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Current distribution and habitat suitability for the present and future scenarios of *Cyrtodactylus angularis* in Thailand

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Abstract. *Khajitmathee N, Kaewtongkum N, Chaiyes A, Suksavate W, Duengkae P, Sribandit P, Phochayavanich R, Chuaynkern C, Chuaynkern Y. 2025. Current distribution and habitat suitability for the present and future scenarios of* Cyrtodactylus angularis *in Thailand. Biodiversitas 26: 1039-1050.* The genus *Cyrtodactylus*, with approximately 381 species, is among the most speciose in the family Gekkonidae. *Cyrtodactylus angularis*, an endemic species of Thailand, was assessed for habitat suitability using Ecological Niche Modeling (ENM). This study evaluates the species' potential risks under current and future environmental conditions. Species identification was based on photographic evidence and morphological traits. The MaxEnt model was employed to estimate the species' potential distribution. The analysis identified dry evergreen forests as the primary environmental variable influencing habitat suitability, showing a strong positive correlation with the species. The current habitat suitability area for *C. angularis* is estimated at 5,879.51 km². Under future climate scenarios, habitat suitability areas are projected to decrease significantly. By 2050, the habitat suitability areas are expected to shrink by 372.00 km² (-6.33%) under SSP2-4.5 and 2,121.69 km² (-36.09%) under SSP5-8.5. 2070 further reductions are anticipated, with declines of 2,120.05 km² (-36.06%) under SSP2-4.5 and 5,309.17 km² (-90.30%) under SSP5-8.5. These projections highlight the substantial threat climate change poses to the species' habitat. The Phu Khiao-Nam Nao and Dong Phaya Yen-Khao Yai Forest Complexes are identified as key potential preserves for *C. angularis*. We recommend prioritizing these areas for conservation efforts to protect the species from future environmental changes. Additionally, intensive surveys across the species' full range are essential to enhance our understanding of its ecological niche. Expanding occurrence data from under-surveyed regions will improve habitat suitability models and help identify critical microhabitats, supporting more effective conservation planning.

Keywords: Bent-toed geckos, *Cyrtodactylus angularis*, MaxEnt, species distribution model, Thailand

INTRODUCTION

The decline of global biodiversity is a pressing environmental issue, driven by a suite of anthropogenic factors, including habitat destruction, overexploitation, invasive species introduction, and climate change (Chuaynkern and Duengkae 2014; Prakash and Verma 2022; Phommexay et al. 2024a, b). These threats contribute to habitat fragmentation, degradation, and significant reductions in species populations, with endemic species particularly at risk. The impacts of climate change, including shifts in temperature and precipitation patterns, are projected to exacerbate these threats by reducing habitat suitability areas and disrupting ecological dynamics.

Cyrtodactylus, commonly referred to as bent-toed geckos, is one of the most diverse genera within the family Gekkonidae, comprising 381 species. This species is distributed across South Asia to Melanesia, encompassing some of the world's most biologically diverse and ecologically rich regions (Nurngsomsri et al. 2014; Chuaynkern et al. 2018; Nurngsomsri et al. 2019; Grismer et al. 2021a, b, 2022; Uetz et al. 2025). Among this remarkable diversity is *Cyrtodactylus angularis* (Smith, 1921), a gecko species endemic to Thailand that is found exclusively within the borders. The species inhabits primarily dry evergreen forests, exhibiting specialized behaviors and ecological preferences. Nocturnal by nature, *C. angularis* forages on the forest floor, moving deliberately through the leaf litter at night, loose at the base of tree trunks, or in rotting logs during the day (Smith 1921; Taylor 1963). Despite its specialized ecological role, the species' restricted range renders it highly vulnerable to environmental changes. Species like *C. angularis*, which have narrow ranges and specific habitat requirements, are especially susceptible to these environmental changes. Localized threats, such as deforestation and land development for agriculture or urbanization, further magnify these risks. As a result, *C. angularis* faces a precarious future, with its limited distribution and high habitat specificity presenting formidable challenges for conservation (Oliver et al. 2012; Nurngsomsri et al. 2014, et al. 2019; Chuaynkern et al. 2018; Grismer et al. 2021a, b; Tran et al. 2023; Uetz et al. 2025).

Ecological Niche Modeling (ENM) has emerged as a vital tool for understanding species-environment interactions, assessing habitat suitability, and predicting species distributions under current and future conditions. By leveraging diverse algorithms, ENM evaluates the relationships between species and their environments, identifying the key environmental variables that govern habitat suitability (de Castro Pena et al. 2017; Peterson et al. 2018; Ahmadi et al. 2019). Furthermore, ENM enables projections of how climate change and other environmental disturbances might alter species distributions, providing insights into potential risks and future challenges (Raghavan et al. 2019; Qazi et al. 2022). For species with restricted ranges, such as *C. angularis*, ENM serves as an invaluable method for identifying critical habitats, understanding ecological requirements, and developing conservation strategies tailored to mitigate environmental threats (Cobos et al. 2019; Tran et al. 2023; Phommexay et al. 2024a, b).

Thailand's forests are rapidly degrading due to human activities, threatening biodiversity and disrupting essential ecosystem services (Chuaynkern and Duengkae 2014). For *C. angularis*, which depends on intact forest habitats and specific microhabitats for survival, such degradation poses a significant threat to its population and long-term viability. Climate change further exacerbates these risks, with shifting temperature and precipitation patterns potentially making parts of its already-limited range unsuitable. Therefore, understanding the species' habitat requirements and responses to environmental changes is critical for effective conservation (Phommexay et al. 2024a, b).

This study employs ENM to assess the current habitat suitability of *C. angularis* in Thailand and to project the potential impacts of climate change and other environmental factors on its future distribution. The study uses key environmental variables such as temperature, precipitation, and forest cover to identify factors shaping the species' distribution and evaluate risks under future climate scenarios, including SSP2-4.5 and SSP5-8.5, with projections for 2050 and 2070.

The findings will provide valuable insights into the ecological requirements and vulnerabilities of *C. angularis*, supporting conservation efforts by identifying current and future suitable habitats. These results will guide actions such as habitat protection and restoration and inform strategies to mitigate the effects of habitat loss and climate change. In the context of accelerating biodiversity loss, this study emphasizes the importance of proactive conservation planning to ensure the survival of endemic species and maintain ecosystem integrity.

