



Assessing the influence of elevational gradient and soil properties on forest diversity in a low tropical hill of Malaysian Sarawak, Southwestern Borneo

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Abstract

This study investigates tree species diversity on a low tropical hill, Teramuo Hill, in Bau District, Sarawak. Although conservation efforts have maintained the vegetation, elevational patterns and soil ecological functions remain underexplored. The study aimed to (1) quantify tree species diversity along the elevational gradient, (2) determine soil property variation along the gradient, and (3) assess the relationship between elevation, soil properties, and tree species diversity. Twenty-eight sampling plots were established along six vertical transects spanning 45–105 m above sea level. A hump-shaped pattern of diversity was observed, with peak diversity at mid-elevation (61–75 m). Soil texture varied systematically, with clay-rich soils dominating lower elevations and sandier soils occurring at higher elevations. Soil moisture content generally declined with increasing elevation. Generalized Linear Model results showed that elevation and soil moisture content had significant negative effects on tree species diversity, while sandy clay loam soils were associated with significantly higher diversity. These findings demonstrate that even modest elevational gradients (<100 m) can structure tree species diversity through interacting topographic and edaphic factors. The study provides important insights for conservation planning and sustainable forest management in low-elevation tropical landscapes.

Keywords Ecosystem · Elevation · Richness · Small hill · Species diversity · Tropical forest

Introduction

The diversity patterns of tree species in Malaysia are assumed to be influenced by several factors, including topographic features such as slope aspect and elevation (Suratman et al. 2020), soil properties (Mahmud et al. 2020), and climate (Ruziman et al. 2022). The land aspects and other geomorphological characteristics are also found to influence species diversity (Laing et al. 2019). Lower plants such as

lianas composition and distribution also are found to be influenced by elevation, soil moisture content, and soil pH and nutrient (Zakaria et al. 2022).

Monge-González et al. (2021) and Brien et al. (2022) respectively examined plant diversity along elevational gradients in tropical forests, primarily focusing on mid- to high-elevation montane systems ranging from 1,000 to 3,500 m above sea level. Monge-González et al. (2021) assessed functional diversity and redundancy across tropical forests and found that both metrics decline with elevation, indicating lower resilience at higher altitudes. O'Brien et al. (2022) highlighted how topography and elevation-driven water availability influence tree growth and survival, with elevation acting as a strong ecological filter through changes in microclimate and biotic interactions. While these studies provide valuable insights into how elevation influences plant communities, they largely neglect low-elevation tropical systems, particularly below 150 m in Southeast Asia and Borneo. This represents a significant knowledge gap, as

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lowland tropical hills host unique environmental gradients and biodiversity patterns that remain poorly understood and underrepresented in global syntheses.

Several local studies have also highlighted important research gaps that warrant further investigation. The Bau District contains several small hills, and while community-led conservation efforts have successfully preserved the local vegetation, other critical ecological aspects such as elevational patterns and soil ecological functions remain underexplored. In a similar low hill known as Gunung Singai, a previous study conducted by Sayok et al. (2013) focused on surveying understory plants. However, this study did not include any survey of trees, and it also did not investigate the potential influence of elevation and soil characteristics on the vegetation in the area. Another study by Ik Pahon et al. (2016) in Gunung Serambu, then only described the composition, distribution, and variety of trees in the hill. However, they did not investigate or explore the factors that might be influencing the diversity of trees in that area. Analysing elements like soil characteristics, climate, terrain, or disturbances could help reveal how these elements affect the variety and distribution of tree species in that area.

Thus, this study aimed to assess tree species diversity, and the impact of elevation and soil properties on diversity at a low tropical hill, Teramuo hill, Bau, Sarawak. The specific objectives are to (1) quantify tree species diversity along the elevational gradient, (2) determine soil property variation along the elevational gradient, and (3) assess the relationship between elevation, soil properties, and tree species diversity. Three hypotheses have been developed i.e., (1) species diversity will decrease along the elevational gradient, (2) soil properties will change along the elevational gradient, and (3) there is a significant negative relationship between elevation and soil properties with tree species diversity.

This study is crucial in understanding the complex mechanisms influencing plant diversity and distribution,

particularly in low-lying tropical hills. It is also essential for developing conservation plans that effectively preserve Malaysia's abundant biodiversity against climate change. The study also provides directions for forests' sustainable management practices.

Methodology

Study area

The study was conducted at Teramuo hill (1.388003° N, 109.992285° E), situated in the vicinity of Kampung Stass, Bau, Sarawak, with an area of about 9.20 hectares (Fig. 1) and serving as a local recreational spot. The hill is divided into three forest types i.e., primary forest, old secondary forest, and agroforest. Over time, the hill faced degradation incidents caused by both natural factors and human activities. Notably, a landslide occurred in the southern part of Teramuo hill around 2020, leading to the absence of significant vegetation in the affected area.

