Correlation between Woody Species and Environmental Variables in a Tropical Forest in Central Laos

Le Van Cuong[1], Nguyen Van Hop[1], Khamphet Phomphoumy[2], Pham Chi Thinh[1], Pham Thanh Trang[2*]

[1]Vietnam National University of Forestry - Dongnai Campus
[2]Vietnam National University of Forestry

Sự liên kết giữa các loài cây gỗ và các yếu tố môi trường trong rừng nhiệt đới ở miền Trung của Lào

Lê Văn Cường[1], Nguyễn Văn Hợp[1], Khamphet Phomphoumy[2], Phạm Chí Thịnh[1], Phạm Thành Trang[2*]

[1]Trường Đại học Lâm nghiệp - Phân hiệu Đồng Nai
[2]Trường Đại học Lâm nghiệp
**Corresponding author: trangpt@vnuf.edu.vn*

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ABSTRACT

The tropical forest biome serves as a significant focal point for conservation endeavors. However, understanding the variations in woody plant composition and the underlying driving factors remains limited. The vegetation gradient within Phou Khao Khouay (PKK) National Park in central Laos presents an intriguing environmental model for investigating these patterns. This study, conducted within PKK National Park, aims to classify woody plant communities of three different forest types: mixed deciduous forest (MDF), dry evergreen forest (DEF), and mixed coniferous forest (MCF), utilizing both the phytosociology approach and multivariate analysis. Data from 32 permanent plots (each measuring 50 m × 50 m) were analyzed, revealing 5,477 tree individuals with a diameter at breast height (DBH) ≥ 5 cm, representing 194 woody species from 64 families and 133 genera. The results indicate significant diversity at the family and genus levels, identifying four distinct plant communities and 44 indicator species based on Tichy and Chytry's phi coefficient method. Stability characterizes the MCF forest type, while the stands of DEF and MDF exhibit differentiation into three communities each. Notably, high heterogeneity in species composition and environmental conditions is evident, with elevation and soil nutrient levels (specifically total phosphorus and total potassium) emerging as primary influencers on species coexistence. The study also highlights correlations between woody plant species composition and topographic and soil variables. These findings underscore the importance of identifying microhabitats conducive to growing and conserving woody plant species within PKK National Park for future research and conservation efforts.

Keywords:
Evergreen forest, habitat, heterogeneity, indicator species, multivariate analysis, TWINSPAN.

TÓM TẮT

Quần xã rừng nhiệt đới đóng vai trò quan trọng đối với các nỗ lực bảo tồn đa dạng sinh học. Tuy nhiên, những biến đổi trong thành phần loài cây gỗ và các yếu tố ảnh hưởng vẫn cần làm sáng tỏ. Sự khác biệt về thảm thực vật ở các khu vực khác nhau trong Vườn quốc gia Phou Khao Khouay (PKK) ở miền Trung của Lào là một môi trường lý tưởng để nghiên cứu vấn đề trên. Nghiên cứu này được thực hiện ở PKK nhằm mục đích phân loại các quần xã cây gỗ trong ba loại rừng: hỗn giao cây rụng lá (MDF), thường xanh khô (DEF) và hỗn giao cây lá kim (MCF). Các phương pháp thực vật quần xã và phân tích đa biến đã được sử dụng trong nghiên cứu. Dữ liệu điều tra trên 32 ô định vị theo dõi sinh thái (50 m × 50 m) đã được phân tích. Tổng số 5.477 cây có đường kính ngang ngực (dbh) ≥ 5 cm đã được ghi nhận. Các cây này thuộc 194 loài thân gỗ của 64 họ và 133 chi thực vật. Kết quả nghiên cứu cho thấy, các quần xã có sự đa dạng về họ và chi, đồng thời 04 quần xã thực vật và 44 loài chỉ thị đã được xác định dựa trên hệ số phi của Tichy và Chytry. MCF được đánh giá là ổn định về thành phần loài, trong khi DEF và MDF thể hiện sự biến động nhất

***Từ khóa**:*
Loài chỉ thị, môi trường sống, phân tích đa biến, rừng thường xanh, tính không đồng nhất, TWINSPAN.

định. Tính không đồng nhất về loài và điều kiện môi trường đã được làm rõ. Cụ thể, độ cao, tổng phốt pho và tổng kali là những yếu tố ảnh hưởng chính đến sự phân bố của các loài. Nghiên cứu nhấn mạnh mối liên kết giữa thành phần loài và các biến đổi về địa hình và đất đai. Kết quả của nghiên cứu cho thấy tầm quan trọng của việc xác định các điều kiện môi trường sống có lợi cho việc phát triển và bảo tồn các loài cây gỗ ở PKK của Lào.

