, correlating strongly with areas of high habitat suitability and emphasizing the species' reliance on regions with significant rainfall during the warmest quarter. The model revealed a positive relationship between Bio18 and Slope, suggesting a preference for specific topographic features, while a negative correlation with distance to unconsolidated sediments indicated a tendency to inhabit areas near such sediments, which may offer shelter and resources. Northeastern Thailand was identified as less suitable for the species, emphasizing the need for more intensive surveys to refine knowledge of its distribution in the region. Jackknife analysis confirmed the importance of Bio18, with its exclusion causing the greatest reduction in model performance. The habitat suitability classification identified a total suitable habitat area of 2,715.90 km², of which 762.20 km² was classified as highly suitable. These findings provide critical guidance for conservation efforts, particularly in prioritizing survey areas and protecting essential habitats.

Model future under difference scenarios

The future habitat suitability for *M. phuwuanensis* was modeled for 2050 and 2070 under SSP2-4.5 and SSP5-8.5 climate change scenarios using the ACCESS-CM2 model. Compared to the current habitat area, projections for 2050 estimate a total suitable habitat area of 925.35 km² under SSP2-4.5 and 809.17 km² under SSP5-8.5, reflecting reductions of 1,790.55 km² (-65.93%) and 1,906.73 km² (-70.21%), respectively. By 2070, suitable habitat areas are projected to decline further to 916.29 km² under SSP2-4.5 and only 302.41 km² under SSP5-8.5, corresponding to decreases of 1,799.62 km² (-66.26%) and 2,413.50 km² (-88.87%), respectively, when compared to the present suitable habitat area (Figure 6, Table 2).

Table 2. Area of suitable habitat for *Mantheyus phuwuanensis* across different suitability levels

Suitability	Present	2050				2070			
		SSP2-4.5		SSP5-8.5		SSP2-4.5		SSP5-8.5	
	km^2	km^2	%	km^2	%	km^2	%	km^2	%
Low	1,025.88	373.27 (-652.61)	-63.61	372.45 (-653.43)	-63.70	406.23 (-619.65)	-60.40	175.51 (-850.37)	-82.89
Medium	927.82	338.66 (-589.16)	-63.50	297.46 (-630.36)	-67.94	344.43 (-583.39)	-62.88	117.01 (-810.82)	-87.39
High	762.20	213.42 (-548.78)	-72.00	139.26 (-622.94)	-81.73	165.62 (-596.58)	-78.27	9.89 (-752.31)	-98.70
Total	2,715.90	925.352 (-1,790.55)	-65.93	809.17 (-1,906.74)	-70.21	916.29 (-1799.62)	-66.26	302.41 (-2,413.50)	-88.87