MATERIALS AND METHODS

Cyrtodactylus angularis data occurrence

Our comprehensive research on *C. angularis* in Thailand involved a thorough compilation of occurrence data. We integrated field surveys, literature reviews, biodiversity databases, and museum specimens to ensure a comprehensive assessment. Field surveys allowed us to observe and record the species in its natural habitat directly. We also consulted a wide range of sources, including published research articles (e.g. Smith 1921, 1935; Ulber and Grossmann 1991), unpublished Thesis (Nurngsomsri 2016), and biodiversity platforms such as GBIF (https://www.gbif.org) and iNaturalist (https://www.inaturalist.org) were also consulted to extract additional occurrence records. The preserved specimens of *C. angularis* housed in the Thailand Natural History Museum (THNHM), National Science Museum (NSM), Pathum Thani, Thailand, and the Field Museum of Natural History (FMNH), Chicago, USA, were crucial to our analysis. We meticulously analyzed the morphological characteristics of these specimens and cross-referenced them with field observations and photographic evidence to confirm species identification and distribution.

Geographic coordinates from all sources were validated using online mapping tools to ensure spatial accuracy. Following these steps, 75 presence records were retained for analysis. The dataset was curated by removing duplicates and erroneous entries and was used as the basis for species distribution modeling.

Environmental variables

To characterize the ecological niche of *C. angularis*, 27 environmental variables were selected (Table 1), encompassing climate, topography, proximity to water bodies, vegetation indices, and land cover types. Climatic data, including 19 variables related to temperature and precipitation, were sourced from the WorldClim database (http://worldclim.org) at a 30-arcsecond resolution. Topographic data, such as elevation (DEM), were obtained from WorldClim and processed in QGIS version 3.30.3 to calculate the slope at the 30-arcsecond resolution.

Distances to water bodies were calculated using data from https://data.go.th and the 'terra' package in R version 4.4.1. Vegetation indices, including the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI), were derived from Landsat 8 imagery (https://www.usgs.gov) and processed in QGIS. Additional variables, such as dry evergreen forest cover (https://data.go.th), Nighttime Light Intensity (NTL; https://www.ncei.noaa.gov), and Percent Tree Cover (PTC; https://www.globalforestwatch.org), were included to capture landscape features.

Four datasets were created to identify the optimal set of variables for modeling: Set 1 included all 27 variables; Set 2 was generated by excluding highly correlated variables (Pearson's $|r|>0.80$) from Set 1, resulting in 12 variables (Shrestha 2020; Sillero and Barbosa 2021; Tran et al. 2023); Set 3 excluded NDVI, NDWI, NTL, and PTC from Set 1; and Set 4 applied the same multicollinearity analysis as Set 2 to Set 3, yielding a final set of 10 variables. These datasets (Table 1) were used to analyze the ecological niche and habitat suitability of *C. angularis*.

Table 1. The environmental variables used to generate ENM for *Cyrtodactylus angularis* in Thailand

Environmental variables		**Sets of environmental variables**			
Name	**Description**	**1**	**2**	**3**	**4**
Bio1	Annual mean temperature	●	-	●	-
Bio2	Mean diurnal range	●	●	●	●
Bio3	Isothermality	●	-	●	-
Bio4	Temperature seasonality	●	●	●	●
Bio5	Ma-imum 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	●	●	●	●
DEM	Elevation	●	-	●	-
Slope	Degree of rise/run	●	●	●	●
Dist_ water	Distance to water bodies	●	●	●	●
NDVI	Normalized Difference Vegetation Inde-	●	-	-	-
NDWI	Normalized Difference Water Inde-	●	●	-	-
Dry everg reen forest	Dry evergreen forest area	●	●	●	●
NTL	Nighttime Light	●	●	-	-
PTC	Percent Tree Cover	●	-	-	-

Note: ●: Indicates inclusion, -: Denotes exclusion

Ecological Niche Modeling (ENM)

The estimation of the potential distribution of *C. angularis* was a crucial step in our research, and for this, we relied on the powerful Maximum Entropy algorithm (MaxEnt) version 3.4.4 (https://biodiversityinformatics.amnh.org/open_source/maxent/). To ensure the accuracy and reliability of our model, we further optimized the process using the *kuenm* package in R version 4.4.1 (Anderson and Gonzalez 2011; Peterson et al. 2018; Cobos et al. 2019) addressing potential issues such as overfitting, parameter tuning, and model complexity. This involved generating candidate models by varying regularization multiplier values (1.0-5.0 in 0.5 increments), testing all 29 feature class combinations, and incorporating four sets of environmental variables.

For each candidate model, datasets were split into training (70%) and testing (30%) subsets to evaluate model performance. The optimization process in *kuenm* followed a structured, multi-step procedure to ensure robust predictions. First, models were filtered based on statistical significance using metrics such as the Area Under the Curve (AUC) and omission rates. Subsequently, omission rate thresholds were applied to refine the set of statistically significant models further. Finally, among the significant models with low omission rates, those with delta AICc values below two were selected as the best-performing models. This approach, which balances model complexity and predictive accuracy, reassures the reliability of our results by systematically adjusting regularization multipliers and feature classes.

In the model calibration process for *C. angularis*, we focused on assessing omission rates, and AICc values were assessed for all models, including non-significant and selected best candidates. This analysis was based on 75 species distribution points and corresponding environmental variables, with the regularization multiplier and feature combinations available in the *kuenm* package. Model selection was guided by statistical significance, omission rates, and AICc criteria. The final model, chosen from Set 3, features the Quadratic Hinge (QH) class with a regularization multiplier of 2, yielding an omission rate of 0.043 and a delta AICc value of 152.82 (Figure 1.A; Table 2). The low omission rate of 0.043 indicates minimal prediction error, underscoring the model's reliability. Among all models with the lowest omission rates (0.043), this model exhibits the lowest delta AICc value (152.82) while maintaining a statistically significant partial ROC ($p<0.05$). These attributes establish it as the most suitable candidate, offering an optimal balance between model fit and complexity. Given these strengths, this model stands out as the most reliable choice for ecological niche modeling (Anderson et al. 2003; Cobos et al. 2019). This model was used for 10 replicates of the modeling process, with the average AUC value across these replicates being 0.995±0.002 (Figure 1.B). The high average AUC indicates excellent model discrimination (Phillips et al. 2006; Prayoon et al. 2021; Phommexay et al. 2024a). The results of this multi-step evaluation provided a comprehensive framework for selecting the optimal model while allowing flexibility and users to apply additional criteria if needed (Cobos et al. 2019).

RESULTS AND DISCUSSION

Current distribution of *Cyrtodactylus angularis*

In the present study, we confirmed the presence of *C. angularis* in five provinces of Thailand: Chaiyaphum (3 localities), Khon Kaen (1 locality), Nakhon Ratchasima (69 localities), Roi Et (1 locality), and Sa Kaeo (1 locality) (Figure 2). In Nakhon Ratchasima, *C. angularis* was found in 68 localities within the Sakaerat Biosphere Reserve and one locality on Dong Phaya Yen Mountain (Thap Lan National Park). In Chaiyaphum, the species was observed in three localities: Phu Khiao Wildlife Sanctuary (Thung

Kamang; Nature Trail near the headquarters), Chulabhorn Dam, and Phu Long Forest (Kaeng Kro District). In Khon Kaen, *C. angularis* was recorded in Phu Wiang National Park (Phu Wiang District). In Roi Et, the species was found in the Pha Nam Tip Non-Hunting Area, and in Sa Kaeo, it occurred in Pang Sida National Park. The species primarily inhabits these regions.