1. INTRODUCTION

Phytosociology, commonly known as the Braun-Blanquet approach, is a specialized field within vegetation science that focuses on classifying forest communities [1]. It comprehensively examines biocoenosis and the complex dynamics of tree communities, including interrelationships, structural arrangements, species composition, spatial distribution, evolutionary trends, and transient factors that impact ecosystems [2]. Systematic surveys conducted in phytosociology provide valuable insights for strategic planning, accurate resource management, and sustainable resource utilization [3]. The main objective is to establish a robust empirical foundation for vegetation by identifying unique combinations of plant species that represent various vegetation units [4]. This process enhances our understanding of ecological systems in theory and practical applications [5].

At the core of phytosociology lies the principle of associations, where a species' habitat defines its recognized environment and influences the dynamics of surrounding populations [6]. Moreover, the niche theory is closely connected with phytosociology, elucidating the biotic and abiotic factors that influence a species' ability to thrive and maintain stable population dynamics within its habitat [2]. Consequently, phytosociology investigates the ecological interactions among plant species and their environment, shedding light on the mechanisms governing species coexistence.

Collecting data to examine population dynamics across abiotic conditions is of great importance [7]. External influences and the historical geography of plants play pivotal roles in shaping forest communities [8]. The distribution patterns of species within the habitat structure are governed by suitable environmental conditions, where the interplay between ecogenesis and phylogenesis intricately shapes species' current distribution [1]. Environmental factors regulate the presence or absence of vegetation [5]. Understanding the intricate relationship between organisms and their surroundings and species diversity and abundance fluctuations in response to varying environmental circumstances is central to ecological research [2]. The wide range of environmental conditions, particularly pronounced in tropical forests, profoundly influences the species composition, richness, and community dynamics of plants [9, 10]. Ecologists employ advanced multivariate analytical techniques to uncover patterns within vegetation data, thus facilitating a more comprehensive understanding of how environmental factors shape spatial assemblages of plant communities [11].

Statistical programs with numerical algorithms have simplified data analysis by categorizing vegetation data and establishing correlations with environmental factors [12]. Additionally, classification and ordination methods address comprehension challenges by condensing multidimensional field data into a few dimensions and grouping species with similar habitats together [13]. Despite their effectiveness, these techniques have been underutilized in forest classification and management in Laos. Traditional Laos classification based on manual table-sorting and dependent on qualitative criteria hinders the accurate assessment of vegetation structure in the field and yields less dependable results [14, 15].

The present study aims to develop an empirical vegetation model using tree species composition to define distinct vegetation types within a seasonal tropical forest in Laos. This investigation contributes to the broader goal of systematically documenting Phou Khao Khouay (PKK) National Park plant communities through a phytosociological approach strengthened by multivariate statistical analysis. In this investigation, we addressed the following inquiries: (i) Do correlations exist between the woody plant composition within PKK National Park forests and topographic and soil variables? (ii) Is it feasible to differentiate woody plant communities based on indicator species about environmental gradients? (iii) Could adopting this classification and ordination methodology enhance conservation planning efforts in PPK National Park?

2. RESEARCH METHODS

2.1. Study area

Laos, a landlocked country situated on the Indo-Chinese peninsula, houses a significant number of designated protected areas, with PKK National Park being one of the notable sites established in 1993 (Figure 1). Positioned approximately 42 km northeast of the capital city, Vientiane, PKK National Park spans an area of approximately 2,000 km² [16]. Its geographic boundaries are defined by the Ang Nam Ngum reservoir, the largest artificial lake in Southeast Asia, located northwest of PKK National Park.

