

Present and future habitat suitability of an endemic tree frog, *Zhangixalus jarujini*, under climate change scenario

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Abstract. *Chuaynkern C, Khajitmathee N, Phochayavanich R, Maiphrom W, Phetcharat E, Chaiyes A, Duengkae P, Chuaynkern Y. 2025. Present and future habitat suitability of an endemic tree frog, Zhangixalus jarujini, under climate change scenario. Biodiversitas 26: 4445-4456. Zhangixalus jarujini*, a tree frog in the family Rhacophoridae and endemic to northeastern Thailand, is increasingly threatened by habitat degradation and the impacts of climate change. This study utilized ecological niche modeling with the Maximum Entropy (MaxEnt) algorithm to evaluate the species' current and future habitat suitability across Thailand, Laos, and Cambodia. A total of 16 confirmed occurrence records and 14 environmental variables were used to generate highly accurate models (mean AUC: 0.991±0.001). The most influential predictor variables were distance to water bodies (25.7%), precipitation seasonality (Bio15: 24.5%), precipitation of the warmest quarter (Bio18: 15.0%), normalized difference water index (NDWI: 13.3%), precipitation of the driest month (Bio14: 10.8%), and isothermality (Bio3: 9.2%). Under current conditions, the total area of suitable habitat was estimated at 9,964.58 km², comprising 5,837.82 km² of low suitability, 3,393.10 km² of medium suitability, and 733.67 km² of high suitability. Future projections, based on the ACCESS-CM2 climate model, were conducted under two Shared Socioeconomic Pathways: SSP2-4.5 and SSP5-8.5. By 2050, suitable habitat is projected to expand to 12,178.84 km² (22.22%) under SSP2-4.5 and 12,451.58 km² (24.96%) under SSP5-8.5. By 2070, it may reach 12,113.35 km² (21.56%) and 12,559.14 km² (26.44%) under the respective scenarios. High suitability areas are predicted to increase significantly, with a maximum of 1,228.58 km² under SSP5-8.5 by 2070, representing a 67.46% gain. The most influential environmental variables shaping habitat suitability were distance to water bodies, precipitation seasonality, and precipitation during the driest month. While these projections indicate a potential expansion of suitable habitat, actual population persistence may be constrained by ecological limitations, habitat fragmentation, and human pressures. Based on the model outputs and the availability of similar habitats in adjacent regions, this study strongly recommends systematic and intensive field surveys in Thailand, southern Laos, and northern Cambodia to identify potential undocumented populations and refine conservation priorities for *Z. jarujini*.

Keywords: Climate change, habitat suitability, MaxEnt, Mekong River, *Zhangixalus jarujini*

INTRODUCTION

The decline of global biodiversity, driven by anthropogenic pressures such as habitat destruction, overexploitation, invasive species, and climate change, has become a pressing environmental challenge (IPBES 2019; IPCC 2021; Pomoim et al. 2022; Prakash and Verma 2022). These factors contribute to habitat fragmentation, degradation, and population declines, placing endemic species at particularly high risk. Climate change is expected to exacerbate these threats by altering temperature and precipitation patterns, reducing habitat suitability, and disrupting ecological processes. In response, Species Distribution Models (SDMs), Ecological Niche Models (ENMs), and Habitat Suitability Models (HSMs) have been increasingly applied to predict shifts in suitable habitats.

However, the accuracy of these projections is often constrained by data gaps and model uncertainties (Araújo et al. 2019; Pomoim et al. 2022; Roy et al. 2022; Nandar et al. 2025). Improving modeling techniques and integrating multiple sources of evidence are therefore critical for refining predictions and guiding conservation efforts.

Zhangixalus jarujini, or Jarujin's treefrog, is a member of the family Rhacophoridae and is currently endemic to northeastern Thailand (Matsui and Panha 2006; Stuart et al. 2006; Thongproh et al. 2018, 2019; Frost 2025). The species was originally described by Matsui and Panha (2006) as *Rhacophorus jarujini*, based on specimens collected from Kalasin and Roi Et Provinces. It can be distinguished from congeners by a unique combination of characters. Its body size is relatively moderate, the dorsal surface is brownish with irregular dark marking, the third

finger has extensive webbing reaching the base of the disk or slightly less on the outer edge, and the fourth finger is webbed up to the distal subarticular tubercle or the base of the disk. Dermal projections are absent on the snout, vent, and heel. The type locality is Phu Si Than Wildlife Sanctuary in Kalasin Province, situated at 16°30'N, 104°10'E, at an elevation of 500 m asl. Subsequent studies by Stuart et al. (2006) and Kaewtongkum et al. (2014) provided detailed descriptions of the tadpole morphology and buccal anatomy, contributing knowledge of its larval characteristics. *Zhangixalus jarujini* was one misidentified as *R. orlovi* in northeastern Thailand, but this taxonomic confusion was resolved through re-examination of specimens from multiple localities (Thongproh et al. 2018), leading to the exclusion of *R. orlovi* from the Thai herpetofauna. Thongproh et al. (2018) confirmed that individuals previously reported as *R. orlovi* from Amnat Charoen and Ubon Ratchathani Provinces were in fact *Z. jarujini*. Their study also extended the species' known distribution to Phu Phan National Park, Sakon Nakhon Province, representing its northernmost record in Thailand. Ecological studies revealed that *Z. jarujini* tadpoles have a varied diet that includes microalgae, fungi-like organisms, diatoms, protozoa, and arthropods (Moonasa et al. 2018). At Yoddom Wildlife Sanctuary in Ubon Ratchathani Province, cannibalistic behavior was also documented, with tadpoles consuming dead conspecifics, a strategy likely influenced by environmental conditions and food availability (Moonasa et al. 2018).

Currently, *Z. jarujini* is known to occur at elevations between 163 and 500 m asl in northeastern Thailand, specifically in Kalasin, Roi Et, Amnat Charoen, Ubon Ratchathani, and Sakon Nakhon Provinces (Matsui and Panha 2006; Stuart et al. 2006; Kaewtongkum et al. 2014; Moonasa et al. 2018; Thongproh et al. 2018, 2019). However, these records may not fully represent the species' distribution. Similar habitats and elevations occur in neighboring regions, including southwestern Laos and northern Cambodia, suggesting the potential presence of *Z. jarujini* beyond Thailand (Frost 2025; IUCN 2025).