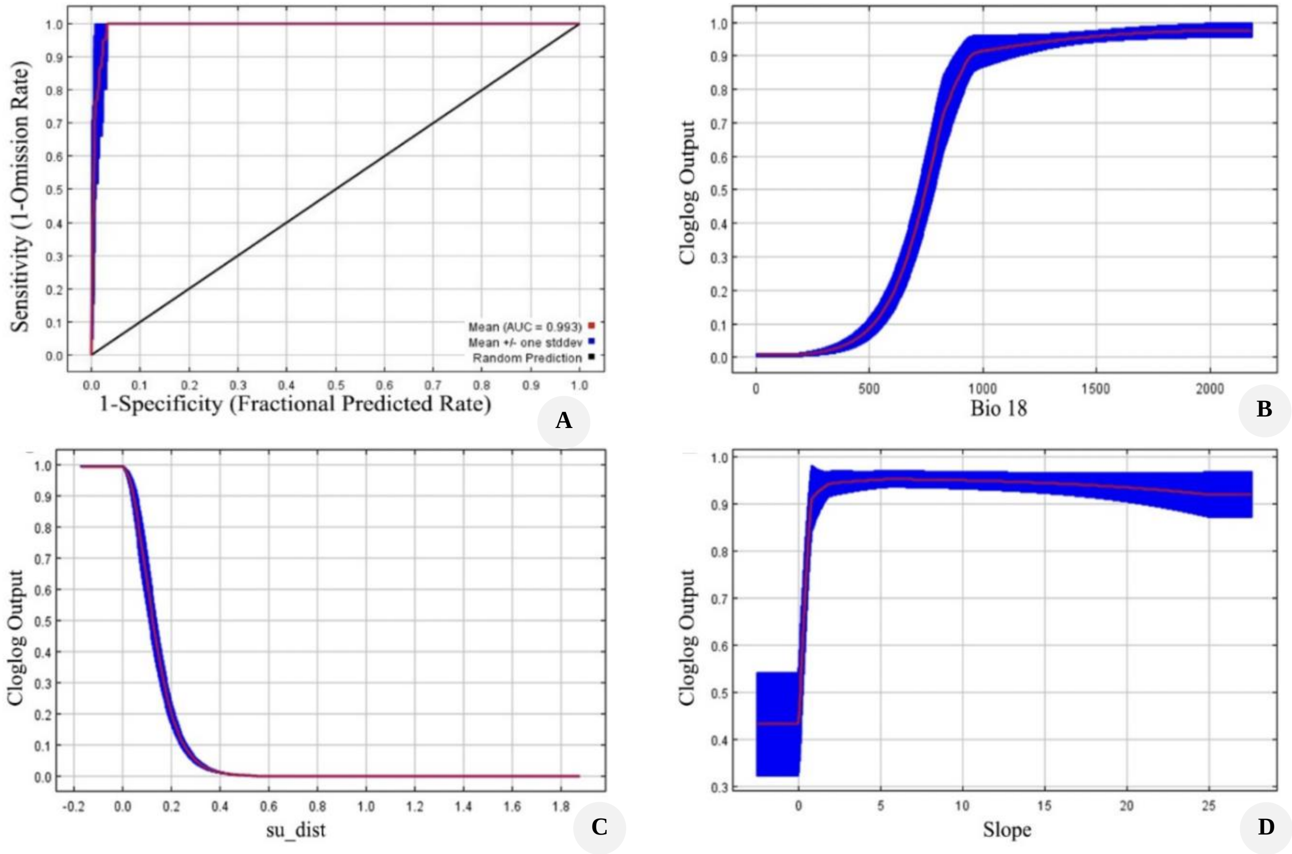

Figure 3. Receiver Operating Characteristic (ROC) curve and response curves for the MaxEnt model predicting the habitat suitability of *Mantheyus phuwuanensis*. The red line represents the mean response derived from the model, while the blue shaded area indicates the standard deviation: A. ROC curve showing the model's performance; B. Response curve illustrating the effect of precipitation of the warmest quarter (Bio18); C. Response curve for distance to unconsolidated sediments (su_dist); D. Response curve for Slope

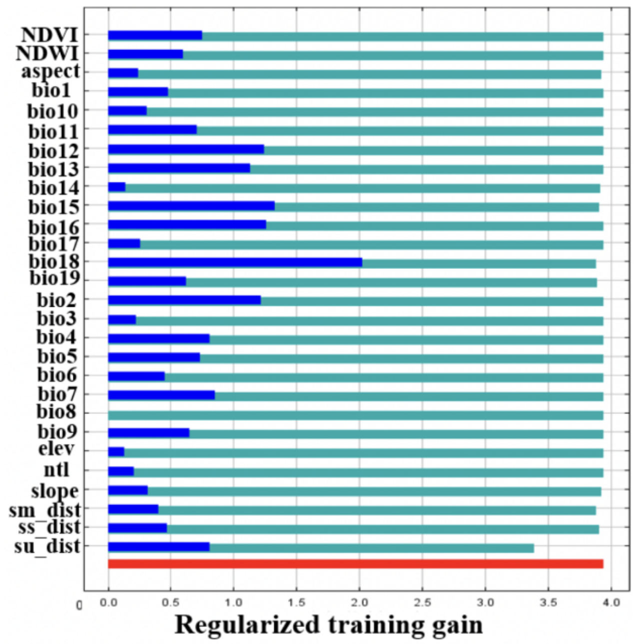

Figure 4. The jackknife method for evaluating environmental variable; the blue graph shows the model's performance with only the specified variable, the green graph represents performance when the variable is excluded, and red graph shows the performance with all variables included

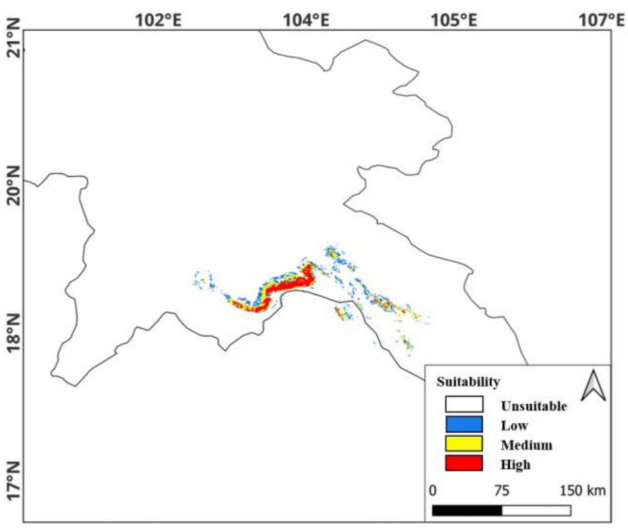

Figure 5. Predicted habitat suitability for *Mantheyus phuwuanensis* under current conditions

The decline is particularly severe under the SSP5-8.5 scenario, which predicts significant losses across all suitability categories. These findings highlight the vulnerability of *M. phuwuanensis* to climate change and the need for targeted conservation measures to mitigate habitat loss.