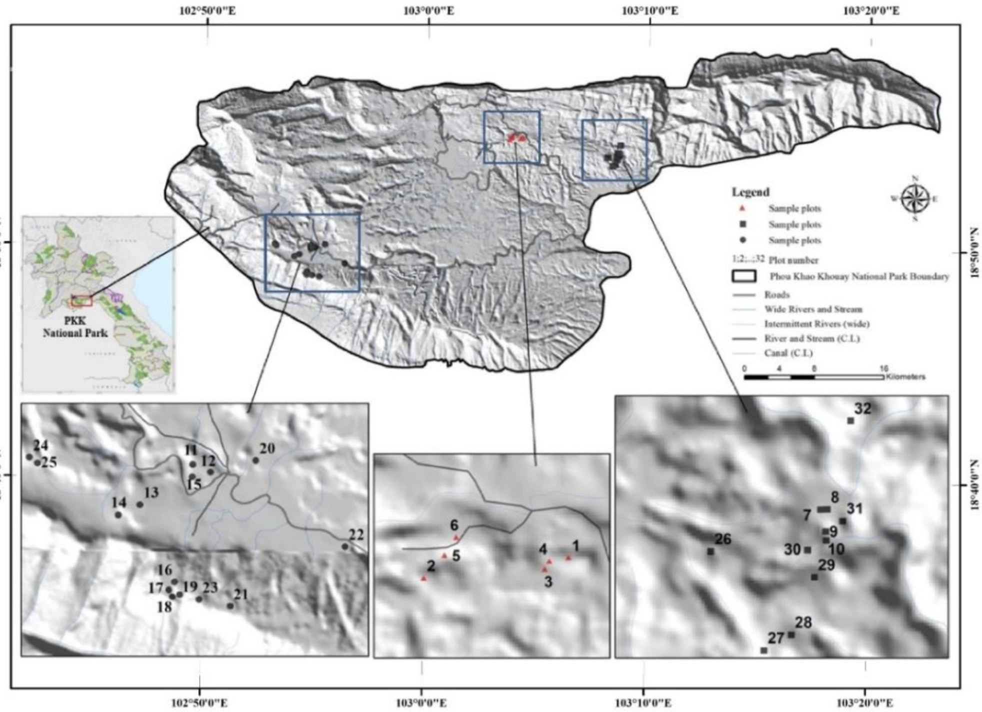

Figure 1. Map of the study area and plot locations

PKK National Park boasts diverse forest types, featuring mixed deciduous forests predominantly dominated by Fabaceae, dry evergreen forests, and mixed coniferous forests primarily composed of Pinaceae species. The park's elevation ranges from less than 100 m to nearly 1,700 m, offering various ecological niches for various species to thrive. The region experiences distinct seasons, which impact its precipitation patterns. During the rainy season, spanning from May to October, PKK encounters an average rainfall of 3,369 mm. Conversely, November to April witnessed significantly lower precipitation levels, averaging around 265 mm [17].

2.2. Data collection

This study employed permanent plots established in 2009 as part of a collaboration between the French National Research Institute for Sustainable Development and the Faculty of Forestry Science at the National University of Laos [18]. In 2009, thirty-two 50 m × 50 m permanent plots were established, with each tree within these plots tagged and mapped. These plots were subdivided into 25 subplots measuring 10 m × 10 m each to facilitate data collection. A comprehensive survey conducted in 2023 included the measurement of diameter at breast height (DBH) and total height (H) of trees, as well as species identification for all woody trees with a DBH ≥ 5 cm within each plot. In cases of uncertainty, specimens were referred to taxonomists working at the herbarium of the Faculty of Forestry Science, National University of Laos, for identification. Furthermore, topographical variables such as aspect, slope, and elevation were recorded using a compass and the Garmin 60s GPS device for each plot.

Soil samples were collected from each study plot at depths ranging from 0 to 20 cm to assess soil characteristics. These samples were subsequently transported to the soil laboratory of the National Agriculture and Forestry Research Institute in Laos for analysis. The primary objective of the soil analysis was to evaluate several crucial soil properties, including soil pH, organic matter content (OM), cation exchange capacity (CEC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), as well as particle size distribution, including sand, clay, and silt.

2.3. Data analysis

The data collected from 32 permanent plots were entered into an MS Excel spreadsheet. Alongside soil and topographic data, species presence or absence data were utilized for multivariate analysis. The Braun-Blanquet method was employed for species and sample classification through reciprocal averaging [19]. The resulting community was named using the TWINSPAN (Two-way Indicator Species Analysis) classification, which is defined by pseudo-species cut levels [2]. Subsequent analyses included cluster and indicator species analysis to identify significant habitat and plant community types [20]. The indicator species analysis was then utilized to establish connections between floristic composition, abundance data, and environmental variables [21]. The Monte Carlo test was employed to calculate and assess indicators for species within each group for statistical significance. A threshold indicator value of 30%, with a 95% significance level (*p-value < 0.05*), was established as the cutoff for indicator species [13].