Additionally, human disturbances began as early as 1941 when the local community sought refuge on the hill during Japanese attacks in the confrontation period. Many trees were cut down to construct shelters during this time. In the 1990s, a forest fire broke out at the hill's summit due to debris burning by local children. As a result, the hill's summit is now devoid of vegetation, and the surrounding area is predominantly occupied by *Cratoxylum glaucum* trees. The lower part of the hill is a mix of forests and fruit trees which is under private ownership by some members of the local community. On the other hand, the upper part of the hill (approximately 75 m and beyond) is co-owned by the Kampung Stass community.

Methods

The main plot size was 20 m x 20 m with one mini-plot (1 m x 1 m) within each of the main plots. The sampling started at below 45 m asl, followed by 46 to 60 m, 61 to 75 m, 76 to 90 m, and finally more than 90 m till the peak of the hill. The 45–105 m asl covers about 60 m of vertical relief in which, microclimate, soil moisture, and community composition may shift detectably over short distances. This approach aligns with recommendations that sampling across fine-grained gradients is critical to unpack taxa- and location-specific diversity mechanisms (Ni and Vellend 2024).

The sampling plots were distributed systematically in a vertical line along the elevational gradient, with each plot spaced at an equal distance of approximately 10–20 m. There were six sampling lines, with a total of 28 main plots.

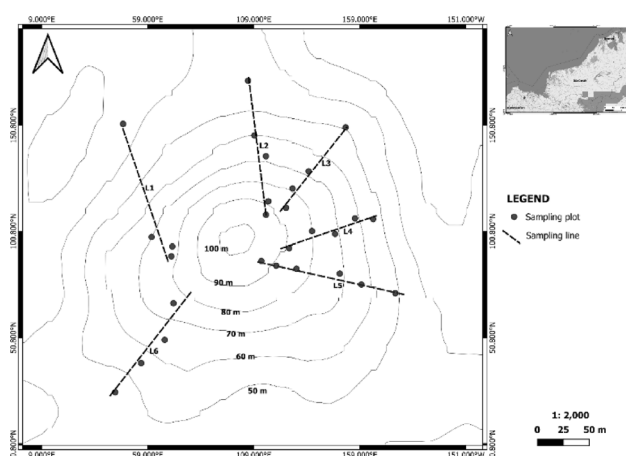


Fig. 1 Sampling sites along the elevational gradient in Teramuo hill

The total sampling area was 1.12 ha. These vertical sampling lines were strategically placed around the hill to represent the dominant elevation patterns and ensure that data were collected across varying elevations. However, some of the plots were relocated slightly due to field constraints such as soil erosion and steep terrain, which made certain areas inaccessible or unsuitable for sampling. This approach provided a more representative sample of the hill's vegetation and elevation characteristics. The accuracy and thoroughness of the survey can also be impacted by the quantity of data gatherers employed. The likelihood of finding rare species may increase since more collectors might potentially cover a bigger area. Hence, the plant survey was conducted with the help of several local correspondents.

To determine the species diversity along the elevational gradient, trees with more than 5 cm diameter at breast height (DBH) were measured in the main plots and the saplings/seedlings (less than 5 cm diameter) in mini-plots. The trees were identified with the help of the local correspondent up to their local names. The identification of the species name was then carried out based on Soerianegara and Lemmens (1993), Lemmens et al. (1995), Soepadmo and Wong (1995), Jensen (1999), and IUCN (2017). At each sampling point, measurements for litter and organic layers were taken, and soil samples were collected and processed following the methods outlined in Carter and Gregorich (2008) and Chaurasia and Gupta (2014). Soil samples were collected from the top 0–15 cm layer using a soil auger, with three subsamples taken within each main plot and composited to form a representative sample. These samples were then air-dried, sieved through a 2 mm mesh to remove roots and debris, and analyzed for soil texture and moisture content. Soil texture was determined based on the percentage of sand, silt, and clay using the hydrometer method, while gravimetric soil moisture content was calculated by oven-drying a separate portion of the fresh soil at 105 °C for 24 h. Finally, the soil type (based on the percentage of sand, silt, and clay) and moisture content were calculated.

Data analysis

The determination of species diversity was carried out following Shannon and Weaver (1964). The species diversity between elevations was compared using the Shannon-Wiener diversity index (H'). The Shannon-Wiener diversity index takes into account both the number of species and their distribution in a given area (Daly et al. 2018). Different transect locations may influence the diversity values. Species richness, defined as the total number of different species observed within a plot, was calculated by counting the distinct tree species recorded in each elevational range. In order to mediate the potential impacts of different transect

location on diversity values, sensitivity analysis was performed by calculating diversity indices separately for different groups of transect locations (Kumar et al. 2022). Typically, the Shannon diversity value falls between 1.5 and 3.5. The Shannon diversity index (H') formula is as follows,

Diversity of a species (H') = $-\sum ((pi) \times \ln (pi))$ in which,

SUM = summation, pi = relative abundance of ith species (ni/N)

The difference in species diversity along the elevational gradient then was depicted in a line graph.

