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Research Article

Interplay of climatic factors and forest biodiversity crafting adaptive strategies for Northern Thailand ecosystems

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Abstract
This study presents a comprehensive investigation into how key climatic parameters—namely, temperature, precipitation, and wind speed—influence the biodiversity of community forests in Northern Thailand. A total of 27 systematic plots (40 m × 40 m) were established across nine forest sites, representing three different community forest governance models. Quantitative data on vegetation (trees, shrubs, herbs) were collected alongside climatic parameters obtained from nearby meteorological stations. Statistical techniques, including Pearson correlation and multiple linear regression analysis, were employed to explore relationships between environmental variables and forest attributes. The results reveal a significant positive correlation between wind speed and tree density (r = 0.336), as well as between tree density and basal area, indicating that forest structural complexity responds predictably to climatic variation. The species–area relationship (SAR) analysis further revealed a pronounced increase in species richness with area expansion, with a SAR exponent (z) of 0.68—substantially higher than typical for mainland ecosystems—suggesting exceptional biodiversity response patterns in the study areas. These findings underscore the heightened vulnerability of Northern Thailand's community forests to ongoing climate change. Moreover, the study demonstrates the critical role of integrating indigenous knowledge systems with empirical science to enhance local conservation strategies. Such adaptive measures are crucial for mitigating anthropogenic impacts and enhancing ecosystem resilience. This research supports the promotion of collaborative governance, involving local communities, academic institutions, and policymakers in the formulation of sustainable forest management practices. Ultimately, the study contributes valuable evidence to inform biodiversity conservation under rapidly changing environmental conditions.

Keywords: Climate Change, Forest Biodiversity, Community Forests, Northern Thailand, Adaptive Management

INTRODUCTION

Forest ecosystems play a crucial role in safeguarding global biodiversity, providing a wide array of ecological, economic, and socio-cultural benefits. In Northern Thailand, community forests epitomize the delicate interplay between ecological diversity and human needs, a relationship vital for both local populations and the broader region. Foundational work by Guts and Volodchenkova (2016) illustrates this synergy by applying differential game theory to elucidate equilibrium conditions within forest ecosystems. Their findings offer critical insights for fostering a sustainable coexistence between biodiversity conservation and resource use in Northern Thailand. Equally significant, Karev's (2006) "Analytical Models of Forest Dynamics" provides a rigorous framework for investigating the structural and functional attributes of these forests. By integrating self-thinning and tree stand models, Karev emphasizes the need to harmonize ecological sustainability with socioeconomic objectives.

Recent advances further reinforce the multifaceted nature of forest conservation. May *et al*. (2024) employ a spatial mixture model for spaceborne lidar data, underscoring the utility of cutting-edge geospatial technologies in managing Northern Thailand's forest heterogeneity. Similarly, the work of Hamilton *et al*. (2016) on carbon storage in mangrove ecosystems offers transferable methodologies for Thai mangrove conservation, especially relevant for climate change mitigation. Mishra (2023) dissertation on the Economics and Human Dimensions of Active Management underscores the vital need for proactive forest management, a principle directly applicable to community forests in Northern Thailand as they grapple with climate-driven risks and developmental pressures. These forests, situated within a distinct tropical to subtropical climate, serve not only as critical reservoirs of biodiversity but also as the underpinning of the region's cultural and economic fabric. Managed by indigenous groups, they reflect a well-established model of ecosystem stewardship, although one that is increasingly strained by shifting environmental conditions.

Indeed, Northern Thailand's forests—renowned for their rich biodiversity—face escalating pressures from climate variability. As demonstrated by Thammanu *et al*. (2020), factors such as elevation, hydrological proximity, and soil moisture drive significant changes in species distribution. Exacerbated by agriculture, tourism, and large-scale deforestation (Trisurat *et al*., 2010), these pressures are further intensified by changing precipitation and temperature regimes (Trisurat *et al*., 2011). Thus, it becomes imperative to deepen our comprehension of these complex interactions to devise robust conservation strategies that maintain ecosystem function while supporting local livelihoods. Given these concerns, more systematic research and targeted policy interventions are urgently needed to preserve these habitats from the adverse effects of climate change and ongoing anthropogenic activities.

Against this backdrop, the present study aimed to elucidate the impacts of key climatic variables on forest biodiversity in the community forests of Northern Thailand. By examining shifts in temperature, precipitation, and other relevant climate indicators, this inquiry contributes to a nuanced understanding of forest health and resilience.