Species richness refers to the total number of distinct species present within a specific area or sample [20]. It serves as a foundational metric of biodiversity and is typically assessed by counting the number of different species observed within a defined habitat, community, or sample set [22]. In this study, species richness will be calculated individually for each plot surveyed.

The indicator value of plant species was computed using Tichy and Chytry's phi coefficient method, with the formula as follows [23].

$$Phi\ coefficient = \frac{N\times n_p - n\times N_p}{\sqrt{n\times N_p\ (N-n)(N-N_p)}} \qquad (1)$$

where,

N is the total number of plots (sample units) in the dataset, while N_p represents the number of plots in the target group. For occurrences of the species in the dataset, we use n, and for occurrences of the species in the target group, we use n_p.

Detrended correspondence analysis (DCA) is a technique that arranges eigenvalues through reciprocal averaging, enabling the simultaneous ordering of species and samples [24]. To ensure clarity and accurate interpretation of ecological gradients, DCA is utilized to mitigate the arch effect in ordination. This effect, if not addressed, could obscure genuine relationships between data points, potentially leading to misinterpretations. The length of the initial DCA axis, expressed in standard deviation units, serves as an indicator of dataset heterogeneity or homogeneity. This metric guides the selection between linear unconstrained ordination methods such as Principal Component Analysis (PCA) or Non-metric Multidimensional Scaling (NMDS), and constrained ordination methods like Canonical Correspondence Analysis (CCA). Prior to conducting DCA, we managed multicollinearity by applying a variance inflation factor (VIF) threshold to exclude highly correlated variables within each group [25]. This process was carried out separately for both the topographical and soil variables. All analytical procedures were conducted using PC-ORD 6 software for TWINSPAN classification and CANOCO 5 software for multivariate analysis [7, 26].

3. RESULTS

3.1. Characteristics of three forest types in the study area

We recorded 5,477 individual trees representing 194 woody species distributed across 64 plant families and 133 genera (Table 1). The data were collected across 32 permanent plots encompassing three distinct forest types: mixed deciduous forest (MDF), dry evergreen forest (DEF), and mixed coniferous forest (MCF), as classified by the Faculty of Forestry Science at the National University of Laos in 2009. The results revealed that the top three families in terms of species richness were Rubiaceae, boasting 12 species, alongside Dipterocarpaceae and Fagaceae, each with ten species. Moreover, 25 families were characterized by a solitary species, while 36 families exhibited a diversity ranging between 2 and 9 species. Among the plant families, the top 10 contributors to species richness accounted for 44.33% of the total documented species, collectively harboring 86 species. Turning to genera, the survey recorded 133, with notable presence from *Diospyros*, *Castanopsis*, *Syzygium*, and *Ficus*, each featuring more than five species. Interestingly, 98 genera were represented by a sole species, while 31 genera exhibited a presence ranging from 2 to 3 species. Reflecting on genera, the top 10 contributors to species richness accounted for 21.13% of the total species documented, encompassing a cumulative total of 41 species.

Table 1. Fundamental characteristics of three forest types in the study area

Forest type	No. of plots	No. of families	No. of genera	No. of species	Density (trees ha^{-1})	Plots
DEF	15	52	101	139	717	1, 2, 9, 10, 11, 12, 15, 19, 23, 31, 32, 7, 26, 28, 30
MDF	11	50	99	127	725	5, 6, 8, 16, 17, 20, 22, 24, 25, 27, 29
MCF	6	35	44	54	530	3, 4, 13, 14, 18, 21
All	32	64	133	194	657	

3.2. Classification of vegetation

Four woody plant communities were delineated using TWINSPAN classification at cut level 4, as illustrated in Figure 2.

