Modeling the Distribution and Habitat Suitability of Slipper Orchids (*Paphiopedilum* spp.) in Thailand Using MaxEnt

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Abstract: - Slipper orchids (*Paphiopedilum* spp.) are classified as one of the most endangered orchid groups in Southeast Asia, mainly caused by habitat loss, overexploitation, and climate change. In order to establish a state of species' conservation of this genus in Thailand, we proposed the species distribution model (SDM) based on MaxEnt v3. 4. 4 with 70 presence records and 10 predictors (climate, topography, and edaphic). The model was evaluated using 10-fold cross-validation and demonstrated good predictive power (AUCtrain =0.858; AUCtest =0.751). According to the threshold analysis, the best cloglog cut-off value was determined for 0.208, ensuring a balanced discrimination of suitable from unsuitable together with an AUC value. Under variable contributions, slope was the most important driving force (30.2%), followed by precipitation of the driest quarter (22.8%), maximum temperature of the warmest month (17.4%), elevation (11.4%) and annual precipitation 10.2%). Response curves showed ecological optima at mid-elevations (500–1500 m), moderate slopes (15–35 °), intermediate dry season rainfall, and moderate heat stress (BIO5 ≈ 28–32 °C). Spatial projections pointed to suitability hotspots in the northern mountains and southern karst regions, whereas lowlands and a large extent of the northeast were unsuitable. Our results help to elucidate the limitations of both physical and climatic factors on *Paphiopedilum* distribution and have implications for informed conservation decisions, including targeted field surveys, microhabitat protection and ex situ efforts.

Key-Words: - *Paphiopedilum* spp., Slipper Orchid, Species Distribution Modeling, Habitat Suitability, Environmental Predictors, Orchid Conservation, Biodiversity.

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1 Introduction

Orchidaceae orchids are among the largest and most diverse plant families in the world, with over 28,000 species known worldwide. They have been attributed to having a significant impact on ecosystem functions, cultural values, and horticultural industries, [1]. Thailand is known as one of the global biodiversity hotspots, with roughly 1,300 orchid species thriving in diverse types of forests, [2]. Among this diversity, the slipper orchids, *Paphiopedilum*, are notable for their limited distribution and specialised ecological niche and are also critically threatened, [3], [4]. These have an attractive flower shape and a unique slipper-like pouch and are currently the focus of global horticultural exchange. Many species of *Paphiopedilum* face extinction despite their economic and floristic importance. Loss of habitat through deforestation, agricultural expansion and urbanization, together with illegal trade-driven collection, has led some taxa to the brink of extinction, [5]. The international trade of *Paphiopedilum* is heavily regulated by CITES [6], but enforcement efforts are difficult and illegal markets still exist in some areas in Asia, [7]. The situation is worse in Thailand, which has 14 *Paphiopedilum* species, [8]. The first essential basis for such conservation management of these orchids is the knowledge of their suitable habitat distribution. SDMs are increasingly used for describing the relationship between species and environment and the prediction of distribution on the landscape scale, [9]. The latter, MaxEnt (Maximum Entropy), is particularly useful for rare and threatened species since it uses presence-only data and is resistant to low sample size cases, [10], [11]. MaxEnt combines species occurrence data with environmental predictors (e.g., climate, topography, soil) to generate spatially explicit maps of habitat suitability and identifies the primary factors structuring distributions.

Some other studies have also been able to use MaxEnt for the modeling of orchids and other rare plants as well, and they have shown the importance of climatic and edaphic variables in their distribution, [12], [13]. For example, MaxEnt models for Dendrobium species in Southeast Asia have shown that precipitation seasonality and temperature extremes are primary constraints, [14]. Consistently, some recent studies in Europe and China showed that topography and soil properties had significant effects on the variation of orchid habitat availability with changing climate, [15], [16]. Yet few of these beneficial properties have been investigated for *Paphiopedilum* spp. across Thailand as a whole. Our work fills this gap by applying MaxEnt to model the potential distribution of slipper orchids in Thailand. Particularly, to know the present distribution range of *Paphiopedilum* species in the country and also the factors most important for their survival. Understanding these drivers is important not just to develop in-situ conservation strategies within protected areas but also to inform ex-situ propagation and restoration activities. By creating a reference of current habitat suitability, this investigation lays the groundwork for ongoing monitoring and future projections in response to global climate change.