The forests of Indochina are rapidly deteriorating due to human activities, threatening biodiversity and disrupting critical ecosystem services (Duong and Cam 2021). For *Z. jarujini*, which depends on intact forests and specific microhabitats, this degradation poses a major threat to population persistence. Climate change further intensifies these risks, as shifts in temperature and precipitation may render parts of its already restricted range unsuitable. Amphibians are highly sensitive to temperature changes throughout their life cycle. The larval stage is particularly vulnerable, with thermal variation influencing growth, development, and survival. The metamorphic stage also responds strongly to temperature shifts, which can alter developmental timing and physiological performance (Deutsch et al. 2008). In response, many amphibians shift habitats or move to higher elevations to search for suitable environmental conditions (Duan et al. 2016). Understanding the habitat requirements of *Z. jarujini* and its potential responses to environmental changes is therefore essential for conservation (Araújo et al. 2019; Prayoon et al. 2021;

Phommexay et al. 2024a; Chuaynkern et al. 2025; Khajitmathee et al. 2025).

This study applies ENM to assess the current habitat suitability of *Z. jarujini* across Thailand, Laos, and Cambodia and to project the potential impacts of climate change and other environmental factors on its future distribution. Key environmental variables, including temperature, precipitation, and forest cover, are analyzed to identify factors influencing the species' distribution and to evaluate risks under future two climate scenarios (SSP2-4.5 and SSP5-8.5) for 2050 and 2070. The findings provide critical insights into the ecological requirements and vulnerabilities of *Z. jarujini* and inform conservation strategies such as habitat protection, restoration, and measures to mitigate the impacts of habitat loss and climate change. In the face of accelerating biodiversity loss, this study emphasizes the importance of active conservation planning to protect endemic species and maintain ecosystem integrity.

MATERIALS AND METHODS

Zhangixalus jarujini data occurrence

Occurrence records of *Z. jarujini* were compiled from multiple sources, including published literatures, museum collections, online databases, and field surveys conducted in northeastern Thailand. Literature-based records were gathered from taxonomic and distribution studies, e.g., Matsui and Panha (2006), Stuart et al. (2006); Thongproh et al. (2018, 2019), while museum specimens were examined from the herpetological collections of Khon Kaen University (Khon Kaen Province, northeastern Thailand) and the National Science Museum of Thailand (Pathum Thani Province, Central Thailand). Additional records were retrieved from online databases such as the Global Biodiversity Information Facility (GBIF; <https://www.gbif.org>) and iNaturalist (<https://www.inaturalist.org>).

Field surveys were conducted from 2022 to 2025 along the Mekong River in northeastern Thailand, focusing suitable habitats such as forests, wetlands, and national parks. Visual Encounter Surveys (VES) were carried out across the provinces of Bueng Kan, Kalasin, Khon Kaen, Loei, Mukdahan, Nong Khai, Phetchabun, Roi Et, Sakon Nakhon, Si Sa Ket, Ubon Ratchathani, and Udon Thani. Surveys focused primarily on protected areas, including the Phu Khiao-Nam Nao Forest Complex (Phu Khiao Wildlife Sanctuary, Chaiyaphum; Phu Luang Wildlife Sanctuary, Loei; Nam Nao National Park, Phetchabun; 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 (Phanom Dong Rak Wildlife Sanctuary, Si Sa Ket; Yoddom Wildlife Sanctuary, Ubon Ratchathani; Phu Jong-Na Yoi National Park, Ubon Ratchathani). Additional surveys were conducted in Phu Wua Wildlife Sanctuary and in non-protected areas of Bueng Kan Province, as well as at six sites under the Plant Genetic Conservation Project, initiated by Her Royal Highness Princess Maha Chakri Sirindhorn

and managed by Khon Kaen University. These sites included Chulabhorn Dam and Huai Kum Dam in Chaiyaphum Province, Khok Phu Taka Forest and Ubolratana Dam in Khon Kaen Province, and Sirindhorn Dam in Ubon Ratchathani Province.

Geographic coordinates were recorded for each confirmed occurrence using a handheld GPS. To minimize misidentification, specimens and clear photographic evidence were evaluated against the species diagnosis, including moderate body size, a brownish dorsum with irregular dark markings, and distinctive webbing on the third and fourth fingers (Matsui and Panha 2006). All records were carefully verified for accuracy, and duplicate or erroneous data points were excluded. In total, 16 confirmed presence records were retained for habitat suitability modeling.

Environmental variables

To investigate the ecological niche of *Z. jarujini*, environmental variables were compiled for Thailand, Laos, and Cambodia. Although the species is currently considered endemic to northeastern Thailand (Matsui and Panha 2006; Stuart et al. 2006; Thongproh et al. 2018, 2019), it may also occur in adjacent areas of Laos and Cambodia, though this remains unconfirmed (Frost 2025; IUCN 2025).

An initial set of 26 environmental variables was compiled, representing climatic, topographic, hydrological, and vegetation-related factors. The study area, which includes northeastern Thailand, southern Laos, and northern Cambodia, features a heterogeneous landscape of lowland floodplains, gently rolling plateaus, and isolated uplands. This variation strongly influences microclimatic conditions and species distributions. For this reason, slope and aspect were included as key predictors. Slope reflects changes in elevation, influencing runoff, erosion, soil stability, and microclimate, while aspect determines solar radiation exposure, which in turn affects local temperature and moisture availability (Wilson et al. 2007). These parameters are widely applied in ecological niche modeling, particularly for amphibians, which are highly sensitive to variation in temperature and humidity (Elith and Leathwick 2009; Sillero and Barbosa 2021).

Climatic data included of 19 bioclimatic variables related to temperature and precipitation, obtained from the WorldClim database (<http://worldclim.org>) at a spatial resolution of 30 arc-seconds. Elevation (Digital Elevation Model) data were also sourced from WorldClim, while slope and aspect were derived using the 'terra' package in R version 4.4.1. Distance to water bodies was calculated using datasets from ArcGIS (<https://www.arcgis.com>) and processed in R. Vegetation indices, including the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI), were derived from Landsat 8 imagery (2014-2024) via Google Earth Engine (<https://www.usgs.gov>). Percent Tree Cover (PTC) was obtained from the Geospatial Information Authority of Japan and Chiba University.

To minimize multicollinearity among predictors, pairwise Pearson correlation coefficients were calculated in

R version 4.4.1. Variables with $|r| \geq 0.8$ were considered highly correlated, and one variable from each correlated pair was excluded. Statistical significance was also tested ($p < 0.05$). This procedure followed Shrestha (2020), Sillero and Barbosa (2021), and Tran et al. (2023). Based on these criteria, a final set of 12 predictors was retained for modeling: Bio2, Bio3, Bio8, Bio14, Bio15, Bio16, Bio18, slope, aspect, distance to water body, NDWI, and PTC (Table 1).