The distribution coordinates of *C. angularis* show that the species is primarily found in Dry Evergreen Forests and surrounding forested areas, a pattern consistent with Chan-ard et al. (2015), who noted its preference for Dry Evergreen Forest habitats. *Cyrtodactylus* species are generally endemic and exhibit varying degrees of environmental specificity, with many being restricted to small, localized areas (Chan-ard et al. 2015; Chuaynkern et al. 2018; Grismer et al. 2021a, b, 2022; Tran et al. 2023; Uetz et al. 2025). While *C. angularis* is found in fragmented habitats across different regions of Thailand, this distribution pattern is like that of other *Cyrtodactylus* species, such as *C. ngati* and *C. intermedius*, which also occupy fragmented environments across multiple areas, with some extending into neighboring countries (Grismer et al. 2021a, b, 2022). Additional surveys and studies are recommended to gather more detailed and precise data to improve the accuracy of these findings, which could significantly impact conservation efforts.

Our study enhances the understanding of *C. angularis* distribution and habitat preferences, providing valuable data for its conservation. The species was most frequently recorded in Nakhon Ratchasima, particularly within the Sakaerat Biosphere Reserve, characterized by Dry Evergreen Forests that appear to provide optimal habitat conditions for its sustained presence. Its occurrence on Dong Phaya Fai Mountain suggests that *C. angularis* may inhabit a range of forested environments, although its presence in this area appears limited. In Chaiyaphum, the species was observed at three locations: Phu Khiao Wildlife Sanctuary, Chulabhorn Dam, and Phu Long Forest indicating its adaptability to both Dry Evergreen and Semi-evergreen Forests, with the biodiversity of Phu Khiao Wildlife Sanctuary likely supporting its presence there. In Khon Kaen, *C. angularis* was recorded in Phu Wiang National Park, where Dry Evergreen, Dry Dipterocarp, and Mixed Deciduous Forests dominate, suggesting that the species can tolerate habitat variability under suitable ecological conditions. In Roi Et and Sa Kaeo, the species was found in the Pha Nam Tip Non-Hunting Area and Pang Sida National Park, respectively. Most of the species' distribution occurs in protected areas managed by the Department of National Parks, Wildlife and Plant Conservation (DNP; National Parks, wildlife sanctuaries, and non-hunting areas), the Royal Forest Department (RFD; Phu Long Forest), the Thailand Institute of Scientific and Technological Research (TISTR; Sakaerat Biosphere Reserve), and the Electricity Generating Authority of Thailand (EGAT; Chulabhorn Dam), which play a critical role in safeguarding *C. angularis* populations from human disturbances. This species is well protected both in terms of its species status and habitat protection; it is listed as one of Thailand's Protected Animals under the Wild Animal Conservation and Protection Act (2019) and benefits from extensive habitat protection through conservation areas. Furthermore, the species is classified as Least Concern (LC) on the IUCN Red List of Threatened Species (Sumontha and Cota 2018).

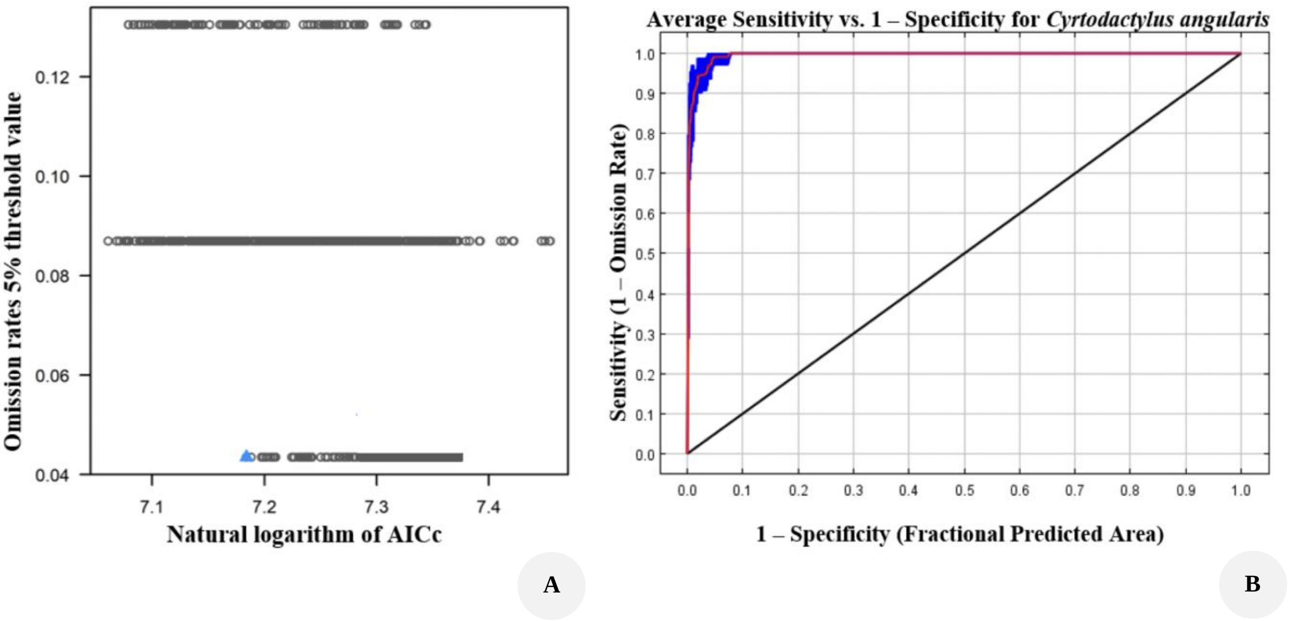

Figure 1. A. Results from the model selection process using the *kuenm* package; blue solid triangles represent selected models, black open circle represents candidate models, and red open circle indicate non-significant models; B. Receiver Operating Characteristic (ROC) curve for the MaxEnt model