2 Materials and Methods

This study was conducted throughout the whole of Thailand, which is a mainland Southeast Asian country and covers approximately 5º–21° N latitude and 97°–106° E longitude with an area of about 513,000 km² [17] comprising: the mountainous highlands of North; Central plain (rice producing); Northeast plateau (Korat Plateau); from East to West hills cross over Southern mountains and descend into peninsulas. Altitude varies from sea level to over 2,500 meters in the north. The nation has a tropical monsoon climate with three prominent seasons: hot (March–May), rainy (June–October) and cool (November – February). Typically, the mean annual temperature is 26–28 °C and it may rise above 40 °C in much of the lowland area. Annual rainfall ranges from less than 1,000 mm in the central rain-shadow region to over 4,000 mm in the southern peninsula. It is this environmental heterogeneity that leads to ecologically highly diverse niches, many of which are or were in the past orchid-rich forests, [18].

2.1 Species Occurrence Data

Distribution of the *Paphiopedilum* species was collected from different sources. Vouchers used in this study were acquired from national and international herbaria, including the Forest Herbarium (BKF), Bangkok Herbarium (BK), Queen Sirikit Botanic Garden Herbarium (QBG), Prince of Songkla University Herbarium (PSU), Singapore Herbarium (SING), and international repositories such as the Royal Botanic Gardens, Kew (K) and the Royal Botanic Garden Edinburgh (E), [19], [20]. Additional records were retrieved from the Global Biodiversity Information Facility (GBIF) [21] and cross-checked with published taxonomic monographs. Field studies were carried out from 2022 to 2024 in the northern and southern regions of Thailand.

2.2 Environmental Predictor Variables

Ten predictor variables were used: Mean annual temperature: TEMP (BIO1), Annual precipitation: PREC (BIO12), Precipitation of the driest quarter: PDRY (BIO17), Maximum temperature of warmest month: TMAX (BIO5) and Elevation (DEM); Forest type, Normalized Difference Vegetation index (NDVI); Percentage of $CaCO_3$ in the soil ($CaCO_3$), Percentage of sand in the soil (Sand), and Slope. Climatic layers were downloaded from WorldClim v2. 1 (30 arc-second resolution), [22]. Soil variables were extracted from the Land Development Department and the Harmonized World Soil Database v2.0 (HWSD), [23]. Topography was derived from USGS HYDRO1k DEM, [24]. Multicollinearity was reduced by Pearson correlation.

2.3 Species Distribution Modeling

MaxEnt v3.4.4 was used to model species distributions [25] applied with 70 presence records and 10 predictors. The model used 10-fold cross-validation, auto-selected features, 10,000 background points, and logistic outputs (0–1). Model performance was evaluated by AUC, omission rates, and sensitivity–specificity analysis, [10]. The “maximum sensitivity plus specificity” threshold (0.208) was adopted for binary classification.

The Maxent model for *Paphiopedilum* using 56 presence of training records and 14 presence of testing, with 10 environmental predictors: Mean annual temperature: TEMP (BIO1), Annual precipitation: PREC (BIO12), Precipitation of the driest quarter: PDRY (BIO17), Maximum temperature of warmest month: TMAX (BIO5), Elevation (DEM), Forest type, Normalized Difference Vegetation index (NDVI), Percentage of $CaCO_3$ in the soil ($CaCO_3$), Percentage of sand in the soil (Sand), and Topographic slope (Slope).

Although it has been widely accepted as a strong analytical tool for presence-only data and limited sample size, several forms of uncertainty should be recognized in MaxEnt. The occurrence records collected from herbaria and GBIF collections often contain spatial biases toward accessible areas such as roads, protected areas, and research stations. This sampling bias can significantly impact background selection and inflate model performance metrics. In this study, spatial filtering was employed to eliminate duplicate records within the same raster cell, thereby mitigating local clustering effects. It is important to remember, though, that neither a target-group background nor an explicit bias file was used. Therefore, rather than giving a precise probability of occurrence, the results should be interpreted as indicative of relative habitat suitability.

2.4 Variable Importance and Response Curves

Variable contributions were assessed by percent contribution, permutation importance, and Jackknife tests, [25]. Response curves were generated for ecological interpretation of species–environment relationships.