Ecological Niche Modeling (ENM)

We developed an ecological niche model for *Z. jarujini* using the Maximum Entropy algorithm implemented in MaxEnt version 3.4.4 (https://biodiversityinformatics.amnh.org/open_source/maxent/). MaxEnt is a widely recognized and robust machine-learning method for SDM (Prayoon et al. 2021; Booth 2024, 2025; Phommexay et al. 2024a; Chuaynkern et al. 2025). It was selected for several reasons. First, MaxEnt is a presence-only model, making it particularly suitable for our dataset of 16 verified occurrence records, which lacks true absence data. Second, it has demonstrated strong predictive performance even with small sample sizes, a common limitation when studying rare or range-restricted species. Third, MaxEnt can model complex, non-linear relationships between species occurrences and environmental predictors, providing a nuanced representation of the ecological niche of *Z. jarujini*.

To reduce overfitting and improve accuracy, we used the kuenm package in R version 4.4.1 (Peterson et al. 2018; Cobos et al. 2019) for parameter tuning and systematic model selection. Occurrence records were randomly partitioned into 70% for training and 30% for testing. A total of 279 candidate models were gathered by varying regularization multiplier (1.0-5.0 at 0.5 intervals) and testing all 29 possible feature-class combinations with 10,000 background points. Model optimization followed the multi-step kuenm framework: first, assessing statistical significance using Area Under the Curve (AUC) and omission rates; then retaining models within acceptable omission thresholds; and finally selecting models with $\Delta AICc$ (Akaike Information Criterion corrected for small sample size) < 2 to balance complexity and predictive power.

Table 1. The environmental variables used to generate Ecological Niche Modeling (ENM) for *Zhangixalus jarujini* in Thailand, Laos, and Cambodia

Environmental variables	Description
Bio2	Mean diurnal range
Bio3	Isothermality
Bio8	Mean temperature of wettest quarter
Bio14	Precipitation of driest month
Bio15	Precipitation seasonality
Bio16	Precipitation of wettest quarter
Bio18	Precipitation of warmest quarter
Slope	Degree of rise/run
Aspect	Direction a slope face
Dist_water	Distance to water bodies
NDWI	Normalized difference water index
PTC	Percent tree cover

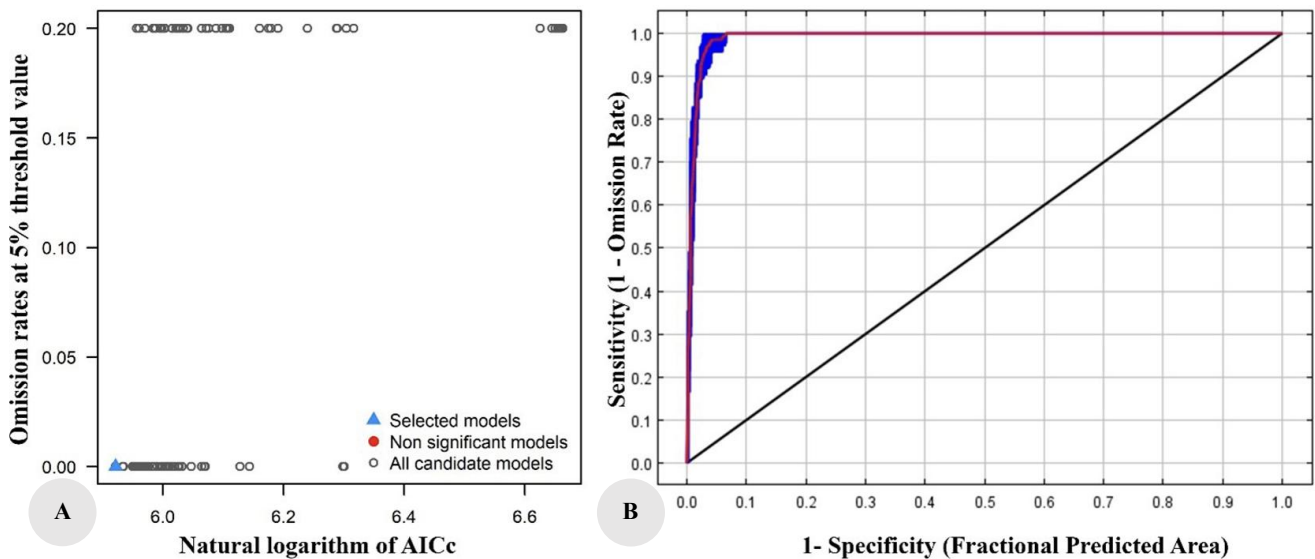


Figure 1. Model selection and performance evaluation for *Zhangixalus jarujini* ecological niche modeling using MaxEnt and the kuenm package. A. Scatterplot of omission rates at the 5% training presence threshold plotted against the natural logarithm of AICc values for all 279 candidate models. Blue triangles represent statistically significant selected models, red circles indicate non-significant models, and gray circles denote all candidate models. The selected model had the lowest omission rate (0) and the lowest delta AICc. B. Partial Receiver Operating Characteristic (ROC) curve showing the average sensitivity (1-omission rate) versus 1-specificity (fractional predicted area). The model achieved a high mean AUC value of 0.991 ± 0.001 across 10 replicates, indicating excellent predictive performance

The final model was calibrated using all 16 occurrence records, with 11 points for training and 5 points for testing, based on the selected predictors. The best-performing model applied a Linear (L) feature class with a regularization multiplier of 1.5. This model achieved an omission rate of 0, an AICc value of 373.21, Δ AICc of 0, and an AICc weight of 0.006, using seven parameters (Figure 1.A). The omission rate of 0 indicates excellent predictive ability, and the model also passed the partial ROC (Receiver Operating Characteristic) test with statistical significance ($p < 0.05$). Across 10 replicates, the model produced an average AUC of 0.991 ± 0.001 (Figure 1.B), reflecting outstanding performance (Prayoon et al. 2021; Phommexay et al. 2024a). This comprehensive evaluation, which combined AUC, omission rates, and AICc, confirmed that the chosen model achieved the best trade-off between accuracy and parsimony. Therefore, it was regarded as the most reliable predictor of the ecological niche of *Z. jarujini* (Cobos et al. 2019).

For future climate projections, we used bioclimatic variables derived from the ACCESS-CM2 global climate model, developed under the sixth phase of the Coupled Model Intercomparison Project (CMIP6). ACCESS-CM2, created by the Australian Community Climate and Earth-System Simulator, has proven reliable in simulating regional climate processes in Southeast Asia. Two Shared Socioeconomic Pathway (SSP) scenarios were applied: SSP2-4.5, an intermediate pathway with moderate mitigation and socioeconomic trends, and SSP5-8.5, a fossil fuel-intensive high-emission pathway with minimal climate mitigation. These contrasting scenarios enabled

evaluation of how different climate trajectories may affect the future distribution of *Z. jarujini*.

