Effects of forest structure on woody plant diversity in an evergreen broadleaved forest in Cao Bang province

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ABSTRACT

The present study was conducted in Phia Oac-Phia Den National Park in Cao Bang province to evaluate the interplay between forest structure and the diversity of woody plant species in an evergreen broadleaved forest. In six 1-ha permanent plots, all trees with a diameter at breast height (DBH) greater than 6 cm were identified, and their DBH, crown diameter, total tree height, and spatial coordinates were recorded. Spatial structure indices, non-spatial structure indices, and species diversity indices were utilized to construct a structural equation model (SEM). The results showed that the SEM model developed exhibited a good fit with CFI=0.98 and SRMR=0.02, signifying its accurate data modelling capabilities. The results emphasized the significant influence of both spatial and non-spatial structure on various woody plant diversity indices, including species richness, Shannon-Weiner diversity, Simpson diversity, and Pielou evenness. Notably, the horizontal spatial structure exerted a more pronounced effect on species diversity than the vertical structure. Furthermore, this study indicated a positive relationship between forest structure and diversity indices, highlighting their benefits. Conversely, interspecies competition negatively affected plant species diversity within the forest stands. This study provides a robust scientific foundation that supports effective strategies for the conservation and sustainable development of forest resources in the study area. It offers valuable insights for forest managers aiming to implement conservation and sustainability initiatives in the tropical evergreen broadleaved forest region.

Keywords:
Pielou evenness, spatial structure, species mingling, structural equation modeling, tropical forest

TÓM TẮT

Nghiên cứu này được thực hiện để đánh giá ảnh hưởng của cấu trúc rừng tới sự đa dạng loài thực vật thân gỗ trong rừng lá rộng thường xanh ở Vườn quốc gia Phia Oắc-Phia Đén, tỉnh Cao Bằng. Tất cả các cây thân gỗ có đường kính ngang ngực từ 6 cm trở lên (DBH ≥ 6 cm) trên 6 ô tiêu chuẩn định vị có diện tích 1 ha đã được xác định tên loài, đo DBH, đường kính tán, chiều cao vút ngọn và lập bản đồ vị trí cây. Các chỉ số cấu trúc không gian, phi không gian và đa dạng loài được sử dụng để xây dựng mô hình phương trình cấu trúc (SEM). Kết quả nghiên cứu chỉ ra rằng, mô hình SEM được xây dựng có mức độ phù hợp cao với CFI=0,98 và SRMR=0,02, biểu thị khả năng mô phỏng dữ liệu một cách chính xác. Kết quả nghiên cứu nhấn mạnh ảnh hưởng đáng kể của cả cấu trúc không gian và phi không gian của các lâm phần đối với các chỉ số đa dạng của thực vật thân gỗ, bao gồm độ giàu loài, đa dạng Shannon-Weiner, Simpson và Pielou. Phát hiện đáng chú ý của nghiên cứu này đó là cấu trúc không gian theo mặt cắt ngang ảnh hưởng rõ rệt hơn cấu trúc theo chiều thẳng đứng đến đa dạng loài. Ngoài ra, kết quả cũng cho thấy mối quan hệ tích cực giữa các đặc điểm cấu trúc của lâm phần

Từ khóa:
cấu trúc không gian, độ đồng đều Pielou, độ hỗn loài, phương trình cấu trúc, rừng nhiệt đới.

và các chỉ số đa dạng loài, điều đó làm sáng tỏ ảnh hưởng có lợi của chúng tới sự ổn định của quần xã cây rừng. Ngược lại, sự cạnh tranh giữa các loài ảnh hưởng tiêu cực đến sự đa dạng loài cây trong lâm phần. Nghiên cứu này cung cấp cơ sở khoa học vững chắc để hỗ trợ các nhà quản lý phát triển các chiến lược hiệu quả trong hoạt động bảo tồn và phát triển bền vững tài nguyên rừng trong khu vực nghiên cứu.

1. INTRODUCTION

In the distribution of trees, both intraspecific and interspecific competition and environmental filtering play significant roles [1]. Instead of conducting separate analyses, combining diversity studies with spatial pattern analyses provides a more comprehensive understanding [2]. Exploring the impact of forest stand structure on species diversity is crucial, but investigations into forest spatial structure can offer insights into how diversity changes across different spatial scales [3]. Such insights can be leveraged to minimize negative impacts on the complex relationship between humans, organisms, and the environment.