The soil properties i.e., soil type (percentage of soil, clay, silt), soil moisture content (percentage), and mean of litter and organic layer depths (cm) along the elevational gradient then were depicted in graphs to illustrate the change in all parameters. The graphical representation helps to understand the relationships between elevation and soil characteristics, which can be essential for ecological and environmental assessments.

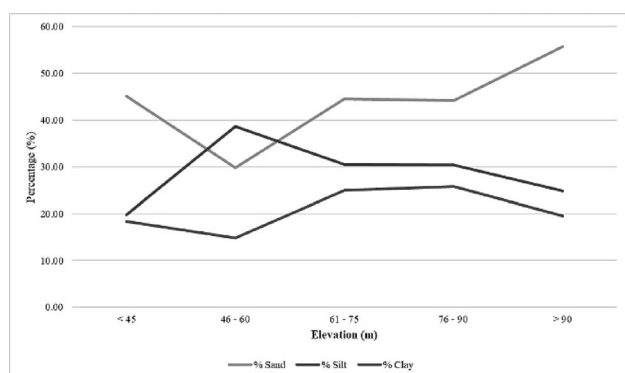
A Shapiro-Wilk test was performed to assess the normality of the dependent variable (tree species diversity). The test yielded a p-value of 0.01, indicating deviation from normality. A correlation matrix was subsequently examined to assess multicollinearity among independent variables (elevation, soil type, soil moisture content, litter layer, and organic layer), and no strong linear relationships were detected.

Given the non-normal distribution of the response variable and the need to evaluate multiple predictor variables simultaneously, a Generalized Linear Model (GLM) was employed (Muller 2004; Dobson and Barnett 2018). Generalized Linear Model was selected over standard linear regression and non-parametric tests because it provides greater flexibility in modelling ecological data that may deviate from strict normality assumptions while allowing simultaneous assessment of multiple environmental predictors within a single analytical framework.

Considering that species diversity (H') is a continuous variable with approximately symmetrical distribution, a Gaussian distribution family with an identity link function was specified. Model adequacy was evaluated using deviance statistics and Pearson chi-square values. The overall significance of the predictor variables was assessed using an omnibus test comparing the full model with the intercept-only model. This analytical framework enabled robust evaluation of the relationships between tree species diversity, elevation, and soil-related environmental gradients.

Table 1 Tree species diversity along the elevational gradient

Elevation	No. of species	Species richness	Diversity (H')
<45 m	89	3.52	2.78
46–60 m	105	3.66	2.94
61–75 m	115	3.98	3.12
76–90 m	161	3.57	3.10
>90 m	70	2.43	2.18

**Fig. 2** Soil type at the sampling sites along the elevational gradient

Results

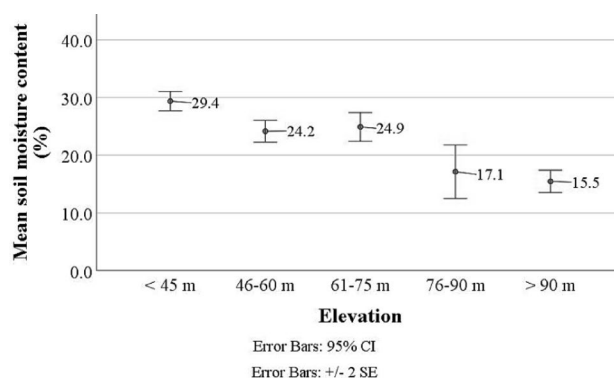
Teramuo hill tree species diversity along the elevational gradient

Tree species diversity along the elevational gradient of Teramuo Hill shows a clear mid-elevation peak pattern (Table 1). The 61–75 m elevation band recorded the highest species richness (3.98) and the highest Shannon diversity index ($H' = 3.12$), indicating that this zone supports the most diverse and structurally balanced tree community along the gradient.

Although the 76–90 m zone had the highest observed number of species (161 species), its standardized species richness (3.57) and diversity value ($H' = 3.10$) were slightly lower than those recorded at 61–75 m. This indicates that the 61–75 m zone not only has high species numbers but also shows greater evenness in the distribution of individuals among species compared to other elevational bands.

At both lower and upper limits of the gradient, diversity metrics decline. The lowest elevation (<45 m) recorded moderate richness (3.52) and diversity ($H' = 2.78$), while the highest elevation (>90 m) showed the lowest richness (2.43) and diversity ($H' = 2.18$). These results suggest reduced species composition and lower evenness at the highest elevation.

Overall, the findings demonstrate a unimodal (hump-shaped) diversity pattern, with peak tree species richness and diversity occurring at mid-elevation (61–75 m), followed by a decline toward both lower and higher elevations.