Future projections under climate change scenarios present significant challenges to the survival of *M. phuwuanensis*. Habitat losses are expected to exceed 88% by 2070 under the high-emission SSP5-8.5 scenario, driven by changes in precipitation patterns, habitat fragmentation, and reduced connectivity. These threats are particularly severe in Thailand, where the species is geographically restricted, highly vulnerable to environmental disturbances, and lacks legal protection under the Wild Animal Conservation and Protection Act (Wild Animal Conservation and Protection Act 2019). Despite its Near Threatened (NT) status on the IUCN Red List (IUCN 2025), *M. phuwuanensis* is not listed under CITES (2025), leaving it vulnerable to international trade pressures. In contrast, while the species benefits from more stable habitats in Laos, its dependence on sandstone ecosystems makes it equally susceptible to human activities. Our SDM analysis predicts significant declines in habitat suitability for *M. phuwuanensis* by 2050 and 2070, with climate-driven habitat degradation exacerbating existing conservation challenges. These factors amplify extinction risks, given the species' primitive evolutionary status, narrow ecological niche, and limited range (Chuaynkern and Duengkae 2014; Prayoon et al. 2021; Pomoim et al. 2022; Phommexay et al. 2024a).

Although land use and land cover changes may not currently be the primary factors influencing *M. phuwuanensis* habitat suitability, future alterations could affect its distribution. Protected forested areas, such as Phu Phan Forest Complex and Phu Wua Wildlife Sanctuary in Thailand, along with Phu Khao Khouay and Nam Kading National Biodiversity Conservation Areas in Laos, provide essential shelter and nesting sites within rocky ecosystems. However, human-induced disturbances, including deforestation and agricultural expansion, pose significant threats by fragmenting habitats and reducing available land for the species (Chuaynkern and Duengkae 2014). Additionally, urbanization and agricultural activities may create dispersal barriers and further degrade habitat quality (Laurance et al. 2011).