Woody plants within forest stands serve as the foundational elements that shape the structure of forest ecosystems [4]. Their role extends from facilitating seedling growth and nutrient recycling to soil conservation and preventing erosion. While the interactions and relationships among tree species are intricate, certain aspects, such as competition for resources and space, can be readily observed. For instance, during their growth, trees vie for light, nutrients, and territory, eventually establishing various canopy layers in the vertical dimension [5]. This stratification is only one facet of the broader and more intricate spatial configuration of forests. It prompts questions like whether the spatial arrangement affects the diversity of tree species more in the vertical or horizontal dimensions and which of these orientations exerts a more substantial influence on plant diversity. Despite the significance of these queries, there still has to be a knowledge gap, especially in studying Vietnam's forests. Thus, delving into the influence of spatial configurations on tree diversity holds both practical and theoretical importance.

Many studies in Vietnam have explored the impact of environmental factors and forest dynamics on species diversity in its evergreen closed forests. Nevertheless, these studies have predominantly concentrated on non-spatial structures and ecological variables. For instance, Nguyen Van Hop and Le Thai Hung *et al.* assessed woody plant diversity by considering species occurrence frequency, elevation, and topography [6, 7]. A handful of other investigations have felt the influence of spatial structure on species diversity. Nguyen Hong Hai and Nguyen Minh Quang, for example, employed spatial statistical analysis techniques to investigate individual species-area relationships [8].

In contrast, earlier studies delved into the interplay of ecological factors employing conventional statistical techniques (first-generation statistical analysis methods) [9]. These researchers relied on individual or groups of observable variables for regression or variance analyses, seeking to extract and scrutinize the connections among these study variables [10]. Essentially, traditional statistical methods focus solely on the explicit associations among observable variables and do not account for the links involving latent variables (unmeasured variables). Consequently, these conventional techniques may only partially capture the causal relationships within the study model [11].

On the other hand, structural equation modelling (SEM) represents a second-generation statistical analysis method with numerous merits [12]. The SEM was created to tackle the intricate web of relationships among multiple variables, encompassing latent variables within the model. It can reveal both the associations and the strength of influence among these latent variables, as well as validate the model's appropriateness. This enables a more comprehensive and precise assessment of relationships. Despite SEM's widespread application in various domains like education, psychology, and economic management, its use in forestry, particularly in forest structure and diversity studies, remains limited.

In this study, we selected the natural stands in the evergreen broadleaved forest in Phia Oac-Phia Den National Park as a research object to analyze the effect of forest structure on woody plant diversity. The study results can provide a reliable theoretical basis for biodiversity conservation and propose sustainable forest management options in the study area but also add a new approach to studying the effect of forest structure on plant diversity in Vietnam at the same time.

2. RESEARCH METHODOLOGY

2.1. Study area

The study was conducted from August 2021 to April 2022 in Phia Oac-Phia Den National Park in Cao Bang province, Vietnam. This park is geographically situated between 22º31'44" and 22º39'41" North latitude and 105º49'53" to 105º56'24" East longitude, covering a total natural area of 10,593.5 ha [13]. The study area falls within a region characterized by a highland continental climate, encompassing two subregions with subtropical and monsoonal tropical climates. The average temperature in the study area is 18°C, with an average annual rainfall of 1,592 mm. The terrain of the national park is predominantly hilly, with elevations ranging from 500 to 1,200 m a.s.l and slopes with gradients between 25 to 30º.

2.2. Field measurements

A total of six permanent plots, each measuring 10,000 m^2 with a side length of 100 m, were established within the natural stands of the evergreen broadleaved forest in Phia Oac-Phia Den National Park. The study area was characterized by a dominant of light-demanding tree species, including *Wendlandia paniculata*, *Aporosa dioica*, *Litsea cubeba*, *Schima superba*, *Macchilus sp*, *Castanopsis indica*, *Euodia bodinieri*, and *Engelhardtia chrysolepis* [13].