**Fig. 3** Soil moisture content at the sampling sites along the elevational gradient

Teramuo hill soil properties along the elevational gradient

The soil type analysis shows that soil texture (percentage of sand, silt, and clay) varies along the elevational gradient (Fig. 2). Sand content increases with elevation, peaking at elevations above 90 m, while clay content decreases, with the highest percentages found below 45 m. Silt content peaks at mid-elevations (46–60 m), suggesting a textural transition zone. These patterns support the observation that lower elevations are dominated by clay-rich soils, whereas upper elevations tend to have sandier textures.

According to the USDA Soil Texture Triangle, the lower elevation zone (<45 m) is dominated by clay and clay loam soils. The mid-elevation zone (46–60 m) exhibits the widest variety of soil types, including clay, clay loam, silt loam, sandy clay loam, and silty clay loam. In the mid-upper elevation zone (61–75 m), the dominant soil types are sandy clay loam, sandy loam, and silt clay, with no presence of clay or clay loam. The upper elevation zone (76–90 m) contains fewer soil types, primarily clay and sandy loam. The highest elevation zone (>90 m) is mainly composed of sandy clay loam, sandy loam, and loam soils.

The soil moisture content graph shows that the moisture content drops with an increase in elevation (Fig. 3). While a minor rise is observed at 61–75 m, this deviation is small and within error range, suggesting the overall pattern of declining moisture remains consistent.

Besides that, the result of mean litter and organic layer depths in Teramuo hill shows different patterns along the elevational gradient (Fig. 4). The mean litter layer depth shows a bell-shaped pattern in which, the mean litter layer depth first decreases from the lower elevation of below 45 m to 46–60 m. The mean depth then increases sharply till its highest at 61–75 m and gradually decreases at higher elevations. On the contrary, the mean organic layer depth pattern shows a curved pattern in which the mean depth increases

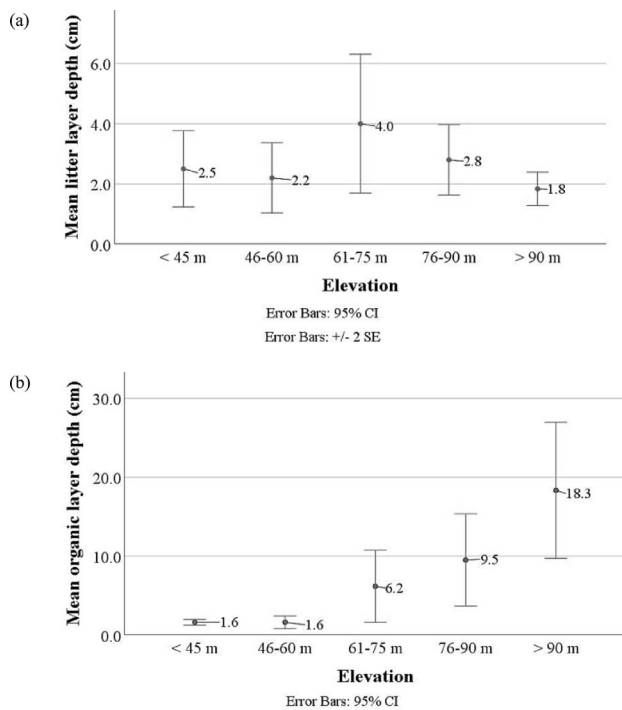


Fig. 4 **a** Mean litter and **b** organic layer depth along the elevational gradient

Table 2 Parameter estimates from the generalized linear model (GLM) predicting tree species diversity as a function of elevation, soil type, soil moisture content, litter layer, and organic layer

(Intercept)	Coef- ficient (B)	Standard error (SE)	Wald Statistic (z-value)	p-value
	8.14	1.81	20.15	0.00
Elevation	- 0.04	0.02	6.93	0.01
Soil type (clay)	0.57	0.63	0.82	0.36
Soil type (clay loam)	- 0.01	0.66	0.00	1.00
Soil type (loam)	- 0.56	0.74	0.57	0.45
Soil type (sandy clay loam)	1.52	0.72	4.46	0.04
Soil type (sandy loam)	0.46	0.58	0.61	0.43
Soil type (silt clay)	- 0.38	0.86	0.20	0.66
Soil type (silt loam)	0.00	—	—	—
Soil moisture content	- 0.15	0.04	11.36	0.00
Litter layer	0.25	0.15	2.91	0.09
Organic layer	- 0.00	0.02	0.02	0.90

slowly at first, then more rapidly after 76–90 m until the highest elevation.

Predictions of factors influencing tree species diversity

The parameter estimates from the GLM (Table 2) indicate that the intercept ($B=8.14$, $p<0.001$) represents the expected baseline value of tree species diversity when all

predictor variables are held constant at zero or at their respective reference categories. Elevation shows a significant negative effect on species diversity ($B = -0.04$, $SE=0.02$, $Wald=6.93$, $p=0.01$), indicating that diversity decreases with increasing elevation. Similarly, soil moisture content shows a significant negative relationship with diversity ($B = -0.15$, $SE=0.04$, $Wald=11.36$, $p<0.001$), suggesting that higher soil moisture levels are associated with reduced species diversity.

