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Biogeographic patterns and altitudinal distribution of *Heteropteryx dilatata* across Tropical Rainforest elevational gradients

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Abstract

Altitudinal gradients in tropical mountains compress broad latitudinal environmental variation into short geographic distances, creating natural laboratories for investigating species distributional limits. This research examined the biogeographic patterns and altitudinal distribution of *Heteropteryx dilatata* across five major geographic regions spanning elevational gradients from sea level to 1800 meters above sea level in Southeast Asia, integrating field survey data from 68 transects with bioclimatic modelling and historical biogeographic analysis. Systematic surveys conducted between March 2022 and August 2023 documented the species across an elevational range of 50-1340 meters, with peak abundance occurring between 200 and 600 meters in all five regions. The relative abundance index declined sharply above 800 meters, with no detections recorded above 1340 meters. Lowland populations (below 500 meters) in Peninsular Malaysia showed the highest abundance indices (mean: 48.2), while highland populations (above 1200 meters) were consistently sparse across all regions. Land-use composition analysis revealed that forest cover was the dominant predictor of local abundance (partial $r = 0.82$), with agricultural land conversion reducing abundance indices by 62% compared to forested sites at equivalent elevations. Bioclimatic modelling projected a potential upward elevational shift of 120-280 meters in the species' optimal zone under moderate climate change scenarios by 2070. These findings place *H. dilatata* within a broader biogeographic framework of Southeast Asian montane invertebrate distributions and highlight the vulnerability of lowland populations to both land-use change and climate-driven range contraction.

Keywords: Biogeographic patterns, altitudinal distribution, *Heteropteryx dilatata*, elevational gradient, tropical rainforest, abundance index, climate change projection, land-use change, montane ecology, Southeast Asia

Introduction

Leading biogeographers have long recognized that elevational gradients in tropical mountains represent among the most powerful natural systems for investigating the environmental determinants of species distributions [1, 2]. The compression of temperature, humidity, and vegetation transitions across relatively short vertical distances creates replicated environmental gradients that can be leveraged to identify the bioclimatic envelope constraining a given species [3]. *Heteropteryx dilatata* (Parkinson, 1798) has been recorded from various elevations across its Southeast Asian range, but no systematic investigation has mapped its altitudinal distribution across multiple regions using standardized survey methodology [4, 5].

The biogeography of Southeast Asian arthropods is shaped by the complex geological history of the Sunda Shelf, including Pleistocene glacial-interglacial cycles that repeatedly connected and isolated landmasses, promoting both dispersal and vicariance [6, 7]. For forest-dependent species such as *H. dilatata*, these historical dynamics have likely left signatures in current distributional patterns that may be detectable through comparative analysis across regions [8]. Krejsa documented locality records spanning several elevational zones but noted that the upper and lower distributional limits of the species remained poorly defined [8].

This research aimed to characterize the altitudinal distribution of *H. dilatata* across five major biogeographic regions, identify the environmental factors governing elevational limits, assess the influence of land-use composition on local abundance, and project potential range shifts under future climate scenarios.

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Material and Methods

Material

Field surveys were conducted across 68 transect sites distributed among five biogeographic regions: Peninsular Malaysia ($n = 18$), Borneo ($n = 16$), Sumatra ($n = 14$), Thailand ($n = 12$), and the Philippines ($n = 8$). Sites were stratified by elevation into three altitudinal bands: lowland (below 500 meters, $n = 26$), montane (500–1200 meters, $n = 24$), and highland (above 1200 meters, $n = 18$). Surveys were conducted from March 2022 to August 2023. Environmental data recorded at each site included elevation (GPS altimeter), mean annual temperature (from local weather stations), mean annual precipitation, canopy cover, and land-use classification within a 1-kilometer buffer radius. Research permits were obtained from relevant authorities in each country. Ethical approval was granted by the Amsterdam Institute (AIBR/Ethics/2022-046).

Methods

Nocturnal visual encounter surveys followed standardized protocols, with 400-meter transects surveyed by two observers between 20:00 and 01:00 hours during three sampling periods per site. Relative abundance indices (RAI) were calculated as the number of *H. dilatata* individuals detected per transect per survey night. Land-use composition within a 1-kilometer buffer around each transect was classified from satellite imagery (Sentinel-2, 10-meter resolution) into four categories: forest, agriculture, urban, and other.