RESULTS AND DISCUSSION

Current distribution of *Zhangixalus jarujini*

This study documents 16 confirmed occurrence points of *Z. jarujini* across northeastern Thailand. These records include Yoddom Wildlife Sanctuary, Ubon Ratchathani Province (2 points), Phanom Dong Rak Wildlife Sanctuary, Si Sa Ket Province (1 point), Phu Chong-Na Yoi National Park, Ubon Ratchathani Province (4 points), Pha Taem National Park, Ubon Ratchathani Province (1 point), Phu Sing-Phu Pha Phung Forest Park, Amnat Charoen Province (1 point), Tham Pha Nam Thip Non-hunting Area, Roi Et Province (2 points), Phu Phan National Park, Sakon Nakhon Province (3 points), and Phu Si Than Wildlife Sanctuary, Mukdahan Province (1 point) (Figure 2.A).

Since the species was first described as *R. jarujini* by Matsui and Panha (2006), available knowledge has remained relatively limited. Most subsequent studies have focused on narrow aspects such as buccopharyngeal anatomy (Stuart et al. 2006; Kaewtongkum et al. 2014), diet and prey items (Moonasa et al. 2018; Thongproh et al. 2019), distribution range (Thongproh et al. 2018), and taxonomic relationships (Jiang et al. 2019; Mahony et al. 2024). Other information has been derived from broader studies on amphibian fauna and regional checklists (Niyomwan et al. 2019; Poyarkov et al. 2021; Makchai et al. 2023).

The present study adds new insights by confirming the occurrence of *Z. jarujini* at 16 localities, most of which are situated within in protected areas, such as national parks and wildlife sanctuaries. Notable sites include Yoddom Wildlife Sanctuary, Phu Chong-Na Yoi National Park, and Pha Tam National Park, all in Ubon Ratchathani Province. This concentration of records suggests that the species depends on forested habitats within conservation areas for its persistence (Matsui and Panha 2006; Stuart et al. 2006; Kaewtongkum et al. 2014; Thongproh et al. 2018, 2019; Moonasa et al. 2018). The distribution across multiple provinces, including Ubon Ratchathani, Amnat Charoen, Sakon Nakhon, Mukdahan, and Roi Et, indicates that *Z. jarujini* occupies a wider range than previous recognized. The northernmost record reported here is from Sreee Thai Cave, Huai Yang Sub-district, Kut Bak District, Sakon Nakhon Province (17.100226°N, 103.973258°E).

The northeastern Mekong River region includes four major forest complexes: Phu Meang-Phu Thong (3,673 km²), Phu Khiao-Nam Nao (7,092 km²), Phu Phan (2,369 km²), and Phanom Dong Rak-Pha Taem (3,069 km²), covering approximately 16,203 km² in total (Pomoim et al. 2022). Despite their ecological importance, these areas have not been surveyed intensively or systematically for amphibians, and species richness is likely underestimated (Stuart et al. 2006; Thongproh et al. 2018; Phimmachak et al. 2019; Poyarkov et al. 2021).

Currently, *Z. jarujini* is considered endemic to northeastern Thailand. However, the tri-border region of northeastern Thailand, southern Laos, and western Cambodia may also support undiscovered populations of the species (Figure 2.B). These neighboring areas remain poorly studied, and the availability of suitable habitats indicates that *Z. jarujini* could extend beyond its presently known distribution. Comprehensive and long-term field surveys are therefore needed, particularly in forested landscapes along the Mekong River and adjacent transboundary regions, to refine knowledge of the species' range and inform effective conservation strategies.

Zhangixalus jarujini habitat suitability

This study identified the key environmental variables influencing the habitat suitability of *Z. jarujini* (Figure 3). The most influential factor was distance to water bodies (25.7%; mean: 4.72±2.21 km; range: 1.41-9.54 km), followed by precipitation seasonality (Bio15: 24.5%; mean: 95.83±0.87; range: 93.83-97.04), precipitation of the warmest quarter (Bio18: 15.0%; mean: 365.27±98.27 mm; range: 282.00-528.00 mm), the Normalized Difference Water Index (NDWI: 13.3%; mean: -0.72±0.06; range: -0.78 to -0.57), precipitation of the driest month (Bio14: 10.8%; mean: 1.55±0.82 mm; range: 1.00-3.00 mm), and isothermality (Bio3: 9.2%; mean: 53.89±1.92%; range: 50.93-55.81%).

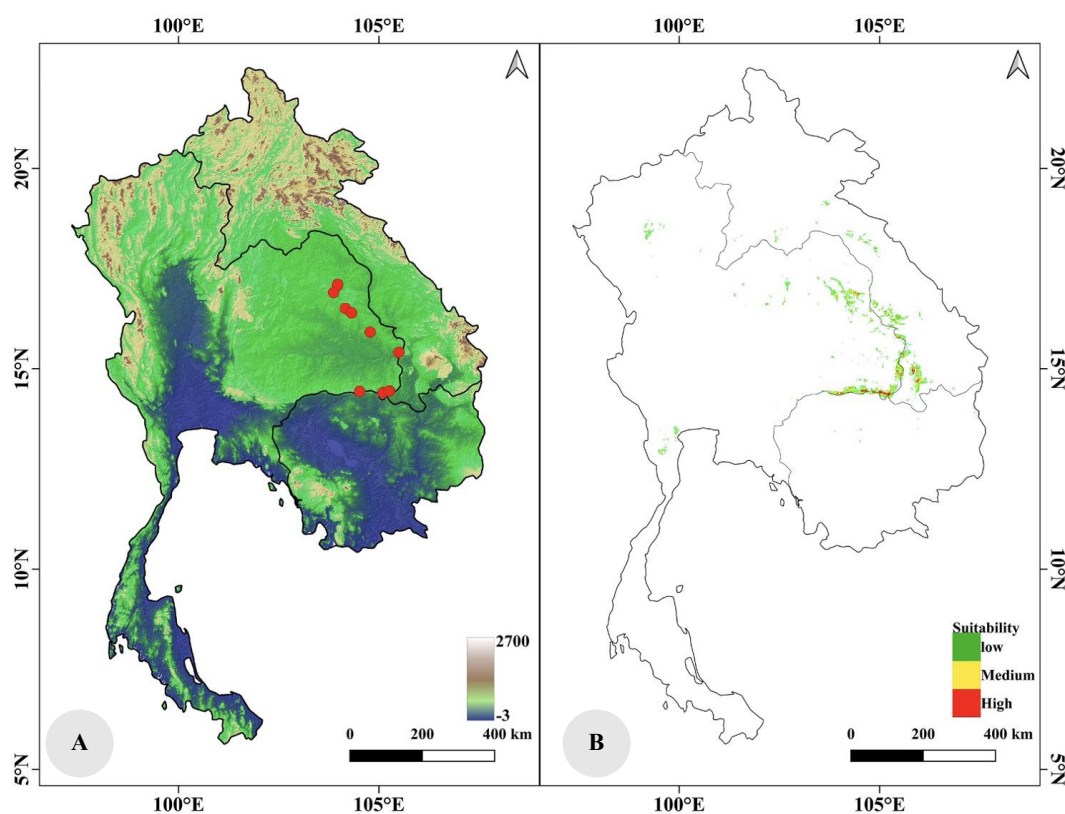


Figure 2. A. Elevation map showing geographic locations of *Zhangixalus jarujini* occurrence records (red dots); B. Current habitat suitability of *Z. jarujini* across Thailand, Laos, and Cambodia, classified into low (green), medium (yellow), and high (red) suitability levels