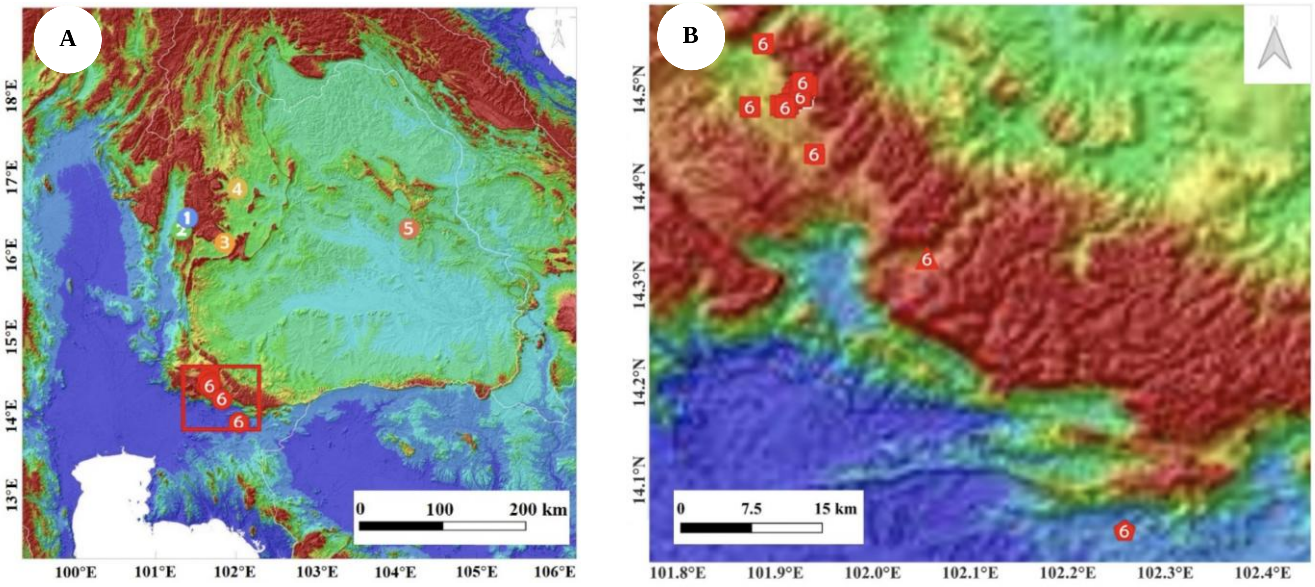

Figure 2. Distribution of *Cyrtodactylus angularis* occurrence data; A. 1: Chulabhorn Dam; 2: Thung Kamang; 3: Kaeng Khro District; 4: Phu Wiang National Park; 5: Pha Nam Thip Non-Hunting Area; 6: Dong Phaya Yen Mountain; B. Zoomed-in view of the red rectangle from (a), showing location sites in Sakaerat Biosphere Reserve (red square), Thap Lan National Park (red triangle), and Pang Sida National Park (red pentagon)

Cyrtodactylus angularis appears to be a forest-dependent species, primarily inhabiting Dry Evergreen and related forest types. Its fragmented distribution across multiple provinces and protected areas highlights the species' reliance on specific habitats, underscoring the need for focused conservation efforts. Despite the species' ability to occur in various forest types, its fragmented distribution suggests that habitat loss and fragmentation could pose significant threats to its populations. Therefore, protecting existing forest habitats and restoring fragmented areas are critical steps in safeguarding the future of *C. angularis*. These findings also suggest that further ecological studies are needed to understand better the species' habitat preferences, population dynamics, and responses to environmental changes. Long-term monitoring and conservation actions, including habitat restoration, management of protected areas, and mitigation of human-induced threats, will be essential for ensuring the continued survival of *C. angularis* in Thailand.

Within the Dong Phaya Yen Mountains, *C. angularis* has been observed at several localities, including the Sakaerat Biosphere Reserve, Thap Lan National Park, and Pang Sida National Park. The Sakaerat Biosphere Reserve, in particular, has recorded the highest frequency of sightings and has been the focus of the most extensive research on this species. Thap Lan and Pang Sida National Parks also host confirmed sightings, with photographic evidence supporting the species' presence. In nearby regions, a closely related species, *C. meesookae*, with similar markings, has been identified. However, *C. meesookae* can be distinguished from *C. angularis* by distinct features, including spots on the head, transverse limb stripes, and a different pattern of bands along its back. Moreover, *C. meesookae* is found in limestone hill environments, which contrasts with the habitat preferences of *C. angularis*.

Similarly, within the Phu Khiao Wildlife Sanctuary, *C. papilionoides* has been documented, while *C. wiboonatthapoli* has been reported in nearby areas, raising the potential for misidentification, a factor that should be approached with caution. Previous studies from the sanctuary (Ulber and Grossmann 1991; Chan-ard et al. 2015) have identified *C. papilionoides* in the area. This study, however, used distinct morphological characteristics to differentiate *C. papilionoides* from *C. angularis*, as *C. papilionoides* exhibits clear spots on the head and transverse stripes on the limbs, features either absent or pale in *C. angularis*. Additionally, *C. wiboonatthapoli*, found in adjacent regions, also displays prominent head spots and limb stripes, further distinguishing it from *C. angularis*. *C. wiboonatthapoli* inhabits limestone hill environments, whereas *C. angularis* prefers other forest types. *C. papilionoides*, on the other hand, is found in limestone caves within dry evergreen forests. Despite these species sharing similar forest habitats, their external characteristics provide clear differentiation (Ulber and Grossmann 1991; Smith 1921, 1935; Chan-ard et al. 2015; Nurngsomsri 2016; Sumontha et al. 2024).

Cyrtodactylus angularis habitat suitability

The habitat suitability for *C. angularis* based on the environmental variables analyzed in this study was influenced primarily by five key factors. The most significant predictor was the Dry Evergreen Forest (69.8%), followed by bio16 (5.4%), DEM (5.3%), bio4 (4.7%), and bio2 (4.2%). Dry Evergreen Forest emerged as the most critical variable, exhibiting a strong positive correlation with *C. angularis*. This suggests that the species is mainly dependent on habitats within this forest type, where higher probabilities of habitat suitability were most concentrated (Figure 3.A). The jackknife method further highlighted Dry Evergreen Forests as the most influential factor for determining suitable habitats. When assessed individually, it produced the highest model gain, indicating it provided the most valuable information. In contrast, removing Dry Evergreen Forest from the model led to the largest decrease in gain, reinforcing its unique and irreplaceable role in predicting habitat suitability (Figure 3.B).

To determine suitable and unsuitable habitats for *C. angularis*, we utilized the 10th percentile training presence logistic threshold of 0.4 (Tran et al. 2023), and habitat suitability was categorized into three levels: low suitability (0.4-0.6), medium suitability (0.6-0.8), and high suitability (>0.8). The analysis revealed a total habitat suitability area of 5,879.51 km^2 within the study region, distributed across the three suitability categories: low suitability (3,330.68 km^2), medium suitability (2,278.89 km^2), and high suitability (269.94 km^2) (Figure 4; Table 3).

These results underscore the model's strong capability to predict habitat suitability for *C. angularis* with high precision. The findings emphasize the critical role of dry evergreen forests in determining habitat suitability for this species. Its identification as the most influential variable aligns with the observed positive association between *C. angularis* and this habitat, suggesting a strong ecological dependency. This pattern is consistent with the distribution documented by Smith (1921), Chan-ard et al. (2015), and the current study, which indicates that the species is primarily confined to Dry Evergreen Forests and adjacent forested areas.