Expanding upon data inherited from two previous surveys conducted in 2015 and 2020 on two permanent plots labelled 12 and 13 by the Northeast Forest Inventory and Planning Institute of Vietnam, this study performed additional investigations and updated information regarding the composition of tree species. The plot of 1 ha was divided into 25 subplots, each measuring 20 m in length, resulting in 400 m^2 per subplot. The diameter at breast height (DBH) and the locations of all trees with a DBH of 6 cm or greater were measured and mapped within the study plots. The information on woody trees in subplots was used to evaluate the relationship between structural characteristics and species diversity. A total of 150 subplots were surveyed. Species were identified in the field using a morphological comparison method. Reference materials, including “Plants of Vietnam” and “Vietnam Forest Trees,” were utilized to determine tree species [14, 15]. All trees’ DBH in the subplots were measured using a calliper with an accuracy of ± 0.1 cm, and total tree height was determined using a Blume-Leiss measurement tape with an accuracy of ± 0.1 m.

2.3. Data analysis

2.3.1. Spatial structure indices

The species mingling index (M) indicates the resemblance in species composition between the focal tree and its closest neighboring trees. Species mingling is determined by considering the proportion of the four species closest to the focal tree. The formula for calculating species mingling is as follows [16]:

$$M_i = \frac{1}{4}\sum_{j=1}^{4} v_{ij} \qquad (1)$$

In the equation 1, j stands for the nearest neighbour of the target tree i, and v_{ij} is equal to 1 when the nearest neighbors and the target tree belong to different species; otherwise, v_{ij} is set to 0. The M_i value falls within the range of 0 to 1, with a higher M_i value indicating a more diverse mix of neighbouring species around the target tree.

The crowding index (C) indicates the competition in the canopy space between the focal tree and its four closest neighboring trees. The formula for calculating crowding index is as follows [17]:

$$C_i = \frac{1}{4}\sum_{j=1}^{4} y_{ij} \qquad (2)$$

In which, y_{ij} is set to 1 when the canopy of the target tree and its four neighbouring trees overlap; otherwise, it is 0. Crowding quantifies the competition for space and nutrients between the target tree and its neighbours, offering insights into the canopy cover and stand density. The C_i value varies between 0 and 1, with a higher value signifying a denser population of trees within the stand.

The height dominance index (U) indicates the connection between the height of the focal tree and its four closest neighboring trees. The formula for calculating height dominance is as follows [18]:

$$U_i = \frac{1}{4}\sum_{j=1}^{4} k_{ij} \quad (3)$$

In the equation 3, k_{ij} is set to 1 if the height of neighbouring trees is less than that of the target tree; otherwise, it is 0. The U_i value ranges from 0 to 1, with a higher value signifying that the target tree's height surpasses its neighbours.

The uniform angle index (W) reflects the spatial distribution pattern of the target trees on the forest ground. It is the proportion of trees with angle $\alpha < \alpha_o$ (72º) in the four reference neighbours of the target tree. The calculation formula for the uniform angle index is as follows [19]:

$$W_i = \frac{1}{4}\sum_{j=1}^{4} z_{ij} \quad (4)$$

In the equation 4, z_{ij} is set to 1 when the angle α is less than α_o, and otherwise, 0. The uniform angle index characterizes how the four closest neighbours are distributed concerning the focal tree. The W_i value varies between 0 and 1, with a higher value signifying a transition in tree distribution from being regularly spaced to randomly dispersed and then clustered.

Three indices, specifically species mingling (M), crowding (C), and the uniform angle index (W), characterize the stand's horizontal spatial arrangement. In contrast, height dominance (U) conveys information about the vertical spatial arrangement of the stand. These spatial structure indices were computed using R version 4.3.1 software, employing the 'forestSAS' package [20].

The edge effect pertains to alterations in ecological circumstances and the mix of species that transpire at the peripheries of habitats. These changes can impact the spatial configuration of a forest stand. Correcting for the edge effect holds significant importance in forest spatial analysis as it allows for the accommodation of these variations and the acquisition of precise outcomes. In this study, we modified the buffer zone within the 'forestSAS' package to a 5-m value, aligning with prior studies and the existing literature on forest spatial structure. This adjustment is instrumental in guaranteeing that the spatial structure indices accurately mirror the attributes of the forest interior while curtailing the influence of edge effects on the analysis.

2.3.2. Diversity indices

Species richness (S): the number of species in each study plot.

Shannon diversity index [21]:

$$H' = \sum_{i=l}^{s} p_i \times ln(p_i) \quad (5)$$

Gini-Simpson diversity index [22]:

$$D = 1 \quad \sum p_i^2 \quad (6)$$

Pielou diversity index [23]:

$$J = \frac{H'}{H_{max}} \quad (7)$$

Where, p_i represents the relative abundance of species i within the plot, and it is calculated as p_i = (the number of individuals of species i in the plot) divided by (the total number of individuals in the plot).