The jackknife test further identified Bio14 (precipitation of the driest month) as the single most influential variable for habitat suitability. When considered alone, Bio14 produced the highest model gain, indicating that it provided the most unique and information. Conversely, removing distance to water bodies resulted the largest decrease in model gain, suggesting that this variable contains critical information not provided by any other variable. These results emphasize that both precipitation during dry periods and proximity to water sources are central to determining the distribution of *Z. jarujini*. All values reported represent averages across replicate model runs (Figure 4).

The habitat suitability model for *Z. jarujini* reveals a specialized ecological niche defined by the interaction of local hydrology, monsoonal climate, and topography. The most influential variable is distance to water bodies (25.7%), highlighting its dependence on aquatic environments for laying foam nests (Matsui and Panha 2006; Stuart et al.

2006; Kaewtongkum et al. 2014; Thongproh et al. 2018). This is further supported by the Normalized Difference Water Index (NDWI), which reflects a preference for moderately moist habitats rather than waterlogged areas. Climatic conditions also play a significant role, with precipitation seasonality (Bio15) contributing 24.5% as the second-most important predictor. The species thrives where seasonal rains initiate breeding but avoids habitats with excessive rainfall during the warmest months (Bio18). It is also adapted to survive dry periods (Bio14) by retreating to humid refuges such as sandstone caves (Thongproh et al. 2018). Elevation further shapes the niche by influencing temperature, humidity, and vegetation structure (Zhao et al. 2022; Hardy et al. 2023; Lenzi et al. 2024). This study found *Z. jarujini* within a mid-elevation range of 173 to 396 meters above sea level, consistent with previous records in deciduous dipterocarp and dry evergreen forests, which provide balanced ecological conditions (Matsui and Panha 2006; Stuart et al. 2006; Thongproh et al. 2019).

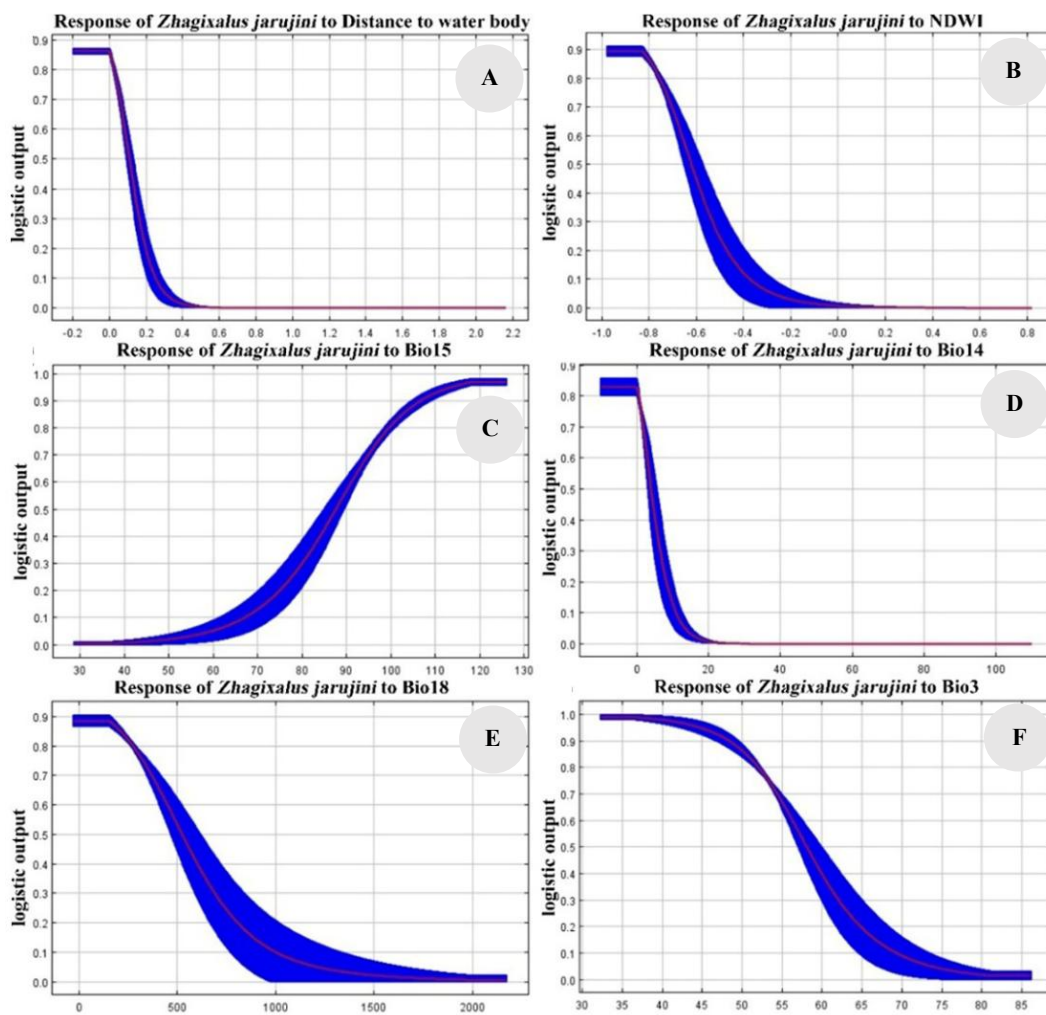


Figure 3. Response curves showing the influence of environmental variables on the predicted probability of *Zhangixalus jarujini* occurrence, generated by the MaxEnt model. The red line represents the mean logistic output, while the blue shaded area indicates the standard deviation. Variables include: A. Distance to water body, B. NDWI, C. Bio15 (precipitation seasonality), D. Bio14 (precipitation of driest month), E. Bio18 (precipitation of warmest quarter), and F. Bio3 (isothermality)