However, while all environmental variables, except Dry Evergreen Forest, contributed less than 6% to the model, their potential influence on the model's accuracy should not be dismissed (Wei et al. 2018; Gunawan et al. 2021). Despite this, the model remains highly effective in predicting suitable habitat areas, providing a reliable foundation for ecological identification. To further refine predictive accuracy, additional studies are needed to explore the impact of other variables, as subtle climatic or topographic factors may still play a role in determining the suitability of microhabitats.

The application of the 10th percentile training presence logistic threshold (0.4) has proven effective in distinguishing suitable from unsuitable habitats, thus optimizing the identification of areas crucial for conservation efforts (Tran et al. 2023). Suitable habitats are primarily concentrated within the Phu Khiao-Nam Nao and Dong Phaya Yen-Khao Yai Forest Complexes, both of which are part of Thailand's protected area (Figure 4; https://www.dnp.go.th/). Notably, the Dong Phaya Yen-Khao Yai Forest Complex contains a significant number of highly suitable areas, which aligns with historical species occurrence data from this region (Smith 1921, 1935; Ulber and Grossmann 1991; Chan-ard et al. 2015; https://www.gbif.org; https://www.inaturalist.org).

Cyrtodactylus angularis is highly vulnerable compared to other species within the *Cyrtodactylus* genus primarily due to its exclusive association with dry evergreen forests. In contrast, *C. papilionoides*, which inhabits a similar region, occupies limestone caves within dry evergreen forests (Chan-ard et al. 2015; Nurngsomsri 2016), thus utilizing a different ecological niche. Similarly, *C. wiboonatthapoli* is found in limestone hill environments in nearby areas (Sumontha et al. 2024), further differentiating it from *C. angularis*. This niche differentiation (Pearman et al. 2008) underscores the varying habitat preferences among species, with *C. angularis* being more restricted in its ecological requirements and therefore more susceptible to habitat loss and environmental changes.

Table 2. Best models from each set used in the model calibration for *Cyrtodactylus angularis* in Thailand; Including Regularization Multiplier (RM) and Feature Classes (FC)

Set	RM	FC	Partial ROC	Omission rate5%	AICc	DeltaAICc	Weight AICc	Number of parameters
1	1	l	0	0.043	1376.01	210.64	0.00	11
2	1.5	q	0	0.043	1473.63	155.43	0.00	9
3	2	qh	0	0.043	1318.20	152.82	0.00	16
4	3.5	qth	0	0.043	1460.08	308.25	0.00	14

Table 3. Area of suitable habitat for *Cyrtodactylus angularis* in Thailand

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	3,330.68	3,730.66 (399.98)	12.01	3,338.09 (7.41)	0.22	2,994.07 (-336.61)	-10.11	570.34 (-2,760.34)	-82.88
Medium	2,278.89	1,772.74 (-506.15)	-22.21	419.73 (-1,859.16)	-81.58	765.39 (-1513.50)	-66.41	0.00 (-2,278.89)	-100.00
High	269.94	4.12 (-265.83)	-98.48	0.00 (-269.94)	-100.00	0.00 (-269.94)	-100.00	0.00 (-269.94)	-100.00
Total	5,879.51	5,507.52 (-372.00)	-6.33	3,757.82 (-2,121.69)	-36.09	3,759.46 (-2,120.05)	-36.06	570.34 (-5,309.17)	-90.30
Unsuitable	507,218.19	507,590.19 (372.00)	0.07	509,339.89 (2,121.69)	0.42	509,338.24 (2,120.05)	0.42	512,527.37 (5,309.17)	1.05

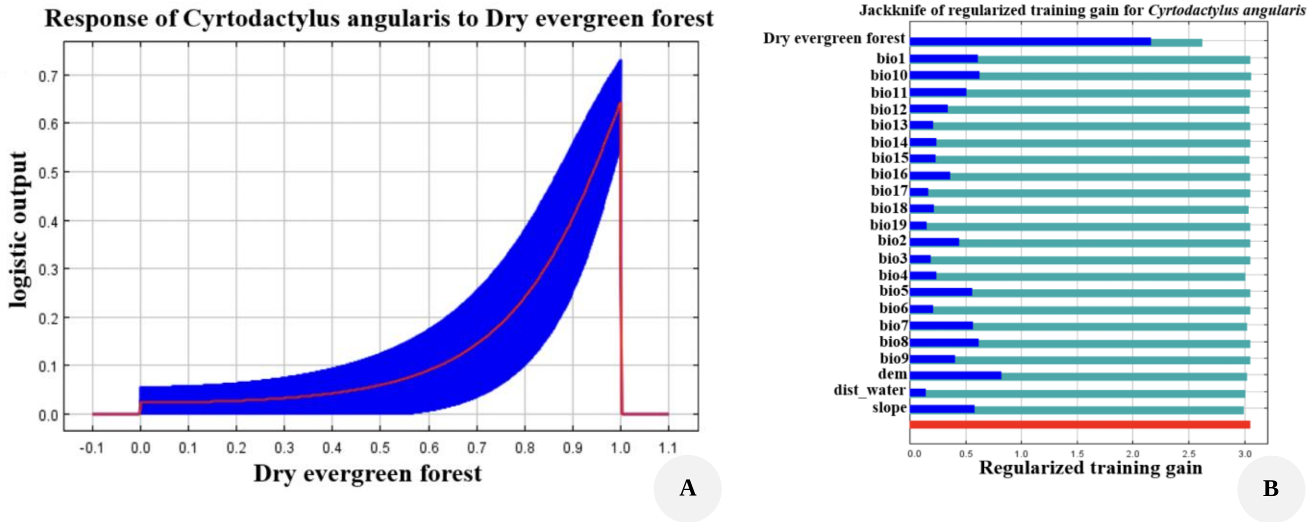

Figure 3. A. Response curves for the Dry Evergreen Forest variable, illustrating its relationship with the probability of occurrence for *Cyrtodactylus angularis*. The red line represents the mean response from the MaxEnt model, while the blue band indicates the standard deviation; B. The jackknife method 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