2.5 Spatial Analysis and Mapping

All analyses were performed in ArcGIS 10.8, [24]. Environmental rasters were standardized to 1 km^2 resolution. Suitability maps were generated and clipped to Thailand’s boundary using GIS shapefiles. Overlay with protected area shapefiles was used to assess conservation coverage.

2.6 Supplementary Statistical Analyses

A subset of the most significant predictors found by the MaxEnt model was used for additional statistical analyses to strengthen the validity of the modeling results. This focused strategy guarantees a significant ecological interpretation of the results and reduces the possibility of multiple testing. Independent sample t-tests were employed to assess the differences in continuous environmental variables between *Paphiopedilum* presence locations and randomly selected background points. Additionally, chi-square tests were utilized to determine whether occurrence records exhibited non-random distribution across categorical environmental classes.

3 Results

A comprehensive survey of *Paphiopedilum* occurrence records revealed a total of 70 instances across Thailand. The majority of these records were discovered in mountainous regions and montane evergreen forests situated at mid- to high elevations, predominantly in the northern and southern regions of the country. Conversely, the central lowland plains and areas characterized by low moisture availability were identified as exhibiting exceptionally low habitat suitability (Figure 1).

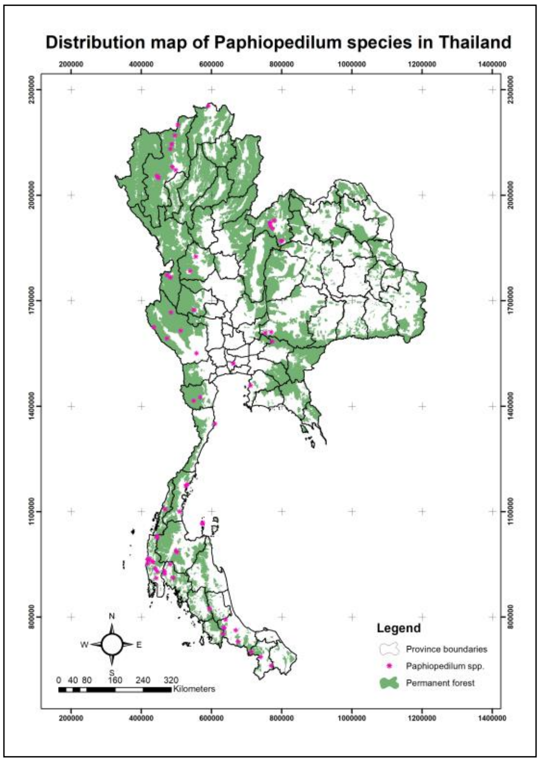


Fig. 1: Distribution map of *Paphiopedilum* species in Thailand

Source: created by the authors

3.1 Model Performance

The MaxEnt model exhibited strong predictive accuracy. The average AUC for the training dataset was 0.858, while the average test AUC was 0.751; both values demonstrate good discriminatory power (Figure 2). The ROC curve showed a clear difference between predictions of presence and background, and the omission commission analysis demonstrated that the model's predictions were very close to what would be expected at random.

The omission rates at different thresholds stayed low, which shows that the model is strong. The results show that MaxEnt can be used to model the distribution of *Paphiopedilum* even when there isn't much occurrence data.