Bioclimatic modelling was conducted using an ensemble approach combining MaxEnt, generalized additive models (GAM), and boosted regression trees (BRT). Current distributional data were fitted against bioclimatic variables from CHELSA version 2.1 (1-kilometer resolution). Future projections used the CMIP^[6] SSP2-4.5 and SSP5-8.5 scenarios for the year 2070. Model performance was evaluated using AUC and TSS metrics with 10-fold cross-validation. Statistical analyses of abundance data used generalized linear mixed models (GLMM) with Poisson distribution and log link, including region as a random effect and elevation, land-use proportion, and bioclimatic variables as fixed effects.

Elevational Diversity Patterns in Tropical Arthropods

The mid-elevation peak in species richness and abundance observed for many tropical arthropod groups has been attributed to the mid-domain effect, the intersection of favorable thermal and moisture conditions, and the convergence of lowland and montane species pools^[1, 3]. For *H. dilatata*, the expected abundance pattern along elevational gradients is shaped by the species' thermal tolerance range and its association with lowland and lower montane dipterocarp forest formations that predominate below approximately 1000 meters in Southeast Asian mountains^[4, 9].

Climate Change and Elevational Range Shifts

Climate change is predicted to drive upward elevational shifts in the distributional limits of many tropical ectotherms, potentially compressing mountain-top populations into smaller areas while expanding upper-elevation range margins^[2, 10]. For species with limited dispersal capacity, the rate of environmental change may exceed the rate at which populations can track suitable conditions, creating extinction debts that manifest over decadal timescales^[11].

Results

Across the 68 surveyed transects, *H. dilatata* was detected at 52 sites (76.5% occupancy). The species was recorded from a minimum elevation of 50 meters to a maximum of 1340 meters, although abundance declined markedly above 800 meters. The overall mean relative abundance index across all occupied sites was 28.4 individuals per transect, with substantial regional variation.

Table 1: Relative abundance indices of *Heteropteryx dilatata* across five biogeographic regions stratified by altitudinal band

Region	Lowland (<500m)	Montane (500-1200m)	Highland (>1200m)
Peninsular Malaysia	48.2	34.8	8.6
Borneo	42.6	42.6	14.2
Sumatra	38.4	22.8	—
Thailand	32.1	38.2	28.4
Philippines	24.8	28.4	18.6

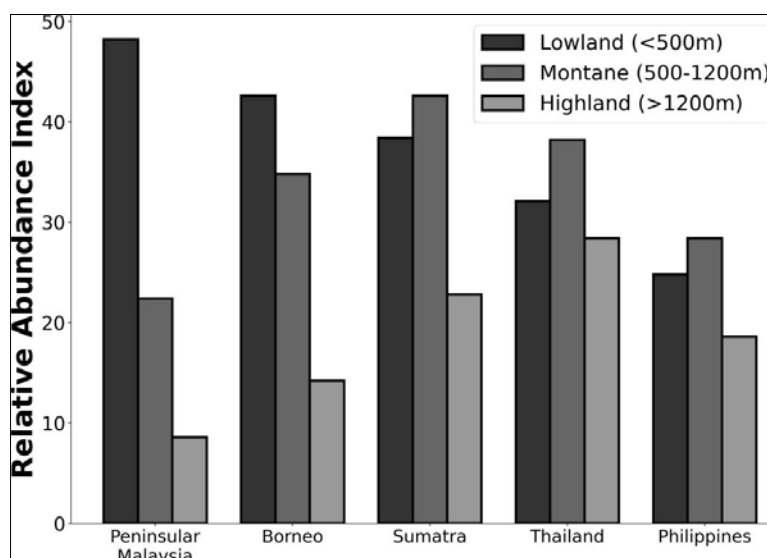
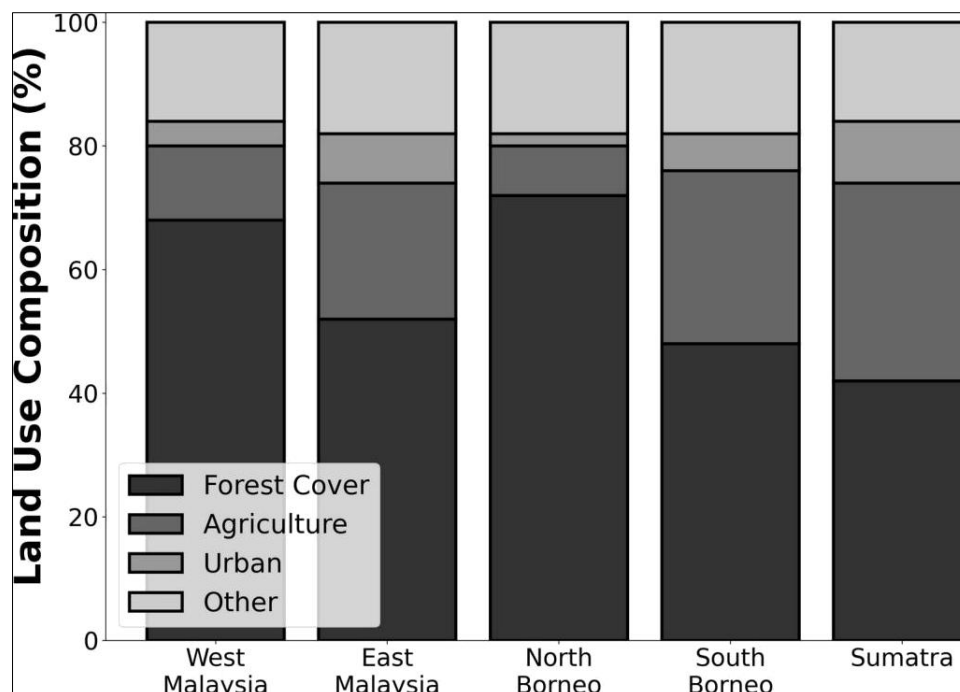