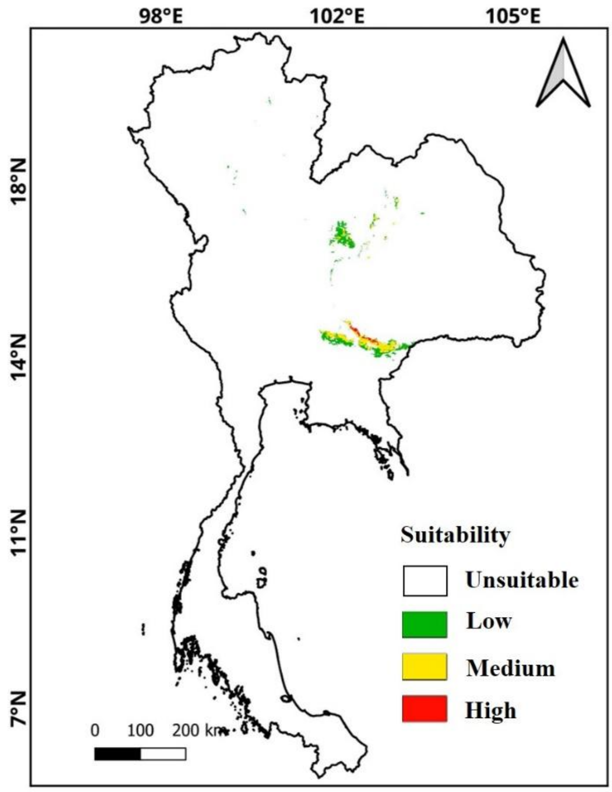

Figure 4. Predicted current habitat suitability for *Cyrtodactylus angularis*

It is important to note that the occurrence points used in this analysis are not evenly distributed across the entire known range of *C. angularis*. The limited geographic coverage of these occurrence points may influence the accuracy and generalizability of the habitat suitability predictions. The lack of comprehensive data from certain areas could result in an incomplete representation of the species' true ecological niche, potentially leading to biased or less reliable model outputs. Therefore, more intensive field surveys are very important to collect wider and more geographically diverse points of occurrence. Expanding the range of occurrence data will improve model accuracy, providing a more robust and reliable prediction of habitat suitability areas across the species' full distribution range.

Despite these limitations, the current analysis has successfully identified areas of high suitability for *C. angularis*, which can serve as a valuable tool for prioritizing ground-truthing efforts. Researchers can optimize resources by focusing field surveys on these high-suitability areas, minimizing the time, cost, and manpower needed for data collection. Field examinations in these targeted regions are likely to yield more efficient and effective validation of habitat suitability, helping to refine conservation strategies while reducing the logistical burden of widespread fieldwork. Thus, the current model provides a practical starting point for further ecological studies and conservation planning.

Model future under the SSP2-4.5 and SSP5-8.5 scenarios

For the future scenarios, we used the ACCESS-CM2 model to project conditions for 2050 and 2070 under the SSP2-4.5 and SSP5-8.5 climate scenarios. In 2050, the predicted habitat suitability area was 5,507.52 km² under SSP2-4.5 and 3,757.82 km² under SSP5-8.5 (Figure 5.A, B; Table 3). Compared to the current habitat suitability area, this represents a reduction of 372.00 km² (-6.33%) and 2,121.69 km² (-36.09%), respectively (Table 3).

By 2070, the predicted habitat suitability area further declines, with total areas of 3,759.46 km² under SSP2-4.5 and just 570.34 km² under SSP5-8.5 (Figure 5.C and D; Table 3). These projections indicate a decrease of 2,120.05 km² (-36.06%) and 5,309.17 km² (-90.30%), respectively, compared to the current habitat suitability area (Table 3). This decline is expected to be particularly pronounced under the SSP5-8.5 scenario, with significant losses in high and low suitability areas. This decline is expected to occur primarily in the SSP5-8.5 scenario, with significant losses in both high and low-suitability regions. Specifically, based on SSP5-8.5, projections show the loss of all high-suitability habitats (Figure 6), highlighting the severity of future habitat loss and the potential challenges for *C. angularis* survival.

For the Mobility-Oriented Parity (MOP) analysis (Owens et al. 2013), values range from zero to one. A zero value indicates strictly extrapolative areas, while higher values suggest increasing similarity between the calibration area and the projection scenario. Areas with a zero value should be interpreted cautiously, as they may not provide reliable predictions. In Figure 6, white areas represent regions with low similarity or strictly extrapolative conditions. In contrast, black areas, which indicate higher similarity to the calibration area, are considered more likely to yield accurate predictions. Since the majority of the habitat suitability area falls within the black regions, we are confident in the reliability of the model's predictions (Figure 7).

The analysis reveals a clear trend of declining habitat suitability for *C. angularis* over time, with even more severe losses projected under the SSP5-8.5 scenario. This highlights the potential consequences of increased greenhouse gas emissions. These findings are consistent with those of Tran et al. (2023), who reported a similar decline in habitat suitability areas for *Cyrtodactylus* species in Vietnam, particularly under the SSP5-8.5 scenario. Such trends also align with patterns seen in other species, where habitat suitability areas are projected to decrease significantly under future climate scenarios (Brunetti et al. 2019; Zangiabadi et al. 2021; Phommexay et al. 2024a).

Similar to current distribution patterns, future habitat suitability areas, though reduced in extent, remain primarily concentrated within the Phu Khiao-Nam Nao and Dong Phaya Yen-Khao Yai Forest Complexes. However, by 2050, under the SSP5-8.5 scenario, high-suitability habitat will be largely restricted to the Dong Phayayen-Khao Yai Forest Complex. By 2070, under the same scenario, it is estimated that there will be no more high-suitability habitat remaining, and the suitable area will shift mainly to the Phu Khiao-Nam Nao Forest Complex. While some species may adapt more effectively to changing conditions and experience greater dispersal success, others may be forced to migrate as their habitats become unsuitable (Hill et al. 2021). However, certain regions may not recover as quickly or in ways that benefit all species, and the speed and nature of recovery are uncertain. The projected climate shifts affecting the habitat of *C. angularis* could have significant, far-reaching impacts on other species within the same habitat, potentially altering species interactions both directly and indirectly, which may disrupt the entire ecosystem (Case et al. 2021).

We recognize that projections of future habitat loss and climate impacts may appear overly pessimistic to some readers. However, it is important to understand the methodologies behind these projections. While uncertainties are inherent in climate modeling, recent frameworks like the Shared Socioeconomic Pathways (SSPs) in the Coupled Model Intercomparison Project Phase 6 (CMIP6) offer a more comprehensive approach than previous Representative Concentration Pathways (RCPs). SSPs incorporate not only greenhouse gas concentration trajectories but also socioeconomic factors such as population growth, economic development, urbanization, and technological advancements, providing a clearer picture of how human activities will influence future climate scenarios (Taylor et al. 2012; Chen et al. 2020). For instance, SSP2-4.5 aligns with current global trends, depicting a moderate development pathway, while SSP5-8.5 represents a worst-case scenario with high emissions and limited mitigation efforts. SSP1-2.6, on the other hand, suggests a sustainable future, but given current global trends, this scenario may be overly optimistic. Meanwhile, SSP3-7.0 paints a more challenging path for climate adaptation and mitigation (Kurniawan and Managi 2018; Yang and Cui 2019). Furthermore, our choice of SSP2-4.5 and SSP5-8.5 scenarios reflects the need to prepare for both moderate and extreme future scenarios (Kurniawan and Managi 2018). Addressing worst-case projections is critical for proactive conservation strategies. We argue that this approach is not overly pessimistic, as human activities often result in habitat degradation at a pace that outstrips natural recovery (Prakash and Verma 2022). While uncertainty remains, these scenarios provide valuable insights into potential environmental changes, helping to assess climate risks, habitat suitability, and species survival, and reinforcing the importance of addressing these interconnected threats.