Among the soil texture categories, sandy clay loam shows a significant positive effect ($B=1.52$, $SE=0.72$, $Wald=4.46$, $p=0.04$) relative to the reference category (silt loam), indicating higher diversity values in this soil type. Other soil types (clay, clay loam, loam, sandy loam, and silt clay) do not show statistically significant effects ($p>0.05$).

The litter layer ($B=0.25$, $p=0.09$) and organic layer ($B\approx 0$, $p=0.90$) do not significantly predict tree species diversity at the 0.05 level, although the litter layer shows a marginal positive trend.

Overall, the model indicates that elevation, soil moisture content, and sandy clay loam soil type are significant predictors of tree species diversity along the elevational gradient.

Discussion

The first objective, which is to quantify tree species diversity along the elevational gradient, found a hump-shaped relationship between elevation and species diversity. This change is frequently linked to mid-elevation peaks. However, this observed pattern is descriptive in nature, and no direct statistical test was performed at this stage to determine a significant linkage between elevation and species diversity. Therefore, no conclusion regarding acceptance or rejection of the hypothesis is made based solely on this pattern.

This pattern aligns with the findings of Hulshof and Spasojevic (2020) and Latt and Park (2022). The earlier studies stated that these differences may be due to the variation in topographic and edaphic factors (Hulshof and Spasojevic 2020) which directly affects how different tree species disperse (Latt and Park 2022). Study by Hulshof and Spasojevic (2020) emphasizes how such factors drive ecological niches along elevation gradients. As elevation increases, environmental conditions become more limiting, including lower temperatures, higher wind exposure, and reduced soil fertility and moisture retention. These conditions filter out less tolerant species, leading to lower diversity. This is consistent with the environmental filtering hypothesis, where only species with traits adapted to harsh conditions can survive at higher elevations. Such abiotic stressors limit functional traits like leaf area, water use efficiency, and

seedling survival. With increasing elevation, photosynthetic rates and net primary productivity tend to decline due to lower temperatures, cloud cover, and shorter growing seasons (Malhi et al. 2017). This can result in lower biomass accumulation, less leaf litter, and reduced nutrient cycling, creating less favourable conditions for diverse species to establish. Consequently, species richness declines as the ecosystem supports fewer individuals and niches. At mid-elevations, where diversity peaks, there may be a balance between environmental harshness and competitive interactions, maximizing niche availability. As elevation increases further, specialist species dominate, but fewer niches and stronger abiotic filters limit coexistence. This decline in both functional and phylogenetic diversity reduces the number of coexisting species (Monge-González et al. 2021).

Similarly, Latt and Park (2022) highlight the role of environmental factors in shaping community structures. The variation in terrain characteristics, such as slope, aspect, and soil composition, can create diverse microhabitats that favour specific species adaptations. For instance, mid-elevation peaks in species diversity might result from an optimal balance of ecological conditions that support a broader range of species. This highlights the importance of considering the combined influence of topography and edaphic factors when interpreting the observed species diversity patterns.

A study by Fatem et al. (2020) in Tambrau Mountains, West Papua Province, Indonesia also found that tree species diversity varied among different elevations. However, different from the current study, they found that the overall diversity values decrease as the elevation increases. They also found that there was a difference between species diversity in the understory and upperstory levels at different elevations. The understory species diversity showed a decreasing pattern along the elevational gradient. On the contrary, the result of the upperstory species diversity in the previous study showed a similar pattern to the current study. The upperstory species diversity shows a bell-shaped pattern in which the values increase from the lower to the middle area and decrease slightly in the upper area. They indicate that the differences may be due to several factors such as seedling establishment rate and seed dispersal.

The land-use history and anthropological disturbance in the forest area also contributed to the difference (Lugo et al. 2020). The study by Lugo et al. (2020) emphasizes the long-term impacts of human interventions on ecosystem dynamics and emphasizes the necessity to take into account both natural and anthropogenic causes when interpreting the observed patterns of species diversity over elevation gradients. These elements have probably changed the biological conditions and habitat suitability at different elevations. Changes in vegetation structure, disruption of

natural ecological processes, and the introduction of invasive species can all result from human activities including logging, cultivation, and infrastructure construction. These disturbances might have altered the species composition and affected some species' ability to survive at particular altitudes.

The second objective which was to determine soil property variation along the elevational gradient then found differences in soil type, soil moisture content, and litter and organic layer along the elevational gradient. The observed variation in soil properties across elevation bands is based on descriptive analyses and graphical trends. Therefore, no formal hypothesis testing was conducted at this stage to statistically confirm these differences.