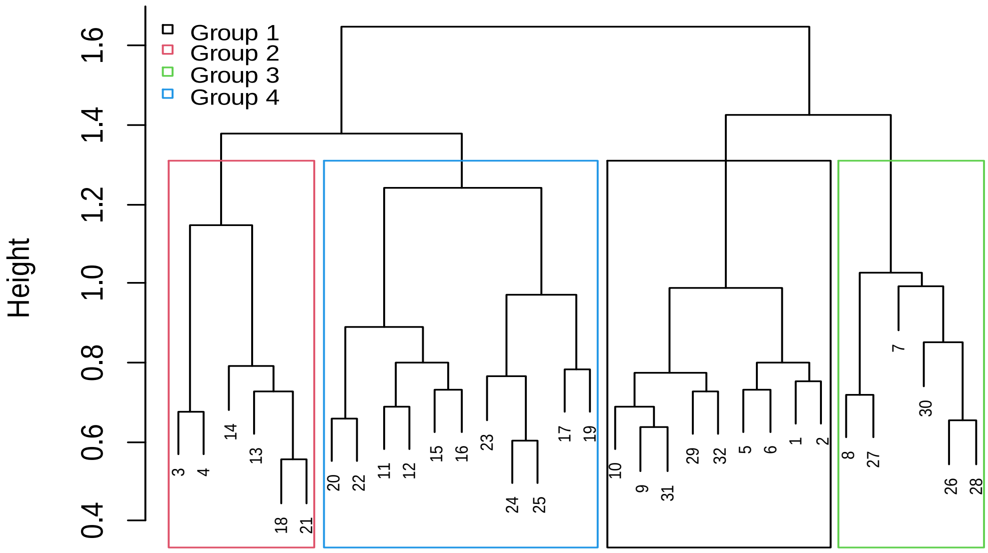

Figure 2. Cluster dendrogram illustrating plant community composition in 32 permanent plots based on indicator species and environmental factors

The TWINSPAN analysis unveiled stability in tree species composition within the MCF forest type over a 15-year period (2009-2023). In stark contrast, the DEF and MEF forest types exhibited fluctuations in species composition during the same timeframe. An examination revealed a consistent trend: plots within the MCF forest type clustered within a single group (Group 2), while those within the DEF and MEF forest types displayed a more intricate pattern, being distributed across three groups with distinct mixing characteristics. Of particular interest was the discovery that plots initially classified under two distinct forest types by the Faculty of Forestry Science at the National University of Laos in 2009 were consistently grouped within the same group across all three groups (1, 3, and 4) at the survey time (Fig. 2).

An analysis was conducted to identify indicator species for four groups within plant communities. Out of the 194 species recorded, 44 were selected as indicators across these groups. Notably, *Cinnamomum iners* emerged as the primary indicator species for Group 1 (9 plots) with an eigenvalue of 0.845. In Group 2 (6 plots), *Pinus merkusii* took precedence as the primary indicator species, boasting an eigenvalue of 1.000. Moving to Group 3 (6 plots), *Hopea ferrea* stood out with an eigenvalue of 0.889. Lastly, in Group 4 (11 plots), *Barringtonia macrostachya* was identified as the primary indicator species. Further details regarding the community groups are outlined below:

(1) *Cinnamomum*, *Aphanamixis*, and *Hopea* Community (Group 1): This community was identified across 9 forest stands, specifically plots 1, 2, 5, 6, 9, 10, 29, 31, and 32, spanning elevations from 300 to 634 m above sea level, with a pH range of 4.54 to 5.52. Within this community, a comprehensive survey documented a total of 99 woody plant species. Notable co-associated species included *Cinnamomum iners, Aphanamixis polystachya, Hopea pierrei, Xerospermum laoticum, Xanthophyllum lanceatum, Alphonsea gaudichaudiana, Diospyros sylvatica, Mangifera odorata,* and *Polyalthia nemoralis*.

(2) *Pinus*, *Dipterocarpus*, and *Schima* Community (Group 2): This community was observed in stands 3, 4, 13, 14, 18, and 21, situated at elevations ranging from 540 to 890 m above sea level. A total of 55 species were recorded within this community, with a pH range of 5.22 to 5.66. Notable co-associated species included *Pinus merkusii, Dipterocarpus obtusifolius,* and *Schima noronhae*.

(3) *Hopea*, *Canthium*, and *Diospyros* Community (Group 3): Identified across stands 7, 8, 26, 27, 28, and 30, this community spanned elevations from 344 to 444 m above sea level. A comprehensive survey revealed a total of 78 species within this community, occurring at relatively higher pH values ranging from 4.62 to 5.89. Co-associated species included *Hopea ferrea, Canthium glabrum, Diospyros pendula, Microcos tomentosa, Lagerstroemia calyculata, Litsea monopetala, Sindora siamensis, Chionanthus ramiflorus,* and *Syzygium grande*.