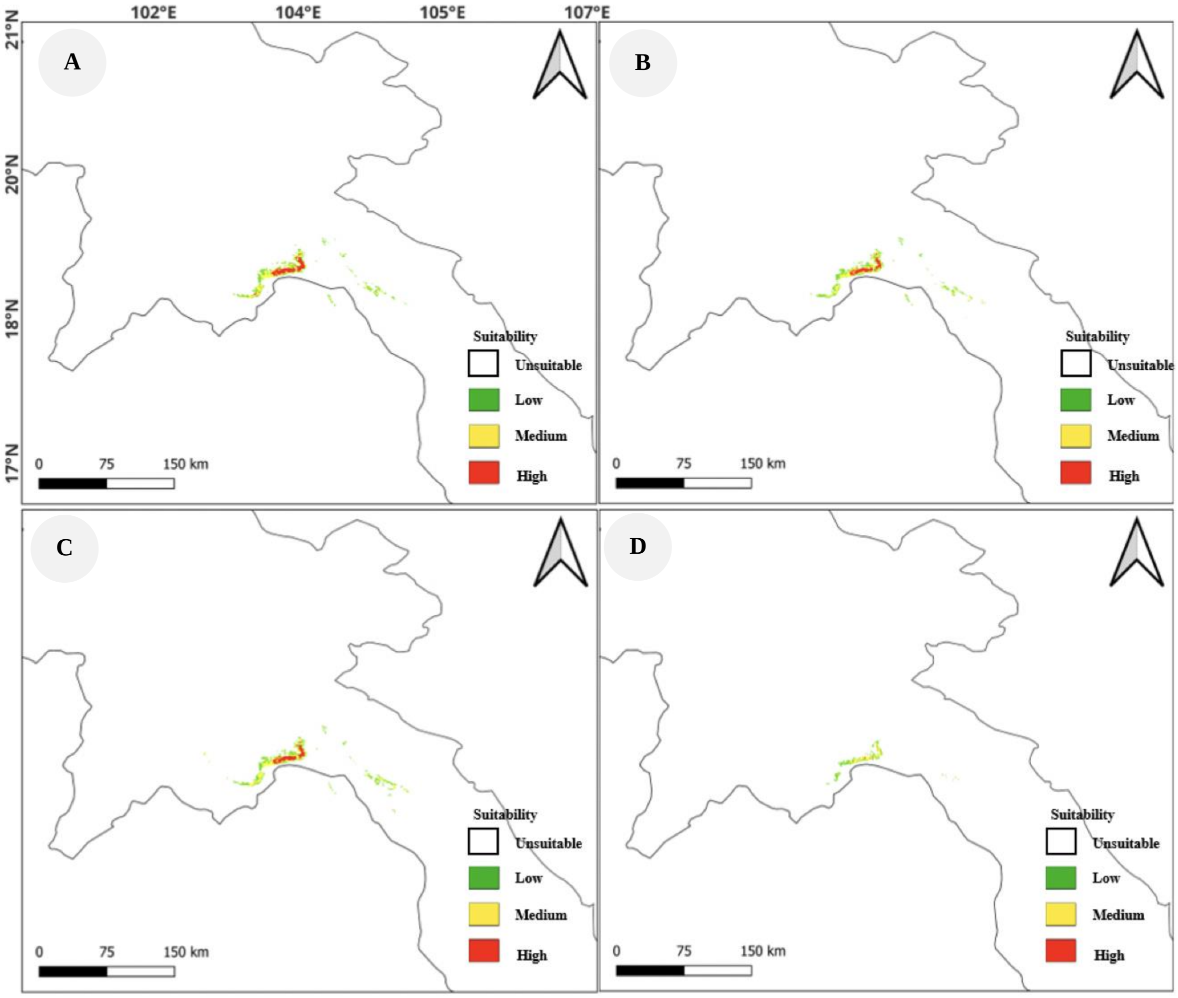

Figure 6. Future habitat suitability for *Mantheyus phuwuanensis* under climate change scenarios. A and B. Projections for 2050 under the SSP2-4.5 and SSP5-8.5 scenarios; C and D. Projections for 2070 under the SSP2-4.5 and SSP5-8.5 scenarios

To address these risks, we strongly advocate for the inclusion of *M. phuwuanensis* on Thailand's Protected Animals list to ensure effective habitat protection and strengthen conservation efforts. Due to the rapid increase in illegal wildlife trade for the pet industry (Chuaynkern and Duengkae 2014; Sas-Rofles et al. 2019), the species' status under CITES requires urgent revision. We recommend listing *M. phuwuanensis* under Category III of CITES to strengthen protection against international trade, address the escalating threats from illegal wildlife trafficking, and support ongoing conservation efforts for this vulnerable species. This increasing threat further exacerbates *M. phuwuanensis*' vulnerability, as its current lack of CITES listing leaves it unprotected from international trade pressures. Strengthening international trade regulations is crucial to curb exploitation and support ongoing conservation initiatives (Chuaynkern and Duengkae 2014). Public awareness campaigns and international collaboration are vital for the species' long-term survival. Future research should prioritize identifying climate-resilient habitats, conducting population viability assessments, and developing conservation breeding programs. Key conservation efforts must focus on protecting critical habitats (Pomoim et al. 2022), such as Phu Wua Wildlife Sanctuary, while implementing ecological restoration projects and establishing corridors to reconnect fragmented populations. Legal protection under Thai law is essential to mitigate habitat destruction, and ex-situ conservation programs could create assurance populations to prevent extinction. Immediate actions should include enhanced field surveys, genetic research, and long-term monitoring to guide effective conservation strategies and secure the species' future.

Based on the findings, *M. phuwuanensis* exhibits a highly restricted distribution across northeastern Thailand and western Laos, with its habitat closely tied to specific environmental factors, including precipitation during the warmest quarter, proximity to unconsolidated sediments, and slope. Current habitat suitability modeling reveals a limited total suitable area of 2,715.90 km² in Laos. However, projections for 2050 and 2070 under SSP2-4.5 and SSP5-8.5 scenarios predict significant habitat reductions, up to 88.87% loss by 2070. These results highlight the species vulnerability to climate change and underscore the urgent need for targeted conservation measures. To protect *M. phuwuanensis*, we recommend its inclusion in Thailand's Protected Animals list and an upgrade to Appendix III under CITES. Cross-border collaboration, habitat protection, and ecological restoration are essential to mitigate threats and secure survival. These findings emphasize the importance of integrating climate resilience into conservation planning for this species.

ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to the institutions and individuals who contributed to this study. We are especially thankful to Khon Kaen University (KKU) and the Department of National Parks, Wildlife, and Plant Conservation, Thailand, for their essential logistical support and resources in facilitating field surveys and data analysis. This study was approved by Kasetsart University Institutional Animal Care and Use Committee (IACUC), Thailand, under reference number ACKU66-SCI-019. The Research has received funding support from the Fundamental Fund of Khon Kaen University (2025) from National Science, Research and Innovation Fund or NSRF, Thailand. Additionally, we also acknowledge the financial support from the National Research Council of Thailand (NRCT) (N34E670115), the Centre of Excellence on Biodiversity (MHESI) (BDC-PG1-167003), and the Fundamental Fund of KKU 2024, all of which were critical in making this research possible. Lastly, we extend our thanks to the reviewers for their valuable feedback and suggestions, which significantly enhanced the quality of this manuscript.

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