The result of the soil type in Teramuo hill shows a difference in soil type along the elevational gradient. The soils are clayey in the lower elevation and sandier in the higher elevation. This variation could be attributed to a combination of factors including topography, parent material, and drainage patterns. This aligns with Bargali and Bargali (2020) and Mishra and Francaviglia (2021) studies. Bargali and Bargali (2020) study in the Nainital district, India also found that the soil sand content increased from very low (up to 350 m) altitude to high altitude (>2000 m). Mishra and Francaviglia (2021) in the Mon and Zunheboto districts of India found that the soil sand content was positively correlated with altitude. The result indicated that the soil sand content increased along the altitude. The gradient in soil texture can significantly influence root growth, nutrient availability, and moisture retention, all of which affect tree species distribution.

The study also found that soil moisture content showed an anomaly pattern along the elevation gradients. This anomaly could potentially be attributed to several interacting factors. Terrain attributes, particularly relative elevation and slope aspect have potential impacts on soil moisture patterns on hillslopes. Yu et al. (2018) found moderate to strong relationships between soil moisture content and two important terrain attributes namely, relative elevation and slope aspect, across the hillslope geographic domain. Both the dry and wet seasons showed this relationship to hold true. Based on these findings, it shows that slope aspect and relative elevation have a big impact on how much soil moisture is distributed on hillslopes.

The result of litter layer depth then is found to be decreasing from the lower elevation of below 45 m to 46–60 m and then increasing sharply till its highest at 61–75 m and gradually decreasing at higher elevations. This supports the observations made by Giweta (2020) and Bohara et al. (2020). Various factors, including anthropogenic and natural disturbances, as well as climatic and seasonal fluctuations, may have an impact on the accumulation of forest

litter (Giweta 2020). The key biotic and abiotic elements that affect the production of in-situ forest litter include climate, soil fertility, actual evapotranspiration, and wind. In addition, elements such as in-situ litter production, litter deposition from outside the system, and litter removal by biotic and abiotic organisms all had a direct effect on the pattern of forest litter accumulation. The difference in litter layer depth may also be due to the rate of decomposition as found by Bohara et al. (2020) in their study at the Shivapuri Nagarjun National Park (SNNP), Nepal in which they found that the rate of decomposition was higher in the lower elevation and decreases along the elevational gradient. The rate of decomposition was also influenced by the precipitation rate and the wet season highlighted higher litter mass loss than the dry season.

Conversely, the organic layer depth pattern then shows that the depth increases slowly along the elevation and gets more rapid until the highest elevation. The current result is comparable to the result of a study by Guzman et al. (2019) at the Rio Bolo watershed within the Cauca Valley in the southwestern Colombian Andes. They found that the percentage of soil organic matter increases from as low as 4.8% in the downslope area to 6.9% in the upslope area. The soil organic matter could be associated with natural and anthropogenic disturbances. The degradation of organic matter may increase the disaggregation of soils which also describes the sandier soil type in both current and previous studies.

Last but not least, the third objective to assess the relationship between elevation, soil properties, and tree species diversity found strong negative relationships between elevation and soil moisture content with species diversity. The species diversity decreases with the increase of elevation and soil moisture content. It was also found that sites with sandy clay loam soil have higher species diversity compared to the other sites. Contrasting from the earlier descriptive analyses, the GLM provides statistical evidence of these relationships. Elevation ($p=0.01$) and soil moisture content ($p<0.001$) show significant negative effects on tree species diversity, while sandy clay loam soil shows a significant positive effect ($p=0.04$). Based on these statistically significant results, the null hypothesis stating that there is no relationship between elevation, soil properties, and tree species diversity is rejected.

Only elevation and soil moisture content have significant negative relationships with tree species diversity. Soil type (sandy clay loam) has a significant positive relationship with tree species diversity. This partially supports previous study by Slik et al. (2009). Slik et al. (2009) in the Southeast Asian tropical forest of Borneo found a negative correlation between tree species diversity and elevation. Similarly, Itoh et al. (2003) at Lambir Hills showed that tree species

distribution in Sarawak is closely tied to topographic variation, with distinct habitat preferences among *Dryobalanops* species. The nature of the habitat differences between these two species was adequate to describe the differences in the spatial distributions.

However, the negative relationship between soil moisture content and diversity in the current study differs from findings by Sarvade et al. (2016) in Himachal Pradesh, India, where higher soil moisture correlated with increased species richness and diversity. This discrepancy may be attributed to regional climatic differences, for example, in humid tropical settings, excess soil moisture could lead to anaerobic conditions, limiting root respiration and reducing tree diversity, especially in clayey soils with poor drainage.

Conclusion

This study provides valuable information the ecological distinction of a tropical hill, highlighting the intricate relationships between elevation, soil, and species diversity. It emphasizes the substantial influence of elevation on forest diversity in the lower hills, with specific tree species dominating different elevational ranges. The study also highlights the role of soil properties, particularly soil type and soil moisture content, as important drivers of species diversity patterns. Conservation strategies should prioritize mid-elevation zones where species diversity is highest, while also maintaining soil integrity and hydrological balance. Protecting areas with favourable soil conditions can enhance ecological resilience and support biodiversity conservation in the face of land-use change and climatic pressures. The current study provides a framework for ecologically informed forest management that can be applied to similar low-elevation tropical landscapes in Southeast Asia and beyond by emphasizing the importance of topographic and edaphic heterogeneity.