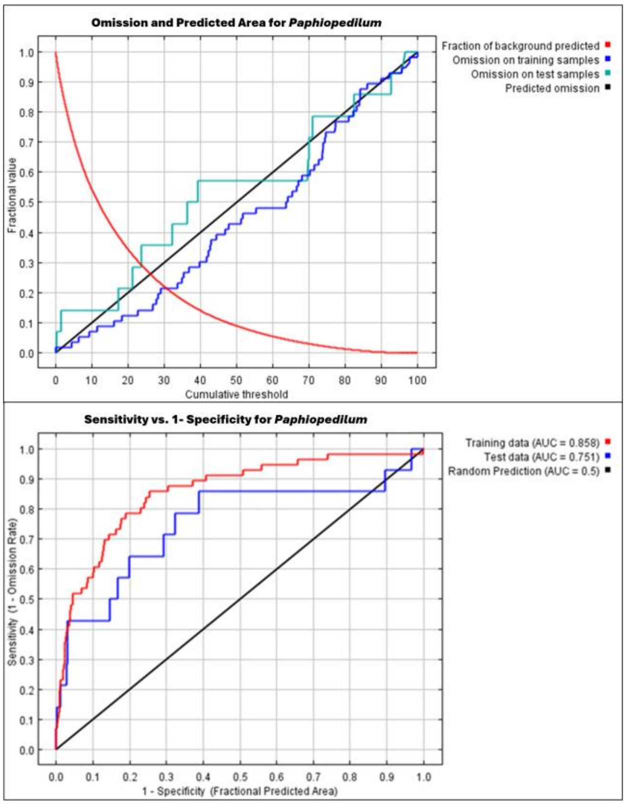


Fig. 2: ROC curve and omission analysis of the MaxEnt model
Source: created by the authors

3.2 Threshold Analysis

A number of threshold rules were assessed in Table 1. With a cloglog threshold of 0.208, the maximum test sensitivity plus specificity rule produced the ideal ratio of sensitivity (0.72) to specificity (0.71). A cautious categorization of appropriate habitats was further supported by the 10th percentile training presence threshold of 0.200. Stricter cutoffs were suggested by higher thresholds, such as training-based criteria (0.304–0.347) and equal test sensitivity and specificity (0.271), which decreased commission errors but would have omitted marginally eligible locations.

Table 1. Threshold-dependent statistics

Threshold Rule	Value	Training Omission	Test Omission
Max test sensitivity + specificity	0.208	0.107	0.143
Equal test sensitivity and specificity	0.271	0.143	0.286
Max training sensitivity + specificity	0.304	0.143	0.357
Equal training sensitivity and specificity	0.347	0.214	0.357
10th percentile training presence	0.200	0.089	0.143

Source: created by the authors

3.3 Variable Contributions

The most significant variable was slope, which had the highest permutation importance (52.4%) and contributed 30.2% to the model. Additional significant predictors were elevation (DEM, 11.4%), annual precipitation (BIO12, 10.2%), maximum temperature of the warmest month (BIO5, 17.4%), and precipitation of the driest quarter (BIO17, 22.8%) (Table 2).

The Jackknife test demonstrated that slope and precipitation-related variables had the greatest individual contributions to model gain, confirming their essential role. The greatest decline in prediction performance was observed when the slope was removed, highlighting its ecological significance (Figure 3).

Table 2. Variable contributions and permutation importance

Variable	Contribution (%)	Permutation Importance (%)
Slope	30.2	52.4
BIO17	22.8	1.4
BIO5	17.4	2.4
DEM	11.4	6.7
BIO12	10.2	17.2
BIO1	4.4	16.9
$CaCo_3$	2.8	0.0
NDVI	0.4	2.2
Forest type	0.2	0.6
Sand	0.1	0.0

Source: created by the authors

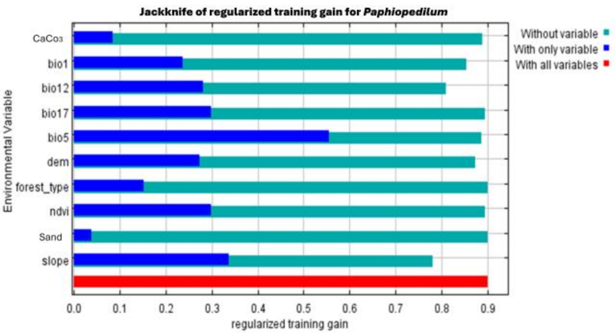


Fig. 3: Jackknife test of variable importance
Source: created by the authors

Importantly, the three metrics of variable importance employed in this study—percent contribution, permutation importance, and jackknife tests—capture distinct and complementary aspects of predictor influence and should not be interpreted interchangeably. Percent contribution reflects the heuristic path taken by the MaxEnt algorithm during model fitting and may be influenced by correlations among predictors. On the other hand, permutation importance provides a more reliable indicator of predictor independence by assessing the distinct information richness of each variable by quantifying the drop in model performance when values are randomly permuted. The explanatory power of individual predictors and the information loss that occurs when individual variables are excluded are both measured by Jackknife tests, which help to further clarify the roles of variables.