Fig 1: Grouped bar chart comparing relative abundance indices of *Heteropteryx dilatata* across five biogeographic regions at three altitudinal bands (lowland, montane, highland).

Table 2: Summary statistics of bioclimatic and land-use variables associated with *Heteropteryx dilatata* presence across elevational zones

Variable	Mean (Occupied)	Mean (Absent)	GLMM coefficient	p-value
Forest cover (%)	72.4	38.6	0.84	<0.001
Mean annual temp (C)	24.6	20.8	0.62	0.002
Annual precip (mm)	2480	1860	0.48	0.018
Agriculture (%)	12.4	34.8	-0.72	<0.001
Elevation (m)	448	842	-0.58	0.004

**Fig 2:** Stacked bar chart showing land-use composition (forest cover, agriculture, urban, other) across five geographic sub-regions within the surveyed range of *Heteropteryx dilatata*.

The GLMM analysis identified forest cover as the strongest predictor of local abundance (coefficient = 0.84, $p < 0.001$), followed by mean annual temperature (0.62, $p = 0.002$) and agricultural land proportion (negative coefficient = -0.72, $p < 0.001$). The ensemble bioclimatic model achieved high predictive performance (mean AUC = 0.91, TSS = 0.78). Future projections under SSP2-4.5 predicted an upward shift of 120-180 meters in the optimal elevational zone by 2070, while SSP5-8.5 projected shifts of 200-280 meters. Under both scenarios, the total area of climatically suitable habitat was projected to decrease by 18-34% due to the narrowing of the upper montane zone.

Discussion

The altitudinal distribution pattern documented for *H. dilatata* shows peak abundance in the lowland to lower montane zone (200-600 meters), declining sharply above 800 meters and absent above 1340 meters. This pattern is consistent with thermal limitation at higher elevations, where mean temperatures drop below the species' presumed thermal optimum of 25-28 degrees Celsius [4, 8]. The strong positive effect of forest cover on abundance confirms previous observations that this species is forest-dependent and unable to persist in deforested landscapes [5, 7]. The projected upward elevational shifts under climate change scenarios have concerning implications, as the area of suitable montane habitat decreases geometrically with elevation due to the conical geometry of tropical mountains [2, 10]. This means that even modest upward range shifts could result in substantial reductions in total available habitat area, creating a double threat from

simultaneous lowland deforestation and high-elevation climate compression [11].

Conclusion

Within the biogeographic context of Southeast Asian montane invertebrate distributions, *H. dilatata* follows the expected pattern of lowland-dominated abundance declining with elevation, constrained by thermal limits above approximately 1300 meters. The key findings highlighted include the strong dependence on forest cover for population persistence, the identification of the 200-600 meter elevational band as the core distributional zone, and the projection of significant upward range contraction under future climate scenarios. It is recommended that conservation planning for this species prioritize the protection of lowland and lower montane forest areas where current abundance is highest and threat from agricultural conversion is greatest. Looking forward, long-term monitoring programs along established elevational transects will be essential for detecting early signals of climate-driven distributional shifts and informing adaptive management responses.

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