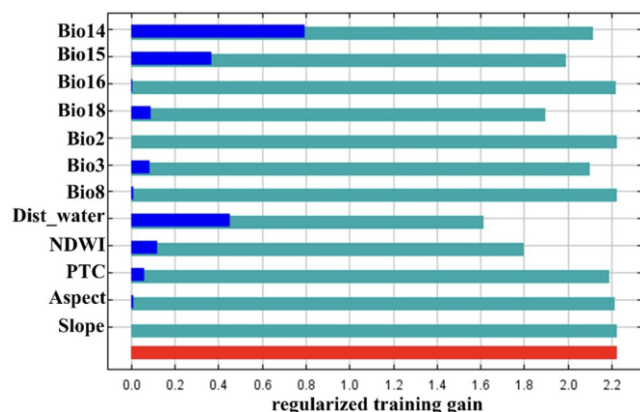


Figure 4. Jackknife test of regularized training gain showing the importance of individual environmental variables in modeling the habitat suitability of *Zhangixalus jarujini*. The turquoise bars represent the training gain when each variable is used in isolation, indicating the unique contribution of that variable. The blue bars show the training gain when each variable is excluded from the full model, illustrating how much the model depends on that variable. The red bar represents the regularized training gain when all variables are used together. Bio14 (Precipitation of the Driest Month) had the highest gain when used alone, while the exclusion of distance to water bodies (Dist_water) caused the greatest drop in training gain, highlighting its unique contribution to the model.

Although local hydrology and mid-elevation range define the ecological niche of *Z. jarujini*, comparative studies reveal that environmental drivers differ significantly among amphibians. The prominence of hydrological variables in this species is especially notable when contrasted with broad-scale climatic predictors in other taxa. For example, a comparative analysis of four *Hylarana* species demonstrated distinct climatic determinants. The distribution of *H. tyleri* was strongly influenced by annual precipitation (48% contribution), whereas the niches of *H. erythraea* and *H. taipehensis* were overwhelmingly shaped by temperature seasonality (85% and 42% contribution, respectively) (Laurence et al. 2023). These differences within a single genus emphasize that although amphibians are generally dependent on moisture, the primary limiting environmental factor can vary substantially. Similar contrasts are reported in other amphibians. The Lao newt (*Laotriton laoensis*) is primarily restricted by high-altitude stability rather than proximity to water (Chunco et al. 2013). *Odorrana aureola* occupies a higher elevational range of 1,000–1,600 meters above sea level (Stuart et al. 2006; Chuaynkern et al. 2010). The Chinese forest frog (*Rana chensinensis*) is more strongly restricted by large-scale climatic factors than by local hydrology or elevation (Fu et al. 2025).

To identify suitable and unsuitable habitats for *Z. jarujini*, we applied the 10th percentile training presence logistic threshold of 0.52 (Tran et al. 2023; Chuaynkern et al. 2025). Habitat suitability was then categorized into three levels: low (0.52–0.68), medium (0.68–0.84), and high (>0.84). The total suitable area within the study region was estimated at 9,964.58 km², including 5,837.82 km² of low suitability, 3,393.10 km² of medium suitability, and 733.67 km² of high suitability (Figure 2.B; Table 2). This

distribution pattern likely influenced by the availability of suitable habitats, particularly moist, forested environments that are essential for breeding and survival. The occurrence of the species across different types of protected areas, including national parks, wildlife sanctuaries, and non-hunting areas, also suggests adaptability to a variety of habitat types. However, predictions based on a limited number of occurrence records must be interpreted with caution. When sample sizes are small, suitable habitats may be underestimated or entirely overlooked, particularly for cryptic or under-surveyed species. Van Proosdij et al. (2016) demonstrated that a minimum threshold of records is necessary to generate robust and accurate species distribution models, highlighting the limitations and potential biases of modeling with restricted datasets.

Despite these challenges, the consistent detection of *Z. jarujini* in several protected areas suggests that these locations may function as important refuges for the species. Nevertheless, further research is needed to identify the specific environmental factors most strongly influencing its distribution and to assess potential threats such as habitat degradation and fragmentation. The presence of populations in relatively isolated areas raises concerns about connectivity, gene flow, and the risks of inbreeding or genetic bottlenecks, particularly where dispersal opportunities are limited. Intensive surveys along the Mekong River in Thailand, Laos, and Cambodia are necessary to uncover additional occurrence records and better define the distribution estimates. Integrating spatial modeling with long-term field surveys and population monitoring will be critical for improving predictive accuracy and informing conservation efforts. This study offers essential baseline information on *Z. jarujini* and highlights the importance of continued ecological research and habitat protection to ensure its long-term survival.

Predicted future habitat suitability under climate scenarios

The ACCESS-CM2 model projected future habitat suitability for *Z. jarujini* in 2050 and 2070 under two climate change scenarios (Figures 5 and 6): SSP2-4.5 and SSP5-8.5. By 2050, suitable habitat is predicted to increase from 9,964.58 km² (present) to 12,178.84 km² under SSP2-4.5 and 12,451.58 km² under SSP5-8.5, representing gains of 2,214.26 km² (22.22%) and 2,487.00 km² (24.96%), respectively (Figures 5.A, 5.B; Table 2). The largest proportional increase is projected in the high suitability class, which expands from 733.67 km² to 1,192.93 km² (62.60%) under SSP2-4.5 and to 1,049.51 km² (43.05%) under SSP5-8.5. By 2070, total suitable habitat is expected to remain higher than present levels, reaching 12,113.35 km² under SSP2-4.5 and 12,559.14 km² under SSP5-8.5, corresponding to increases of 2,148.77 km² (21.56%) and 2,634.56 km² (26.44%), respectively (Figures 5.C, 5.D; Table 2). High suitability areas also increase, reaching 961.64 km² (31.07%) under SSP2-4.5 and 1,228.58 km² (67.46%) under SSP5-8.5.

Across all scenarios, areas of low, medium, and high suitability areas expand relative to the present conditions, with the most substantial gains under SSP5-8.5. The rank order of expansion is 2070 under SSP5-8.5 > 2050 under SSP5-8.5 > 2050 under SSP2-4.5 > 2070 under SSP2-4.5.

These results suggest a sustained increase in suitable habitat, with SSP5-8.5 providing the largest gains, particularly in high-suitability areas (Figure 6; Table 2). The overall expansion of suitable habitat contrasts with projections for many amphibians, which often face range contractions under climate change. For *Z. jarujini*,

ecological flexibility and the ability to exploit warmer and wetter environments projected by the ACCESS-CM2 model may underlie this positive trend. This finding aligns with previous studies showing that some amphibians, particularly arboreal or generalist taxa, may benefit from climate-driven habitat shifts (Button et al. 2025).