2.3.3. Structural equation modeling

Structural Equation Modeling (SEM) comprises measurement and structural models [9]. The measurement model delineates the connections between latent variables (variables that cannot be measured directly) and observed variables (variables that can be directly measured), including factors like reliability and influence. The structural model, on the other hand, illustrates the associations among latent variables.

The formula of the measurement model is as follows [10]:

$$X = \Lambda_x \xi + \delta \quad Y = \Lambda_y \eta + \varepsilon \quad (8)$$

In the equation 8, X represents the vector formed by observable variables, while Y is the vector composed of latent variables. ξ constitutes a vector of exogenous latent variables, which are latent variables not influenced by other latent variables in the model, and η represents a vector of endogenous latent variables, which are latent variables affected by other latent variables within the model. Λx denotes the matrix of factor loading coefficients, illustrating the extent of influence between observable variables and exogenous latent variables. Λy stands for the factor loading coefficient matrix, portraying the relationship between exogenous latent variables and endogenous latent variables. Additionally, δ and ε correspond to the measurement errors associated with observable and latent variables, respectively.

The structural model reflects the relationship between latent variables, and its formula is as follows [12]:

$$\eta = B\eta + T\xi + \zeta \qquad (9)$$

In equation 9, η stands for the endogenous latent variable, B represents the matrix of factor loading coefficients that describe the connections between endogenous latent variables, ξ denotes the exogenous latent variable, and T is the factor loading matrix that illustrates the strength of the relationship between the exogenous latent variable and the endogenous latent variables, indicating whether the influence is strong or weak. ζ accounts for the residual value in the model.

Before conducting SEM, this study employed the correlation matrix and conducted Exploratory Factor Analysis (EFA) to standardize the input data and remove observed variables with inadequate factor loadings. Eventually, the study treated both the non-spatial structure (NSS) and the spatial structure of the stand (SS) as exogenous latent variables. Among these, variables such as DBH (diameter at breast height), H (total tree height), V (volume), and BA (basal area) were regarded as observed variables linked to NSS. Conversely, observed variables related to SS encompassed aspects such as species mingling (M), crowding (C), uniform angle (W), and tree height dominance (U). The endogenous latent variable was species diversity (DIV), with indices like species richness (SR), Shannon-Weiner diversity (SHA), Simpson diversity (SIM), and Pielou index (PLO) serving as observed variables (Fig. 1).

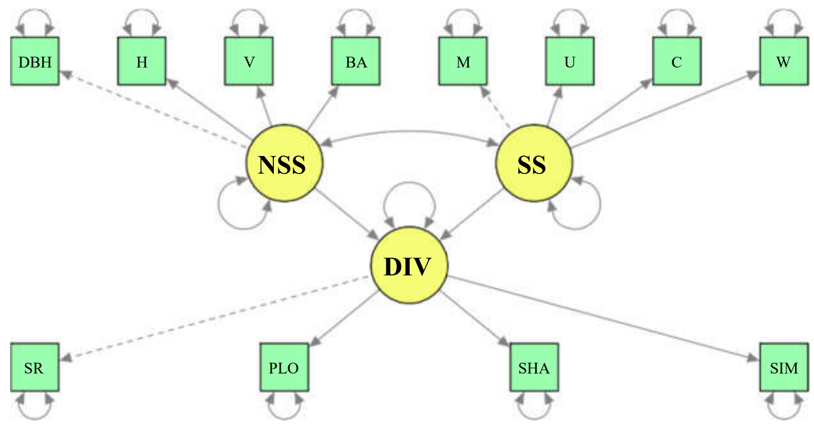

Figure 1. Theoretical model

Dotted arrows represent no significant results, while solid arrows mean significant results. Standardized path coefficients are on the single-headed arrows; correlation appears on curved double-headed arrows

In order to make sense of the SEM findings, this study employed various indices to assess the model's goodness of fit. These commonly used fit indices encompass the chi-square test, the Comparative Fit Index (CFI), the Tucker-Lewis Index (TLI), the Root Mean Square Error of Approximation (RMSEA), and the Standardized Root Mean Square Residual (SRMR) [12].