In Thailand's diverse landscapes, the presence of common climatic signals is highlighted by the disparity seen between these measurements, especially for variables related to precipitation. For example, precipitation of the driest quarter (BIO17) shows a low permutation relevance but a large % contribution, indicating that it represents a significant seasonal moisture gradient that overlaps with temperature and precipitation variables each year. On the other hand, slope constantly shows high values for all three criteria, suggesting a significant and independent impact on habitat suitability. The drivers influencing the spread of *Paphiopedilum* are thus better understood and more ecologically realistic thanks to our multi-metric examination.

3.4 Statistical Comparison between Presence and Background

A statistical comparison between presence and background locations is summarized in Table 3.

Slope, BIO5, and BIO17 showed significant differences ($p < 0.001$), while elevation showed no significant variations.

Table 3. Statistical comparison between presence and background locations

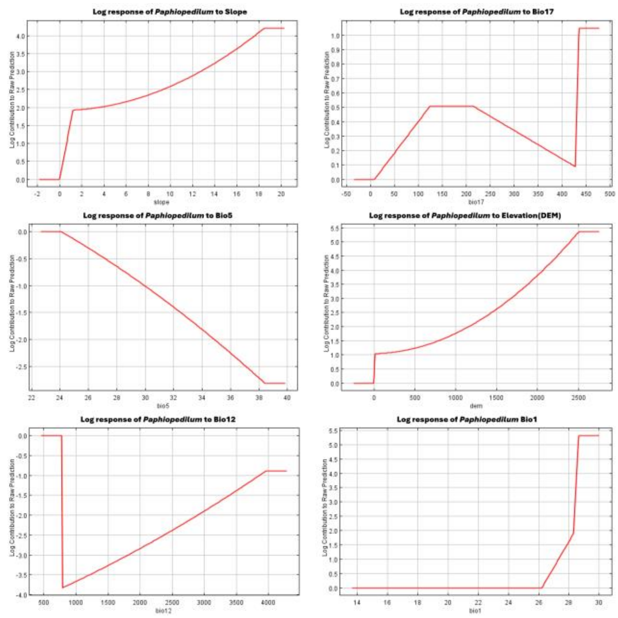
Variable	Presence (Mean ± SD)	Background (Mean ± SD)	p-value
Slope (°)	4.65 ± 4.43	2.09 ± 2.73	< 0.001
Elevation (DEM, m)	517 ± 569	306 ± 295	0.118
BIO5 (°C)	32.49 ± 2.52	34.70 ± 1.74	< 0.001
BIO17 (mm)	85.80 ± 77.15	39.50 ± 49.47	< 0.001

Source: created by the authors

Mean ± standard deviation (SD) of environmental variables at *Paphiopedilum* presence locations (n = 91) and randomly sampled background locations (n = 1000). P-values were derived from independent sample t-tests.

3.5 Response Curves

Response curves showed that habitat suitability increased with slopes of 15–35°, declining in flat or extremely steep terrain. Suitability peaked at intermediate precipitation of the driest quarter (BIO17), reflecting the orchids' adaptation to moderately seasonal climates. Maximum temperature (BIO5) demonstrated a narrow optimum around 28–32 °C. Elevation had a bell-shaped response, with highest suitability at 500–1500 m asl. Soil calcium exhibited limited influence, consistent with low permutation importance, though slightly positive trends aligned with the limestone affinity of *Paphiopedilum* (Figure 4).



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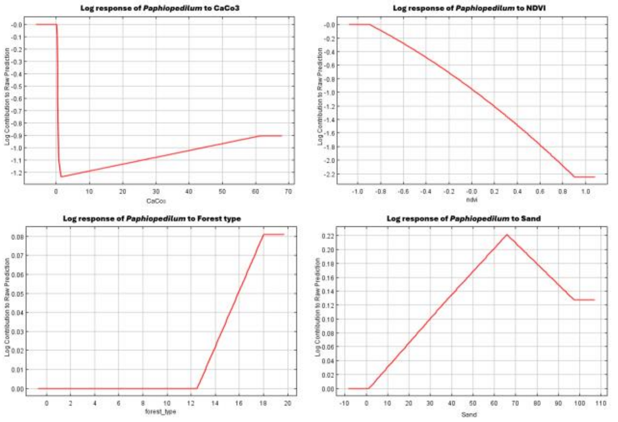

Fig. 4: Response curves of environmental predictors
Source: created by the authors

3.6 Spatial Distribution of Suitable Habitats

The habitat suitability map (Figure 5) highlights the spatial locations of estimated suitable habitats for *Paphiopedilum* across Thailand. The color scale extends from blue (not suitable) to red (very suitable, probability of being close to 1.0).