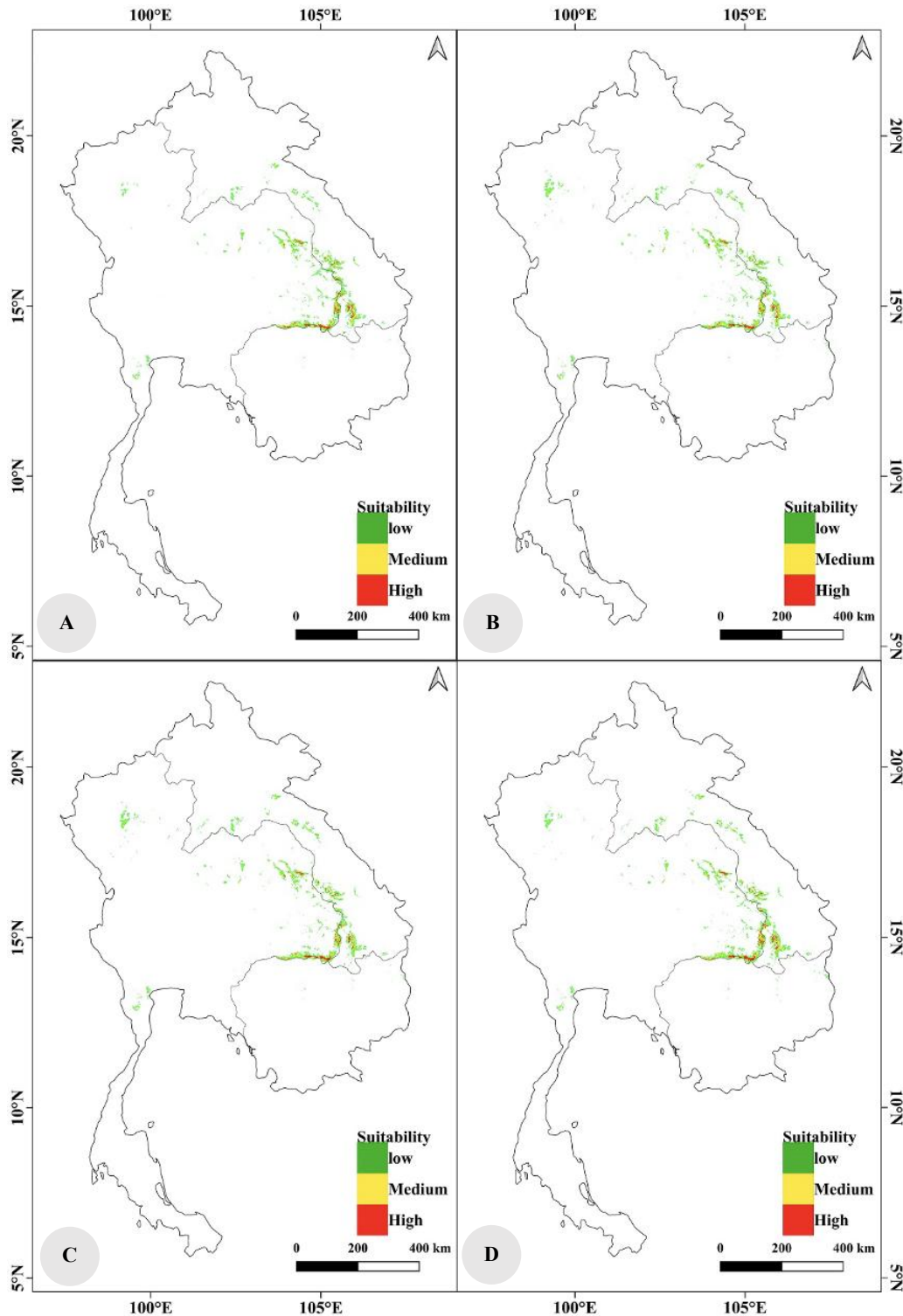


Figure 5. Future habitat suitability predictions for *Zhangixalus jarujini* under climate change scenarios: A, B: For 2050 under SSP2-4.5 and SSP5-8.5; C, D: For 2070 under SSP2-4.5 and SSP5-8.5

Table 2. Estimated suitable and unsuitable habitat areas (in km²) for *Zhangixalus jarujini* under current and future climate scenarios (SSP2-4.5 and SSP5-8.5) for the years 2050 and 2070 across the study region. Values in parentheses indicate the change in area (km²) compared to the present, and percentages represent the proportional change relative to current suitable habitat

Suitability	Present	2050				2070			
		SSP2-4.5		SSP5-8.5		SSP2-4.5		SSP5-8.5	
		km ²	%	km ²	%	km ²	%	km ²	%
Low	5,837.82	6,929.61 (1,091.79)	18.70	7,425.35 (1,587.54)	27.19	7,324.22 (1,486.40)	25.46	7,354.06 (1,516.24)	25.97
Medium	3,393.10	4,056.30 (663.20)	19.55	3,976.71 (583.62)	17.20	3,827.49 (434.40)	12.80	4,016.51 (623.41)	18.37
High	733.67	1,192.93 (459.27)	62.60	1,049.51 (315.85)	43.05	961.64 (227.98)	31.07	1,228.58 (494.91)	67.46
Total	9,964.58	12,178.84 (2,214.26)	22.22	12,451.58 (2,487.00)	24.96	12,113.35 (2,148.77)	21.56	12,559.14 (2,634.56)	26.44
Unsuitable	920,558.91	918,344.65 (-2,214.26)	-0.24	918,071.91 (-2,487.00)	-0.27	918,410.14 (-2,148.77)	-0.23	917,924.34 (-2,634.56)	-0.29

It is important to note, however, that SSP5-8.5 is a high-emission scenario characterized by continued reliance on fossil fuels, limited climate mitigation, and rapid economic growth (IPCC 2021). Under this scenario, global greenhouse gas emissions projected to rise throughout the 21st century, leading to substantial increases in global temperatures and, in some regions, intensified precipitation. In parts of Southeast Asia, such climatic changes may temporarily benefit tropical forest-dependent species such as *Z. jarujini* by expanding areas with warmer and wetter conditions (Warren et al. 2018). Nevertheless, SSP5-8.5 does not represent a pathway toward effective climate change mitigation or a solution to global warming. Rather, it assumes minimal international policy action and follows the highest emissions trajectory, making it widely regarded as a worst-case or business-as-usual scenario in climate impact assessments (Hausfather and Peters 2020). Although this scenario predicts substantial gains in suitable habitat for *Z. jarujini*, it also entails long-term ecological risks, including extreme weather events, habitat degradation, and biodiversity loss (Urban 2015). Thus, SSP5-8.5 should not be interpreted as favorable from a conservation or policy perspective. Lower-emission pathways such as SSP1-2.6 or SSP2-4.5, which emphasize climate mitigation and sustainable development, remain critical for safeguarding ecosystems more broadly (Hausfather and Peters 2020; IPCC 2021).