The chi-square test evaluates the dissimilarity between the observed and predicted covariance matrix. Nevertheless, it is sensitive to sample size and might not yield precise results for extensive sample sizes. The CFI and TLI compare the model's appropriateness to the null model, with a range between 0 and 1, where values exceeding 0.90 signify a favourable fit. The RMSEA quantifies the inconsistency between the model and the population covariance matrix, with values below 0.08 indicating a solid fit. The SRMR gauges the average distinction between the observed covariance matrix and the projected covariance matrix, with values lower than 0.05 indicating a solid fit [12].

Besides assessing the model's fit, this study also examined the parameter estimates to gain insights into the connections between the latent variables. These estimates offer valuable information about the intensity and direction of relationships between the latent variables, shedding light on the underlying mechanisms that influence the observed data.

This study employed R version 4.3.1, along with specialized packages for computing spatial structure indices (forestSAS-package) and biodiversity indices (BiodiversityR-package). The SEM creation and subsequent goodness-of-fit assessment were conducted using the 'lavaan' package [24, 20].

3. RESULTS

3.1. Basic characteristics of study plots

The number of woody plant species recorded in six study plots was 68 species belonging to 23 families, with 2247 individual trees. Among them, the highest number of species was found in Plot 6 (with 42 species), while the lowest number was observed in Plot 1 (with 28 species). The tree density ranged from 134 to 629 stems ha^{-1}. Tree DBH, total height, tree density, and total volume varied among the study plots, with most forest stands having a volume of less than 100 m^3 ha^{-1}. The results are summarized in Table 1.

Table 1. Basic characteristics of the study plots

No.	Study plot	Mean DBH (cm)	Mean H (m)	N (stems ha^{-1})	M (m^3 ha^{-1})
1	1	17.7	10.2	134	26.63
2	2	12.7	8.9	277	24.02
3	3	13.9	9.4	338	39.91
4	4	15.8	13.0	629	123.30
5	5	16.2	12.0	468	87.73
6	6	15.8	10.4	401	61.01

Note: $BA=0.785*(DBH/100)^2$; $V = BA*H*0.45$

3.2. Spatial structural characteristics

Table 2 displays the spatial structural characteristics of the forest stands. The results reveal that most of these stands share a common characteristic of having a high species mingling index, with M values ranging from 0.73 to 0.84. The crowding (C), uniform angle (W), and height dominance (U) indices indicate that trees in the study plots had low density (sparse), were randomly distributed, and competed for light among canopy layers.

Table 2. Spatial structural characteristics of the study plots

No.	Study plot	Species mingling	Crowding	Uniform angle	Height dominance
1	1	0.83	0.35	0.47	0.60
2	2	0.74	0.23	0.46	0.55
3	3	0.73	0.24	0.48	0.52
4	4	0.82	0.43	0.54	0.49
5	5	0.77	0.36	0.53	0.50
6	6	0.84	0.33	0.52	0.50

3.3. Characteristics of plant diversity

Table 3 illustrates the characteristics of tree species diversity within the six plots. The results showed that Plot 6 displayed the highest species diversity, as evidenced by the Shannon and Gini-Simpson diversity indices (3.21 and 0.95), while Plot 2 exhibited the lowest diversity (2.79 and 0.89). The evenness of tree species composition across the study plots ranged from 0.46 to 0.61, as indicated by the Pielou index.

Table 3. Species diversity characteristics of the study plots

No.	Study plot	Species richness	Gini-Simpson diversity	Shannon diversity	Pielou index
1	1	28	0.92	2.84	0.61
2	2	35	0.89	2.79	0.46
3	3	29	0.91	2.80	0.56
4	4	36	0.92	2.86	0.48
5	5	41	0.91	2.97	0.47
6	6	42	0.95	3.21	0.59

3.4. Effects of stand structure on plant diversity

A CFI value of 0.98 and an SRMR value of 0.02 indicated a good fit of the study model to the data (Fig. 2). The CFI assesses model fit improvement relative to a null model, and a value of 0.95 or higher is typically indicative of a well-fitting model. The SRMR quantifies the dissimilarity between the observed covariance matrix and the model's expected covariance matrix, with a value below 0.05 indicative of a good fit. Consequently, our results suggested that the SEM model accurately represents the relationship between forest stand structure and species diversity in the study area.