(4) *Barringtonia*, *Diospyros*, and *Aporosa* Community (Group 4): This community was distributed across stands 11, 12, 15, 16, 17, 19, 20, 22, 23, 24, and 25, found at elevations between 740 and 900 m above sea level. A total of 146 species were documented within this community, which thrives in low pH conditions ranging from 4.54 to 4.80. Notable co-associated species included *Barringtonia macrostachya, Diospyros defectrix, Aporosa villosa, Elaeocarpus tectorius, Nephelium hypoleucum, Artocarpus gomezianus, Diospyros martabanica, Cain, Castanopsis indica, Maesa ramentacea, Eurya acuminata, Choerospondias axillaris, Triadica cochinchinensis,* and *Chaetocarpus castanocarpus.*

3.3. Ordination

The data initially utilized for TWINSPAN classification underwent further analysis for ordination. Within Bray-Curtis ordination, axis 1 encompassed distances ranging from plot 18 to plot 28, accounting for 22.30% of the variability in the original matrix. The scores for axis 1 ranged between 0.03 and 0.71. Axis 2 extended from plot 7 to plot 27, exhibiting ordination scores ranging from 0.02 to 0.66. Axis 2 captured 11.09% of the original distance matrix variability (Fig. 3a).

In DCA ordination, the PKK exhibited a variation of 3.86, with the eigenvalues peaking for axis 1 (0.63), followed by axis 2 (0.41), axis 3 (0.27), and axis 4 (0.07). Notably, the greatest gradient length was observed along axis 1, measuring 3.95.

The analysis of species distribution in the DCA ordination space revealed distinct clustering patterns. Several plant species exhibited cohesive habitat preferences (Fig. 3b). Examining the DCA ordination of stands, axis 1 revealed pronounced variation among species, notably between plot 18 and plot 28. Similarly, axis 2 highlighted significant species variation, particularly evident between plot 7 and plot 27 (Fig. 3a).

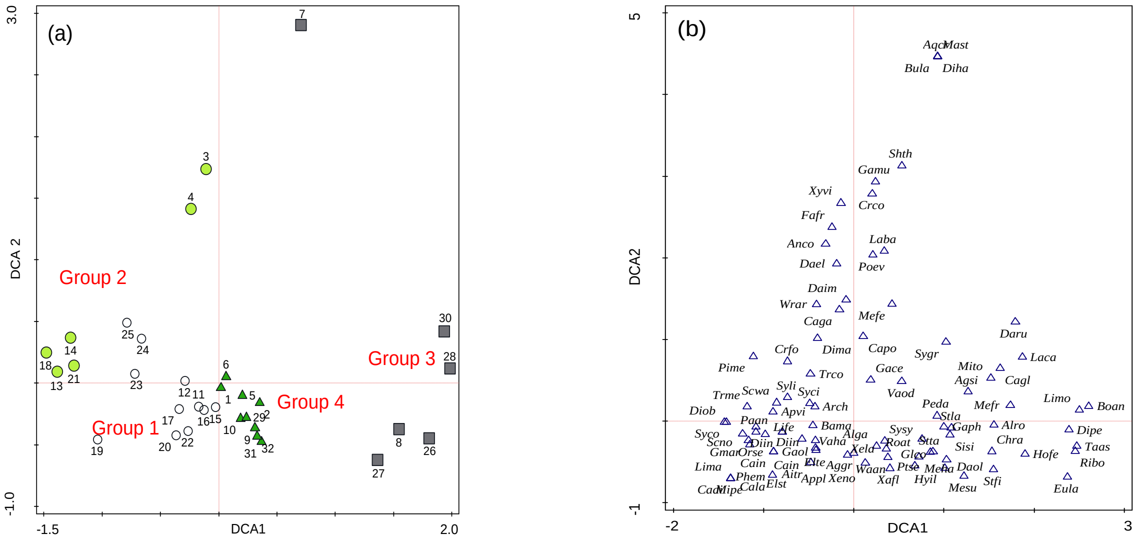

Figure 3. DCA ordination of stands (a) and species (b) of PKK National Park

(Scientific names and abbreviations for 194 woody species listed on https://github.com/quyforest/data-PKK)

DCA analysis revealed that the first axis spanned 3.95 standard deviation units, indicating a diverse compositional dataset, thus suggesting a preference for unimodal ordination techniques. Subsequently, Canonical correspondence analysis (CCA) was conducted to investigate the relationship between forest stand attributes and environmental fluctuations within PKK. In this CCA ordination, both the species matrix and environmental factors were incorporated. The results showed that axis 1 had a maximum eigenvalue of 0.58, axis 2 had 0.42, and axis 3 had 0.26. The pseudo-Canonical correlation value across all axes was calculated as 0.94. Moreover, permutation tests across all axes indicated a pseudo-F value not exceeding 0.1, with a p-value of 1 (Fig. 4).