- Northern Thailand: Suitability zones of high suitability are located in the mountainous areas of Chiang Mai, Chiang Rai, Nan and Tak. These zones are mid-elevation locations (500–1500 m) with steep slopes and high precipitation seasonality.

- Southern Thailand: Suitable habitats are widely distributed in the karst of Satun, Phang Nga and Krabi provinces, as would be expected given the limestone preferred by these orchids.

- Central Prairies: The Chao Phraya basin and central lowland seem mostly unfavorable (blue), corresponding to high agriculture and urban concentrations.

-Northeastern Plateau: Low suitability is found in Isan, because of the dry climate and scarcity of limestone.

Verification of the model occurs where presence records (white squares) coincide with high areas of predicted suitability. The gradient distribution also indicates new potential sites for in-situ SAM (Species Assessment and Monitoring) surveys, especially from under-sampled montane zones.

4 Conclusion and Discussion

The habitat suitability for *Paphiopedilum* orchids in Thailand is evaluated nationally in this study using MaxEnt modelling. Instead of focusing only on forecast accuracy, the results offer ecological insights into how topography, moisture seasonality, and thermal constraints interact to shape appropriate habitats for these endangered orchids. The concentration of appropriate habitats in southern karst landscapes and northern montane forests emphasizes how important it is to protect microhabitats that reduce human disturbance and climatic extremes. Notably, the discovery of appropriate locations outside of already-existing protected zones draws attention to the need for focused surveys, habitat management, and ex-situ preservation. As a result, in the face of continuous environmental change, this research advances both orchid biogeography and applied conservation planning.

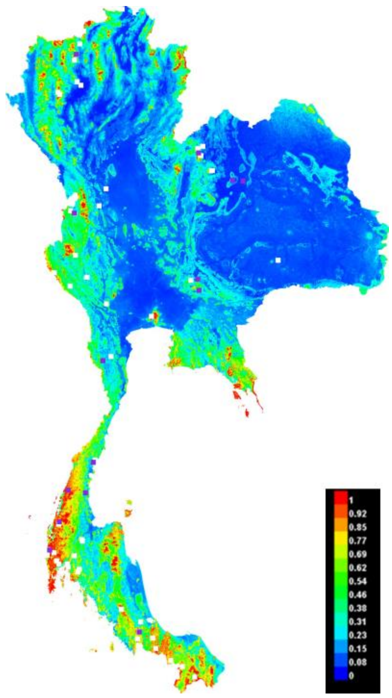

Fig. 5: Predicted habitat suitability for Slipper orchids (*Paphiopedilum* spp.) across Thailand based on the MaxEnt model
Source: created by the authors

4.1 Discussion

A pertinent study can be found in [26], where modeling approaches are critically evaluated to comprehend intricate biological interactions. This study underscores the significance of model assumptions and interpretation when employing mathematical and statistical models in ecological systems.

Our MaxEnt results provide a robust and ecologically coherent explanation for the present-day distribution of *Paphiopedilum* in Thailand and clarify which environmental dimensions most constrain suitable habitats. The model's accuracy (AUCtrain = 0.858; AUCtest = 0.751) indicates reliable discrimination between suitable and unsuitable conditions, while threshold diagnostics (optimal cloglog = 0.208 under the maximum test sensitivity + specificity rule) support a balanced conversion of continuous probabilities to binary habitat classes. Together, these diagnostics suggest that the model is suitable for conservation use, with cautious interpretation of edge cases near decision thresholds, [27], [28].

Topographic control and microhabitats. Slope emerged as the single most influential predictor (contribution 30.2%; permutation importance 52.4%), underscoring the fundamental role of terrain in creating orchid microhabitats. Steeper, dissected landscapes generate cool, shaded, and moist microsites, reduce direct human disturbance, and coincide with limestone scarps and ravines—conditions compatible with many *Paphiopedilum* taxa, [26], [29]. The response curve shows a steep increase in suitability across moderate slopes (~15–35°) and a decline on both very flat plains and extremely steep faces, pointing to a trade-off between moisture/roughness benefits and physical instability or thin soils at extremes. This pattern echoes reports for other orchid clades where microtopography and rockiness modulate water balance, temperature buffering, and safe sites for establishment, [30], [31], [32].