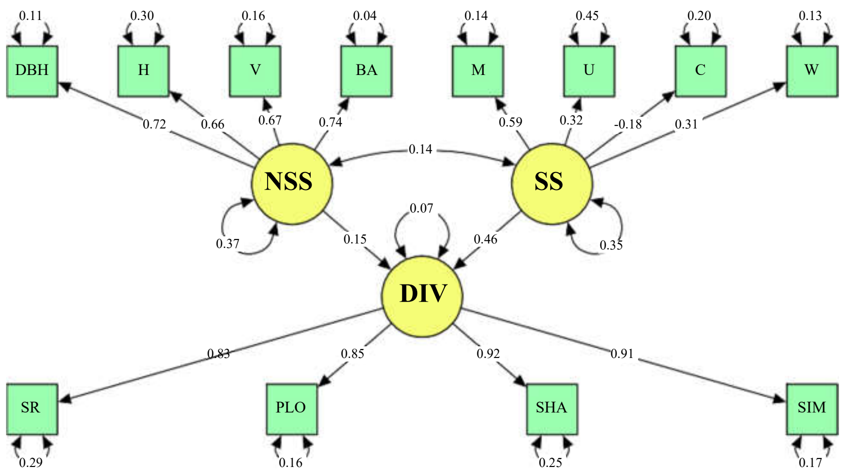

Figure 2. Study model

(The variables in the model include NSS and SS, two exogenous latent variables representing non-spatial and spatial structure indices, respectively. DIV is an endogenous latent variable that signifies species diversity indices, whereas DBH (diameter at breast height), H (total tree height), V (volume), and BA (basal area) are observed variables associated with NSP, and M (species mingling), C (crowding), W (uniform angle), and U (tree height dominance) are observed variables associated with SP. SR (species richness), SHA (Shannon-Weiner diversity), SIM (Simpson diversity), and PLO (Pielou index) are observed variables linked to DIV. The direction of the arrows reflects the interaction between the variables. A factor loading coefficient value of < 0 suggests a negative correlation, while a value of > 0 indicates a positive correlation)

In the study model, the factor loading coefficient for the latent variable BA exhibited/presented the highest value (0.74) among non-spatial structures. Regarding the latent variable representing spatial structure, M had the highest factor loading coefficient at 0.59. Lastly, in the case of the latent variable related to species diversity, SHA had the highest factor loading coefficient, measuring 0.92, as illustrated in Table 4.

Table 4. Factor loading coefficient of study model

No.	Latent variable	Observed variable	Factor loading coefficient	Significance level
1	SS	W	0.31	*
		C	-0.18	**
		U	0.32	*
		M	0.59	***
2	NSS	BA	0.74	**
		V	0.67	*
		H	0.66	*
		DBH	0.72	*
3	DIV	SIM	0.91	**
		SHA	0.92	*
		PLO	0.85	***
		SR	0.83	ns

*Significance level: *: p < 0.05: **: p < 0.01; ***: p < 0.001, 'ns': non-significant.*

According to the findings in Table 5, the study model revealed a positive correlation between stand structure and species diversity. The factor loading coefficients for spatial and non-spatial structures were 0.46 and 0.15, respectively. These findings suggested that spatial structure exhibits a relatively stronger correlation with species diversity compared to non-spatial structure. As a result, stand structure had a significant impact on stand species diversity, with spatial structure playing a more influential role.

Table 5. Effects of stand structure on tree species diversity

No.	Direction of influence			Factor loading coefficient
1	DIV	⟵	NSS	0.15*
2	DIV	⟵	SP	0.46**

*Significance level: *: p< 0.05; ***: p< 0.001*

4. DISCUSSION

Investigating the impact of environmental factors and forest dynamics on species diversity is crucial for uncovering the mechanisms governing the formation and preservation of plant communities [25]. The SEM analysis revealed that within a forest stand, spatial structure indices exert a more substantial influence on diversity indices than non-spatial structure indices. Among these indices, the horizontal spatial structure, encompassing species mingling (M), exhibited the highest factor loading coefficient at 0.59, directly affecting the forest's spatial structure and, consequently, the diversity indices. This effect overshadowed other variables such as crowding (C), uniform angle (W), and height dominance (U), which had factor loading coefficients of -0.18, 0.31, and 0.32, respectively (Table 4).

Our findings align with the study conducted in China. For instance, Zhang *et al.* explored the influence of spatial structure on species diversity within mixed forests in Hubei province, China [26]. They reported that diversity indices were most strongly impacted by horizontal spatial structure, particularly species mingling. Similarly, Li et al. proposed that the Shannon-Wiener diversity index is notably affected by two horizontal spatial structure indices: the species mingling index and the uniform angle index [27]. Our study and these studies elucidated that horizontal spatial structure directly impacts the nutrient space available to tree species on the forest floor. In mixed natural forests, tree species compete fiercely for nutrient space, changing their distribution patterns from clustered during the seedling stage to random or regular at the juvenile and mature stages, thereby reducing competition [28]. Alterations in the spatial arrangement of trees can subsequently bring about shifts in the species composition of the community [6].