The CCA ordination analysis revealed that both stand characteristics and plant species exhibited a clear sensitivity to various environmental factors. Woody species associated with elevation, slope, aspect, and soil attributes such as CEC, TN, sand content, and silt content showed positive correlations, predominantly clustering within Groups 1 and 2. Conversely, species positively correlated with TK, TP, OM, and pH were mainly grouped in Groups 3 and 4.

Regarding the three topographical variables (elevation, slope, aspect), positive correlations were evident across all three variables. These topographical parameters displayed negative associations with soil properties, including OM, TK, TP, and pH. Notably, elevation, TK, and TP exhibited the most robust correlations, followed by sand content, pH, OM, CEC, TN, silt content, aspect, and slope.

4. DISCUSSION

4.1. Characteristics of three forest types in the study area

In recent decades, there has been a significant surge in efforts to comprehend forest dynamics, mainly through prolonged and repetitive studies focused on the species composition of natural forest communities [27]. Researchers have consistently stressed the imperative nature of these investigations, highlighting their pivotal role in untangling the intricacies inherent within forest ecosystems [28, 29]. In contrast to prior presumptions, recent studies have debunked the notion of tropical forests as static entities with immutable community structures [22, 30]. Instead, they have unveiled the dynamic nature of these ecosystems, showcasing fluctuations in community composition across both temporal and spatial dimensions [19]. Following the changes in species composition within these forests is paramount for formulating robust management and conservation strategies [7].

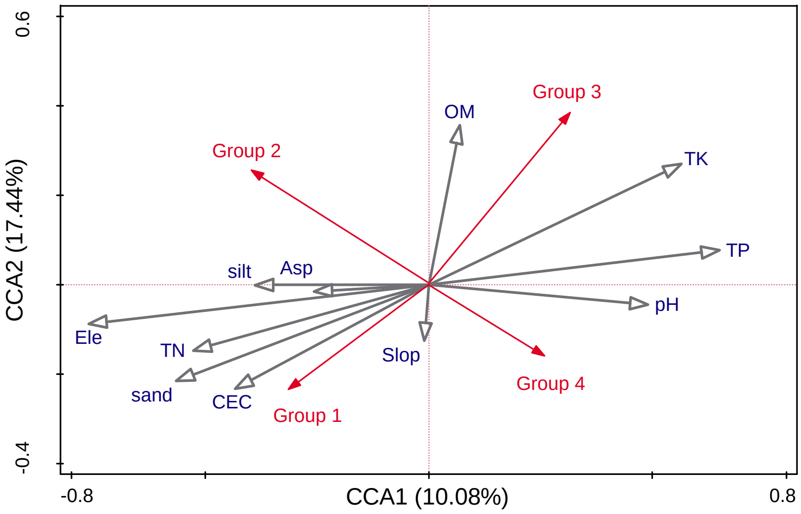

Figure 4. CCA ordination of species groups with environmental variation in PKK National Park

Examining the three forest types within PKK National Park in this study has provided insights into the diversity of woody plant families and genera within the seasonal tropical forest in Laos. Among the 64 documented families, ten have emerged as contributing the most to species richness, hosting a total of 86 species. Remarkably, these ten families alone represent 44.33% of the total species recorded across the 32 permanent plots surveyed, highlighting their pivotal role in shaping the tropical tree communities within the national park. Based on Tomachop's perspective, the woody plant communities under consideration exhibit significant family diversity, further accentuating the ecological dynamics within forest communities in the study area [31]. The presence of a diverse array of families underscores the complex interactions between various plant species and their habitat [32]. Moreover, when considering genera, it becomes evident that a group of ten top genera with the highest species richness accounts for 21.13% of the total recorded species, further corroborating the woody plant diversity within PKK National Park.

4.2. Classification of vegetation

Within the natural sciences, the term "indicator" denotes a plant, animal, substance, or object used to authenticate a variable that eludes direct measurement [24]. These indicators span various categories like biological, physical, or chemical, commonly acknowledged as ecological indicators [6]. Of particular note are bioindicators, organisms intricately linked to specific environmental factors, enabling their deployment as indicators of such factors [12]. Predominantly, species and communities emerge as the most prevalent bioindicators [13]. In their analysis of biodiversity and ecosystem services indicators, Feld et al. noted a higher prevalence of community-based indicators (49.3%) over species-based ones (32.8%) [33]. Despite this, the longstanding practice of employing indicator species to monitor and evaluate environmental conditions remains firmly entrenched in the realm of ecology [34].