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Author contributions Tonga Noweg is the primary author, provides main idea and involves in data collection and writing, Jongkar Grinang provides main idea and involves in data collection and writing, Julia Nelson is the corresponding author, involves in data collection, data analysis and writing, Bridgette Philip, Alfred Keleman, Vivian Patrick, and Selvana Eyra Felix involves in data collection, and Mohd Effendi bin Wasli involves in proofreading.

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Data availability The datasets generated during and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known conflict of financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [IUCN] International Union for Conservation of Nature (2017) Malaysian threatened and rare tree identification and landscape guideline. Sime Darby Property Berhad. Petaling Jaya (Malaysia)
- Bargali VK, Bargali SS (2020) Effect of size and altitude on soil organic carbon stock in homegarden agroforestry system in Central Himalaya, India. *Acta Ecol Sin* 40(6):483–491
- Bohara M, Acharya K, Perveen S, Manevski K, Hu C, Yadav RKP, Shrestha K, Li X (2020) In situ litter decomposition and nutrient release from forest trees along an elevation gradient in Central Himalaya. *CATENA* 194(May):104698
- Carter MRR, Gregorich EG (2008) Soil sampling and methods of analysis. In: Carter MRR, Gregorich EG (eds) Canadian Society of Soil Science, Second, vol 44. CRC Press Taylor & Francis Group, Florida (USA)
- Chaurasia S, Gupta AD (2014) Hand book of water, air and soil analysis (a lab manual). International Science Congress Association, India
- Daly AJ, Baetens JM, De Baets B (2018) Ecological diversity: measuring the unmeasurable. *Mathematics* 6(7)
- Dobson AJ, Barnett AG (2018) An introduction to generalized linear models, 4th edn. CRC
- Fatem SM, Djitmau DA, Ungirwalu A, Wanma AO, Simbiak VI, Benu NMH, Tambing J, Murdjoko A (2020) Species diversity, composition, and heterospecific associations of trees in three altitudinal gradients in bird's head peninsula, Papua, Indonesia. *Biodiversitas* 21(8): 3596–3605
- Giweta M (2020) Role of litter production and its decomposition, and factors affecting the processes in a tropical forest ecosystem: a review. *J Ecol Environ* 44(1):1–9
- Guzman CD, Villada FH, da Silva M, Zimale FA, Chirinda N, Vargas CB, Vargas AM, Rivera B, Moreno P, Steenhuis TS (2019) Variability of soil surface characteristics in a mountainous watershed in Valle del Cauca, Colombia: implications for runoff, erosion, and conservation. *J Hydrol* 576:273–286
- Hulshof CM, Spasojevic MJ (2020) The edaphic control of plant diversity. *Glob Ecol Biogeogr* 29(10):1634–1650
- Ik Pahon IW, Sayok AK, Tagi J (2016) Diversity of trees at Gunung Serambu, Bau district, Sarawak, Malaysia. In: Das I, Tuen A (eds) Naturalists, explorers and field scientists in South-East Asia and Australasia. Topics in biodiversity and conservation. Springer, Berlin (Germany), pp 185–196
- Itoh A, Yamakura T, Ohkubo T, Kanzaki M, Palmiotto PA, LaFrankie JV, Ashton PS, Lee HS (2003) Importance of topography and soil texture in the spatial distribution of two sympatric dipterocarp trees in a Bornean rainforest. *Ecol Res* 18(3):307–320
- Jensen MM (1999) Trees commonly cultivated in Southeast Asia: an illustrated field guide. FAO Regional Office for Asia and the Pacific. Craftsman Press Co., Ltd., Bangkok. (Thailand)
- Kumar P, Dobriyal M, Kale A, Pandey AK, Tomar RS, Thounaojam E (2022) Calculating forest species diversity with information-theory based indices using sentinel-2A sensor's of Mahavir Swami Wildlife Sanctuary. *PLoS ONE* 17(5):e0268018
- Laing RS, Ong KH, Kueh RJH, Mang NG, King PJH, Sait M (2019) Stand structure, floristic composition and species diversity along altitudinal gradients of a Bornean mountain range 30 years after selective logging. *J Mt Sci* 16(6):1419–1434
- Latt MM, Park BB (2022) Tree species composition and forest community types along environmental gradients in Htamanthi wildlife sanctuary, Myanmar: implications for action prioritization in conservation. *Plants* 11(16)
- Lemmens RHMJ, Soerianegara I, Wong WC (1995) Plant resources of South-East Asia timber trees: minor commercial timbers, vol 5. Issue 2). Backhuys, Zuid-Holland. (the Netherlands)
- Lugo AE, Abelleira Martínez OJ, Medina E, Aymard G, Heartsill Scalley T (2020) Novelty in the tropical forests of the 21st century. In: Alex TMF, Dumbrell J, Turner EC (eds) Advances in Ecological Research, vol 62. Academic, Massachusetts (the USA), pp 53–116
- Mahmud K, Khairulakwa H, Nur Fatimah HN, Nornasuha Y, Khandaker MM, Halmi MIE, Noor-Amalina R, Wan Juliana WA (2020) The association of tree species diversity and abundance with the soil edaphic factor in a largest tropical recreational forest of Terengganu, Peninsular Malaysia. *Malaysian Appl Biology* 49(1):159–171
- Malhi Y, Girardin CAJ, Goldsmith GR, Doughty CE, Salinas N, Metcalfe DB, Huaraca Huasco W, Silva-Espejo JE, del Aguilla-Pasquell J, Farfán Amézquita F, Aragão LEOC, Guerrieri R, Ishida FY, Bahar NHA, Farfan-Rios W, Phillips OL, Meir P, Silman M (2017) The variation of productivity and its allocation along a tropical elevation gradient: A whole carbon budget perspective. *New Phytol* 214(3):1019–1032. <https://doi.org/10.1111/nph.14189>
- Mishra G, Francaviglia R (2021) Land uses, altitude and texture effects on soil parameters. A comparative study in two districts of Nagaland, northeast India. *Agric (Switzerland)* 11(2):1–14
- Monge-González ML, Guerrero-Ramírez NR, Krömer T, Kreft H, Craven D (2021) Functional diversity and redundancy of tropical forests shift with elevation and forest-use intensity. *J Appl Ecol* 58(9):1827–1837. <https://doi.org/10.1111/1365-2664.13955>
- Muller M (2004) Generalized linear models. In: Gentle J, H'ardle W, Mori Y (eds) Handbook of computational statistics (volume 1): concepts and methods. Springer-, Berlin/Heidelberg (Germany)
- Ni M, Vellend M (2024) Soil properties constrain forest understory plant distributions along an elevation gradient. *Philosophical Trans B* 379:20230373. <https://doi.org/10.1098/rstb.2023.0373>
- O'Brien MJ, Slik JWF, Baillie IC, Field R, Lloyd J, Phillips OL (2022) Topography in tropical forests enhances growth and survival differences within and among species via water availability and biotic interactions. *Nat Ecol Evol* 6(4):552–561. <https://doi.org/10.1111/1365-2435.13977>
- Ruziman HH, Ismail A, Pardi F, Mohd Hatta SK (2022) Edaphic influences on tree species composition and community structure in a secondary-lowland dipterocarp forest of Kota Damansara Forest Reserve, Selangor. *Malaysian Appl Biology* 51(4):11–21. <https://doi.org/10.55230/mabjournal.v51i4.06>
- Sarvade S, Gupta B, Singh M (2016) Composition, diversity and distribution of tree species in response to changing soil properties with increasing distance from water source - a case study of Gobind Sagar Reservoir in India. *J Mt Sci* 13(3):522–533