Our study demonstrated that the vertical spatial arrangement within the forest stand impacts species diversity, as indicated indirectly by the effects of the height dominance index. The various canopy layers of the forest define the vertical spatial structure at different elevations, directly impacting the species' habitats through environmental factors such as light, temperature, humidity, and wind speed [29]. The vertical spatial structure of the stand significantly influences the tree species residing beneath the forest canopy by modulating light intensity. This factor, in turn, plays a crucial role in determining the survival rates of shade-tolerant seedlings and regenerating trees, which ultimately affects the composition of the species [30].

Moreover, the vertical spatial configuration also influences the forest floor, including gap distribution and transpiration patterns. In forests characterized by multi-layered canopy structures, the overlapping canopy layers result in a more evenly distributed occurrence of weak points. This reduces transpiration rates compared to forests with more superficial canopy structures [31]. The elevated humidity levels and a thick litter layer in multi-canopy forests create favourable conditions for soil microorganisms to thrive, enhancing organic matter content and soil fertility. This, in turn, supports the favourable growth and development of plant species [32].

Consequently, the vertical spatial structure impacts both the species count and the evenness of tree species composition.

Furthermore, our study identified a negative relationship between the crowding index and species diversity. This relationship is attributed to intense competition among tree species resulting from limited growing space. The competitive behaviour of mature individuals impacts the regenerating and seedling tree layers, thus diminishing the initial richness of species composition in the plant community.

Natural forests represent intricate ecosystems, and describing the interplay between their structural characteristics and functions cannot be achieved through superficial one-way or two-way relationships among factors. Consequently, it is imperative to consider the multi-dimensional relationships among these factors [33]. In the realm of ecology, SEM offers a distinct advantage when it comes to exploring intricate relationships. SEM leverages measurable variables to estimate latent variables that cannot be directly observed, thereby illustrating the multi-faceted connections among these latent variables within the model [9]. SEM is recognized for its efficiency compared to traditional statistical methods [34]. However, it is worth noting that SEM necessitates a substantial sample size, a requirement that fields like social sciences and economics often fulfil by using hundreds or even thousands of samples to enhance the model's goodness of fit [35]. Consequently, for forthcoming research endeavours, an expansion in the number of samples is essential to enable comparisons of results and the development of specific standards for the requisite sample size when employing SEM to investigate the influence of spatial structure on species diversity.

Our findings have practical implications for forest management and conservation initiatives. Forest managers can leverage this information to guide their restoration efforts in areas where forest stands have been damaged or destroyed. By considering the factors that impact species diversity, for example, spatial structure indices, forest managers can prioritize activities aiming at restoring the spatial structure of forests or creating favourable conditions for the growth and development of specific tree species. Similarly, conservation organizations in Vietnam can use this data to pinpoint regions most susceptible to a decline in species diversity and focus their conservation efforts accordingly within the study area. In essence, our results offer value to anyone interested in comprehending the intricate relationships within natural ecosystems and those striving to advance the sustainable management and conservation of natural resources.

5. CONCLUSIONS

In the present study, SEM exhibited intense goodness of fit, with a CFI of 0.98 and an SRMR of 0.02, signifying its capability to simulate the data accurately. The findings underscore the significant influence of both the spatial and non-spatial structure of forest stands on the diversity indices of woody plant species, including species richness, Shannon-Weiner diversity, Simpson diversity, and Pielou diversity. Notably, the horizontal spatial structure had a more pronounced impact than the vertical structure.

Moreover, our results revealed positive relationships between the forest stand's structural characteristics and species diversity indices, illuminating their beneficial influence. Conversely, species competition exhibited a negative correlation, adversely affecting tree species diversity within the ecosystem. The observed variables, encompassing both spatial and non-spatial structure indices, significantly impacted the exogenous latent variables, specifically the diversity indices. This valuable insight enhances our comprehension of the dynamic mechanisms governing tree species composition in this spatial context.

In summary, our findings provide a robust scientific foundation that can aid forest managers in developing effective strategies for the management, conservation, and sustainable development of forest resources within the study area.

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