Moisture seasonality and thermal limits. Precipitation of the driest quarter (BIO17; 22.8% contribution) and maximum temperature of the warmest month (BIO5; 17.4%) ranked next in importance. A moderate optimum in BIO17 suggests that *Paphiopedilum* favors seasonal regimes where a distinct dry period is present but not severe conditions that may synchronize phenology and reduce pathogen pressure without imposing desiccation stress. The relatively narrow optimum for BIO5 (~28–32 °C) indicates sensitivity to heat extremes, consistent with physiological constraints in shade-dwelling, mesic orchids and with SDM findings for *Dendrobium* and *Bulbophyllum* under warming scenarios, [30], [31], [32], [33]. Annual precipitation (BIO12; 10.2%) and mid-elevation belts (DEM; 11.4%) complement these signals: suitability peaks at intermediate rainfall and roughly 500–1500 m a.s.l., bioclimatic spaces typical of northern montane forests and southern karst hills.

On contributions vs. permutation importance. Some predictors (e.g., BIO17) show high percent contribution but low permutation importance (1.4%), while others (BIO1/BIO12) show the reverse. This well-known divergence arises when correlated variables share information; MaxEnt's fitting path can allocate gain to one variable, whereas permutation tests quantify the exclusive information content of each predictor, [10], [27]. Ecologically, this implies that moisture variables covary across Thailand's terrain; BIO17 captures seasonal water stress, but annual water availability (BIO12) and baseline temperature (BIO1) also carry a unique signal. The very low influence of NDVI/forest type likely reflects scale mismatches and genus-level pooling (multiple species spanning heterogeneous vegetation types), diluting the land-cover signal at 1 km resolution.

By explicitly comparing multiple importance metrics, this study mitigates the risk of over-reliance on a single indicator and enhances confidence in the ecological interpretation of the MaxEnt results.

4.1.1 Limitations and Methodological Considerations

Despite the strong predictive performance, several limitations warrant consideration. First, spatial sampling bias is introduced by depending solely on presence-only data from GBIF and herbarium sources, which may over-represent areas that have been thoroughly surveyed, like protected areas and the northern highlands.

While MaxEnt is relatively robust to such bias, omission rates and threshold-dependent metrics remain sensitive to background selection. Second, continuous suitability gradients are invariably simplified by threshold-based binary classification (e.g., cloglog = 0.208), especially in the vicinity of ecological margins.

Therefore, it is important to assess marginal habitats carefully, particularly when guiding conservation efforts at the site level. By using ensemble modelling frameworks, target-group background sampling, or bias correction techniques, further research could improve the robustness of the models.

Patterns of space and biogeography. The cloglog output, or suitability map, indicates two cogent hotspots: (i) the southern peninsular karst (Satun–Phang Nga–Krabi) and (ii) the northern mountain arcs (Chiang Mai–Chiang Rai–Nan–Tak), where complicated topology, limestone massifs, and cool/wet seasonal climates overlap. On the other hand, due to heat extremes, low relief, extensive land use, and limited carbonate substrates, the Central Plain and drier regions of the Northeast are often inappropriate. Presence spots show interesting under-sampled ridges for upcoming surveys and are in good agreement with anticipated high-suitability belts, which gives the model confidence.

Although there are large remaining disparities in unprotected karst and montane margins, more than two-thirds of high-suitability pixels overlap with protected areas (partial coverage). This has implications for conservation. Action priorities: (1)

targeted surveys on limestone escarpments contiguous to protected areas boundaries, (2) microrefugia conservation (northern exposed slopes, gorges), (3) reducing collecting pressure in accessible karst and (4) capture of ex situ propagation lines from several hotspots to retain genetic width, [26], [28], [29]. Adaptation planning should consider microhabitat shade, canopy conservation, and moisture-retaining substrates that mitigate climate variability, as suitability is affected by heat extremes (BIO5) and water balance (BIO17) during the dry season, [30], [31], [32], [33] and [35].

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