Given these projections, it is crucial to prioritize both the Phu Khiao-Nam Nao and Dong Phaya Yen-Khao Yai Forest Complexes in conservation strategies. This approach will help safeguard *C. angularis*'s habitat across different future climate scenarios, ensuring its long-term survival despite challenges posed by changing environmental conditions.

Conserving wildlife populations within their natural habitats should be the primary focus, as habitat suitability is essential for long-term ecosystem stability. In contrast, conservation strategies such as captive breeding and translocation should be considered emergency interventions rather than primary solutions. Captive breeding presents challenges, including species-specific reproductive limitations in artificial environments, and does not always ensure long-term survival (Fraser 2008; Farquharson et al. 2018; Badia-Boher et al. 2022). Likewise, translocation, if not carefully planned and studied, can result in unintended ecological consequences, including disruptions to recipient ecosystems and negative impacts on source populations (Novak et al. 2021; Mitchell et al. 2022). Therefore, these approaches should be used as supplementary conservation measures only when natural populations are no longer capable of self-sustaining recovery (Rahbek 1993).

We acknowledge that both ecosystem-level and species-specific conservation approaches are valuable and can complement each other. While prioritizing broader ecological systems can help maintain the integrity of ecosystems and support a range of species, it is equally important to focus on specific species, particularly those that are endemic or particularly vulnerable. This targeted approach can highlight critical conservation needs and mobilize resources to protect habitats that may otherwise be overlooked (Pearman et al. 2008; Ferraro and Pressey 2015; Hemming et al. 2022).

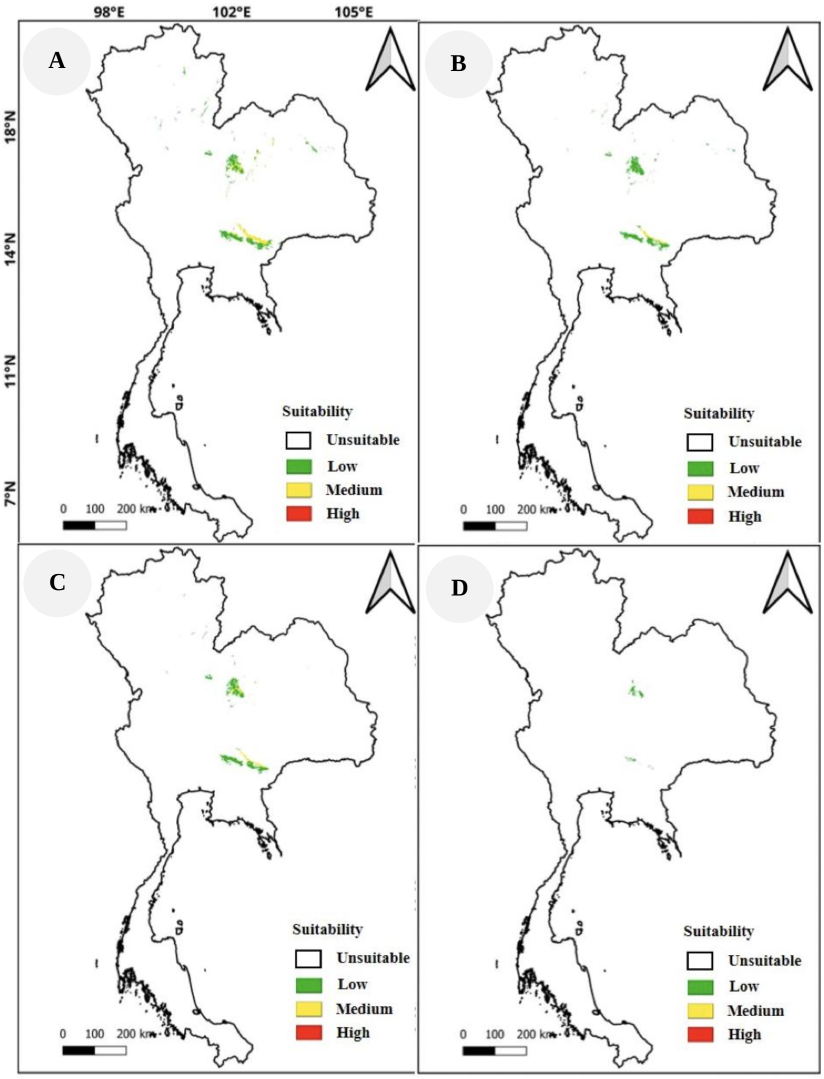

Figure 5. Predicted habitat suitability for *Cyrtodactylus angularis* under climate change scenarios. A and B. for 2050 under the SSP2-4.5 and SSP5-8.5 scenarios; C and D. for 2070 under the SSP2-4.5 and SSP5-8.5 scenarios

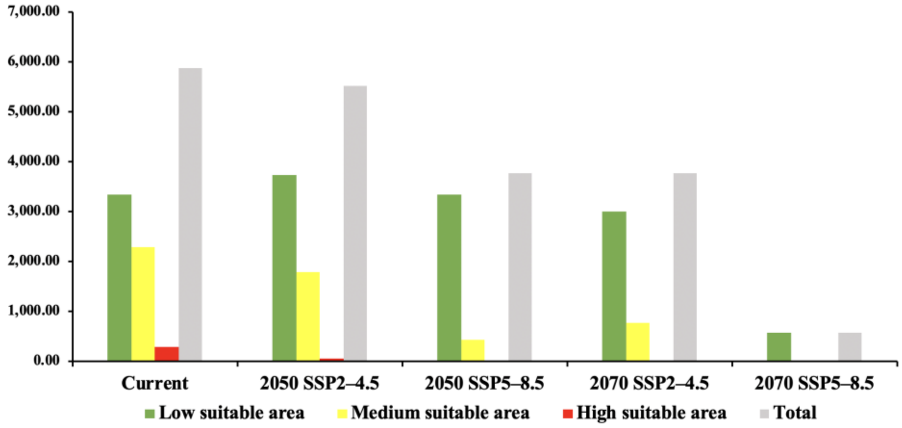

Figure 6. Suitability area for *Cyrtodactylus angularis* under current, 2050, and 2070 conditions across SSP2-4.5 and SSP5-8.5 scenarios