- Shannon CE, Weaver W (1964) The mathematical theory of communication. Board of Trustees of the University of Illinois, vol 10. The University of Illinois Press, Illinois. (the USA)
- Slik JWF, Raes N, Aiba SI, Brearley FQ, Cannon CH, Meijaard E, Nagamasu H, Nilus R, Paoli G, Poulsen AD et al (2009) Environmental correlates for tropical tree diversity and distribution patterns in Borneo. *Divers Distrib* 15(3):523–532
- Soepadmo E, Wong KMM (1995) Tree flora of Sabah and Sarawak Volume 1 (1st ed.). Forest Research Institute Malaysia (FRIM), Sabah Forestry Department, and Sarawak Forestry Department 1995. Forest Research Institute Malaysia (FRIM), Kepong (Malaysia)
- Soerianegara I, Lemmens RHMJ (1993) Plant resources of South-East Asia no 5(1) timber trees: major commercial timber, vol 5. Issue 1). Pudoc Scientific, Singapore
- Suratman MN, Abd. Hamid NH, Md Sabri MD, Kusin M, Yamani SAK (2020) Changes in tree species distribution along altitudinal gradients of montane forests in Malaysia. In M Suleiman, A Latiff, AKM Nordin, J Sugau (Eds.) *Tropical Forest Ecology and Management for the Anthropocene* (Chap. 19). Springer. https://doi.org/10.1007/978-3-319-12859-7_19
- Yu B, Liu G, Liu Q, Wang X, Feng J, Huang C (2018) Soil moisture variations at different topographic domains and land use types in the semi-arid Loess Plateau, China. *CATENA* 165:125–132
- Zakaria R, Mohamad Syafiq J, Addo-Fordjour P (2022) Local environmental factors shape liana community structure along an elevation gradient in a tropical rainforest. *Ecoscience* 29(1):1–13

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