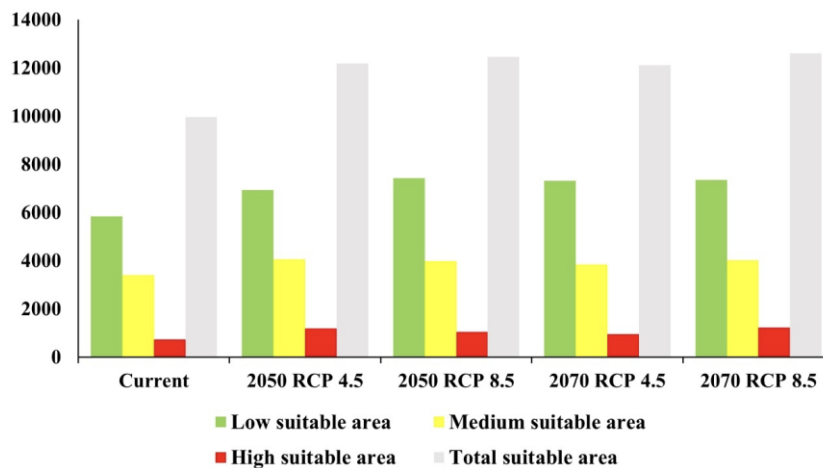
At the regional scale, suitable habitat for *Z. jarujini* is projected to increase in Thailand, Laos, and Cambodia, with the exception of Cambodia in 2050 under SSP5-8.5, where a decrease is predicted. The largest gains are projected for Laos and Cambodia in 2070 under SSP5-8.5, while in Thailand the maximum increase occurs in 2050 under SSP5-8.5. Overall, Laos shows the greatest projected expansion, followed by Thailand and Cambodia (Table 3), with suitable areas generally concentrated near or overlapping with current distributions. Although these results suggest an ecological niche expansion, the quality of newly suitable habitats remains uncertain, as colonization may be limited by dispersal barriers, biotic interactions, or human disturbances (Araújo et al. 2019). Field-based assessments, long-term monitoring, and surveys in highly suitable but unprotected forests, such as those in Champasak Province, Laos, are therefore essential. Species distribution models

(SDMs) continue to serve as powerful tools for amphibian, reptile, and mammal conservation (Pomoin et al. 2022; Tran et al. 2023; Phommexay et al. 2024a, b; Chuaynkern et al. 2025; Khajitmathee et al. 2025). For instance, SDMs for *Mantheyus phuwanensis* predict reductions and fragmentation of suitable habitat under climate change, while *Cyrtodactylus angularis* is projected to lose up to 90.30% of suitable habitat by 2070 (Khajitmathee et al. 2025). Similarly, models for the critically endangered northern white-cheeked gibbon (*Nomascus leucogenys*) forecast a dramatic contraction, with suitable habitat in Laos shrinking to only 0.3% of its current extent by 2070 (Phommexay et al. 2024a). These examples demonstrate that, unlike *Z. jarujini*, many species are expected to undergo severe range reductions, underscoring the importance of targeted conservation measures to address habitat loss, hunting, and climate change.

The insights derived from these SDMs are critical for conservation planning, as they identify regions of high habitat suitability and highlight areas at greatest risk from environmental changes. For instance, the predicted habitat contraction for *C. angularis* emphasizes the need for proactive conservation strategies that focus on key refugia, such as the Phu Khiao-Nam Nao and Dong Phaya Yen-Khao Yai Forest Complexes, which are essential for maintaining viable populations of this gecko species. Likewise, the projected reduction of suitable habitat for *N. leucogenys* in Laos underscores the importance of expanding protected areas and implementing effective habitat restoration programs to ensure the species' survival. Furthermore, these models can guide future monitoring efforts by pinpointing areas that require more intensive surveys to track changes in species populations and habitat quality. Ultimately, SDMs serve as powerful tools in identifying conservation priorities, informing decisions about land use, and ensuring that conservation resources are directed to areas where they are most needed (Phommexay et al. 2024a; Chuaynkern et al. 2025; Khajitmathee et al. 2025; Nandar et al. 2025). By integrating these models with other conservation tools, authorities and organizations can develop more effective, data-driven strategies to mitigate the impact of climate change and human activities on vulnerable species such as *M. phuwanensis*, *C. angularis*, and *N. leucogenys*.

Table 3. Comparison of suitable habitat areas under current and future climate scenarios (SSP2-4.5 and SSP5-8.5) for the years 2050 and 2070 in three countries: Thailand, Laos, and Cambodia

Country	Present km ²	2050				2070			
		SSP2-4.5		SSP5-8.5		SSP2-4.5		SSP5-8.5	
		km ²	%	km ²	%	km ²	%	km ²	%
Thailand	5,798.03	6,575.63 (777.60)	13.41	6,978.52 (1,180.50)	20.36	6,800.29 (1,002.26)	17.29	6,664.33 (866.30)	14.94
Laos	3,767.81	5,204.46 (1,436.66)	38.13	5,097.52 (1,329.72)	35.29	4,875.35 (1,107.54)	29.39	5,417.52 (1,649.71)	43.78
Cambodia	398.75	398.75 (0)	0	375.54 (-23.21)	-5.82	437.71 (38.96)	9.77	517.30 (118.55)	29.73

**Figure 6.** Projected habitat suitability for *Zhangixalus jarujini* under current conditions, and for the years 2050 and 2070, based on SSP2-4.5 and SSP5-8.5 scenarios

Although *Z. jarujini* is currently assessed as Least Concern (LC) on both the IUCN Red List (IUCN 2025) and the Thai Red Data list (Office of Natural Resources and Environmental Policy and Planning 2017), and is not listed as a protected species under Thailand's Wild Animal Conservation and Protection Act (2019), its specialized ecological requirements demand targeted conservation measures to ensure long-term survival. Historical and ongoing habitat modification in this part of Thailand has been implicated in local amphibian declines (Matsui and Panha 2006; Chuaynkern and Duengkae 2014) and is likely affecting this species' population. Because *Z. jarujini* is not harvested for food (Chuaynkern and Duengkae 2014; Moonasa et al. 2018; Thongproh et al. 2018, 2019), habitat destruction remains its principal threat. At the local level, management should prioritize strict protection of freshwater systems and adjacent riparian buffers, as proximity to water is the primary factor shaping its distribution. Protection should also encompass surrounding mid-elevation forests (173-396 m asl) and critical microhabitats such as sandstone caves. Much of its known range in Thailand already falls within protected areas with effective law enforcement; therefore, immediate listing under the Wild Animal Conservation and Protection Act is not urgently required. However, a landscape-scale review is recommended to confirm that all high-suitability zones and hydrological corridors are adequately safeguarded.

Long-term monitoring is also crucial to track population responses to climate change and habitat fragmentation, enabling adaptive management. Finally, urgent surveys are needed in neighboring Laos and Cambodia, where the species' presence remains uncertain and habitat protection may be less secure.

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