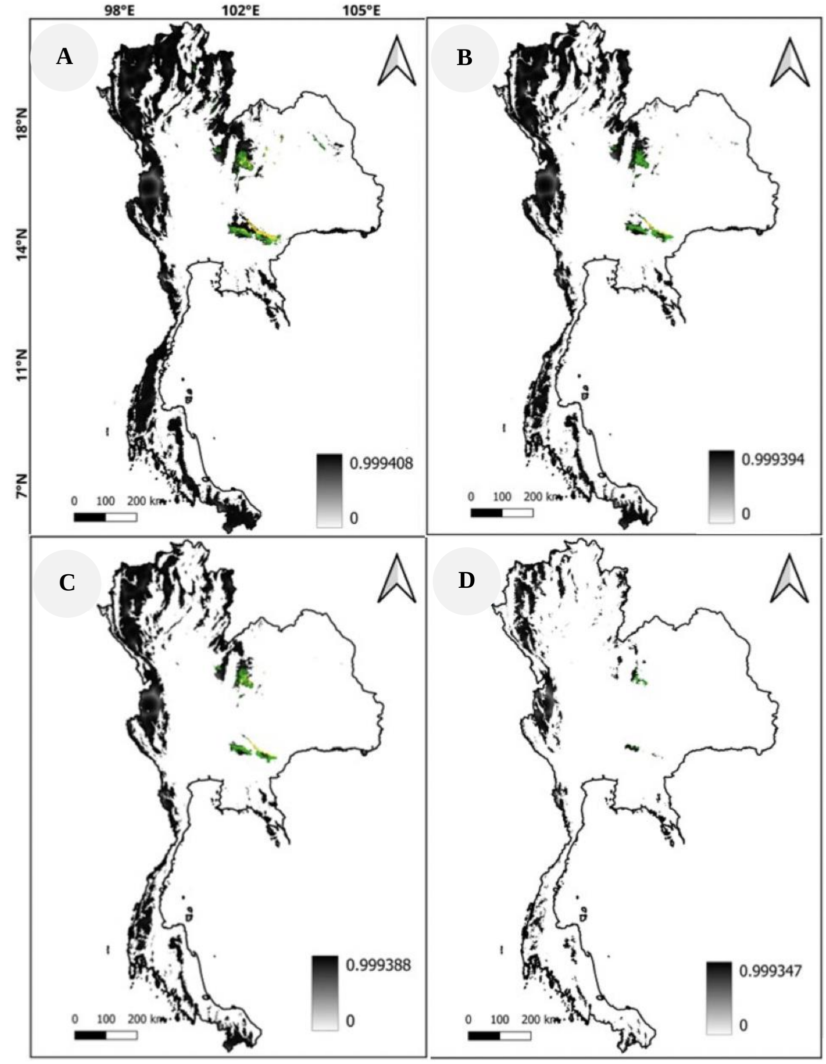

Figure 7. Mobility-Oriented Parity (MOP) analysis of Thailand for *Cyrtodactylus angularis* under climate change scenarios. A and B. 2050 under SSP2-4.5 and SSP5-8.5 scenario; C and D. 2070 under SSP2-4.5 and SSP5-8.5 scenarios

Ecosystem conservation lays the groundwork for biodiversity protection, yet certain species, such as *C. angularis*, with specific habitat requirements, demand tailored conservation efforts to ensure their survival (Kraus et al. 2023). Given that *C. angularis* is closely linked to dry evergreen forests, prioritizing key areas like the Phu Khiao-Nam Nao and Dong Phaya Yen-Khao Yai Forest Complexes will address both its specific habitat needs and broader conservation goals. These extensive areas are well-suited to support a combination of species-specific and ecosystem-level conservation strategies, providing a more holistic approach to preserving biodiversity.

Conservation of *C. angularis* in key preserves, particularly dry evergreen forests, requires focused efforts on maintaining habitat suitability. Management strategies should prioritize the preservation and restoration of these critical habitats. Additionally, conducting further population surveys is essential to assess the current status of the species, whether it is still present, has disappeared, or is in decline. Identifying and evaluating potential threats contributing to population decline is crucial for determining whether recovery is feasible (Warret et al. 2021; Legge et al. 2022). Conservation strategies should be tailored to the specific context of the preserve, carefully considering the advantages, disadvantages, and potential impacts of each approach (Novak et al. 2021; Warret et al. 2021; Badia-Boher et al. 2022; Hemming et al. 2022; Mitchell et al. 2022). This comprehensive assessment will ensure that conservation efforts are effective and provide a clearer path to preventing the species' extinction in the area.

We acknowledge that climate variability, invasive species, and urban development are all significant threats to *C. angularis* and other species. However, habitat loss due to urban development should be seen as a primary issue, as it often acts as a precursor to other challenges. While urban development is often viewed as a sign of progress, it leads to habitat fragmentation and destruction, diminishing biodiversity and destabilizing ecosystems (Prakash and Verma 2022; Simkin et al. 2022). Moreover, urban expansion intensifies human-wildlife conflicts, which can undermine conservation efforts. These conflicts arise when wildlife damages property, consumes crops, or causes fear within communities, often eroding public support for conservation (Schell et al. 2020). Therefore, habitat loss not only threatens natural environments but also amplifies the impacts of invasive species and climate change. A holistic conservation strategy must address these interconnected threats to ensure long-term species protection.

Some species have the potential to adapt to changing environmental conditions (Lapwong et al. 2021), including certain *Cyrtodactylus* species (Worthington-Wilmer and Couper 2016). However, species with specific habitat requirements remain highly vulnerable, as environmental changes can lead to population declines or even extinction (Stigall 2012). While widely distributed and invasive species often demonstrate greater adaptability and resilience to environmental fluctuations, the extent to which *C. angularis* can adapt remains uncertain. Further research is needed to assess its adaptive capacity, but given its ecological requirements, *C. angularis* remains a species of conservation concern.

In summary, our study utilized ecological niche modeling to assess the habitat suitability of *C. angularis* and identify the key environmental variables influencing its distribution, with a particular emphasis on dry evergreen forests. The results highlight the critical role of the Phu Khiao-Nam Nao and Dong Phaya Yen-Khao Yai Forest Complexes as key conservation areas for the species, especially under future climate scenarios. These findings provide a strong foundation for developing targeted conservation strategies to mitigate climate change and habitat loss impacts. Further research and field surveys are necessary to refine habitat predictions and accurate our understanding of the environmental factors shaping *C. angularis*'s distribution. In particular, exploring the specific relationship between dry evergreen forests and the species will be essential. Investigating which forest components, such as vegetation type, canopy cover, and microclimate conditions, are most critical to the species' survival will deepen our understanding of its ecological requirements. By examining these dynamics at the microhabitat level, we can better understand how ecological changes within dry evergreen forests influence the species and, in turn, develop more effective, long-term conservation strategies.

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