In this study, we employed TWINSPAN classification to examine the community composition in the study area, utilizing both indicator species and environmental factors. Our findings unveil a subdivision of the three forest types initially identified by the French National Research Institute for Sustainable Development and the Faculty of Forestry Science at the National University of Laos in 2009 into four distinct communities. Particularly noteworthy is that within the MCF forest type, the original forest stands remained cohesive within a single group, whereas for the DEF and MDF forest types, the stands were categorized into one of three disparate clusters. The differences in species composition among these communities, as delineated by the indicator value of the species they encompass, distinctly mirror the gradient in prevailing ecological conditions across habitat types for the species under consideration.

Building upon the results of the TWINSPAN classification, the categorization of the DEF and MDF forest types in 2009, as observed during the study, has become obsolete, necessitating additional efforts to update the dynamics of forest resources. The findings of the classification, which identify four distinct communities and their indicator species in this study, provide essential groundwork for forest managers at PKK to undertake this endeavor.

4.3. DCA and CCA ordination

This study established four plant communities by analyzing data from 32 stands, encompassing 194 woody plant species, and employing the TWINSPAN method. Kabir et al. proposed that alterations in environmental conditions influence shifts in plant communities, affecting both habitat and flora [35]. Our investigation focused on the primary flora unit and its response to environmental changes. Both DCA and CCA analyses revealed connections between woody plant communities in PKK National Park and fluctuations in topography and soil composition. Our results indicated a correlation between the distribution of woody plant species and 12 environmental variables.

Ordination techniques are pivotal tools in ecological research, enabling the exploration of ecosystem dynamics and the elucidation of flora distribution patterns based on ecological factors [2, 24]. In this study, elevation and soil nutrients, including TK and TP, emerge as key determinants, significantly shaping both the quantity and quality of existing flora. As elevation increases, so do temperature and evaporation rates, leading to decreased moisture levels [36]. Notably, Karemii observed that certain plant species exhibit a preference for lower elevations, driven by shorter growing seasons and less favorable temperatures [37]. Our findings echo those of numerous preceding studies, underscoring the critical influence of environmental variables on plant coexistence [12, 13, 20]. Soil, a cornerstone natural resource, serves diverse ecological functions [2]. Our research underscores the profound impact of soil properties—including pH, OM, CEC, nutrient availability, and particle size distribution—on plant species composition and interactions.

Certain authors have noted that PKK National Park faces significant challenges posed by local residents, namely the exploitation of non-timber forest products and deforestation, both of which impede the regeneration of woody plants [38, 39]. The exponential expansion of human populations, coupled with the depletion of non-timber forest resources and various other factors, exacerbates habitat loss, soil erosion, and compromises the functionality of the forest ecosystem within the surveyed area. Consequently, safeguarding the biodiversity of the region emerges as imperative, ensuring the sustenance of vital resources for the prosperity of forthcoming generations.

5. CONCLUSION

This study was conducted in Phou Khao Khouay National Park in central Laos, utilizing data collected from 32 permanent plots across three forest types: DCF, MDF, and MCF. Our findings documented 5,477 tree individuals representing 64 species from 133 genera across 32 stands. By analyzing the species richness of 10 families and 10 genera, we identified significant diversity in both the families and genera of woody plants in the study area. Four plant communities, each with 44 indicator species within the three forest types, were classified. TWIN analysis revealed minimal fluctuation in species composition within the MCF forest type from 2009 to 2023, indicating stability. In contrast, DEF and MDF forest types exhibited differentiation into three distinct plant communities.

Additionally, DCA analysis underscored high heterogeneity in species composition and environmental conditions across the study area. CCA analysis unveiled a strong correlation between woody plant species composition and topographic and soil variables. Notably, elevation, along with two soil nutrients—TP and TK—emerged as primary influencers on species coexistence among the 12 environmental variables examined. Moreover, our study elucidated the significant correlation between specific habitat types and the presence of particular species across the forest stands in the research area.

Given the prevalence of evergreen trees with large leaves in PKK National Park, indicating heightened water demand compared to deciduous plants, elevation emerged as a crucial determinant shaping species distribution. Our findings underscore the importance of future research aimed at identifying specific microhabitats conducive to the growth and conservation of woody plant species within PKK National Park.

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