MATERIALS AND METHODS

Study area

This investigation focused on nine representative community forest exemplars situated in the northern territories of Thailand. These exemplars are systematically categorized into three distinct groups based on their management and governance frameworks. Model 1 comprises community forests recognized at the national scale. Model 2 involves community forest territories administered at the provincial scale, and Model 3 pertains to community forest zones designated for the devolution of management responsibilities. Detailed descriptions and the spatial distribution of these models are comprehensively documented (Table 1) and illustrated (Fig. 1).

Data collection methodology

Sample plot configuration

The investigation utilized a stratified sampling approach, establishing sample plots measuring 40 x 40 square meters. A total of 27 plots were implemented and divided into three groups of nine plots each to ensure comprehensive spatial representation.

Geographic and physical characterization

This phase encompassed a detailed analysis of the geographic and physical attributes of the selected areas. Parameters, such as topography, elevation, slope gradient, and aspect, were rigorously assessed to elucidate their influence on the study outcomes.

Meteorological and microclimate data acquisition

Meteorological data, including precipitation, temperature, humidity, wind speed and direction, and solar radi-

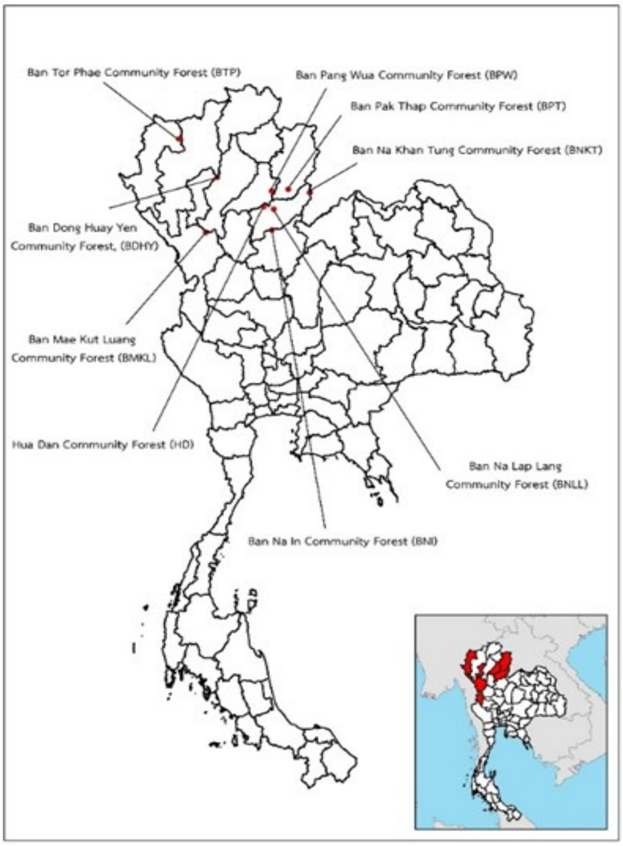

Fig.1. *Study area of 9 community forests in northern Thailand*

Table 1. Delineating the study areas, comprising nine community forests across three models, situated in Northern Thailand

Model 1	Model 2	Model 3
Ban Tor Phae Community Forest, Tor Phae Subdistrict, Khun Yuam District, Mae Hong Son Province (TP-MH)	Ban Pak Thap Community Forest, Village No. 7, Pha Luat Subdistrict, Tha Pla District, Uttaradit Province (PT-UTT)	Ban Na In Community Forest, Moo 6, Na In Subdistrict, Phichai District, Uttaradit Province (NI-UTT)
Ban Mae Kut Luang Community Forest Located at Moo 1, Mae Kasa Subdistrict, Mae Sot District, Tak Province (MKL-TK)	Hua Dan Community Forest, Moo 8, Wang Daeng Subdistrict, Tron District, Uttaradit Province (HD-UTT)	Ban Na Khan Tung Community Forest, Village No. 6, Saen Tor Subdistrict, Nam Pat District, Uttaradit Province (NKT-UTT)
Ban Dong Huay Yen Community Forest, Village No. 14, Ban Hong Subdistrict, Ban Hong District, Lamphun Province (HDY-LP)	Ban Na Lap Lang Community Forest, Moo 5, Pa Khai Subdistrict, Fak Tha District, Uttaradit Province (NLL-UTT)	Ban Pang Wua Community Forest, Moo 7, Khun Fang Subdistrict, Mueang Uttaradit District, Uttaradit Province (PW-UTT)

ation, were systematically collected daily using the Julian day notation. This information was obtained from secondary sources, including automated meteorological stations located near the research sites, which facilitated the examination of surface microclimate conditions (Thai Meteorological Department, https://www.tmd.go.th).

Methodological approach to analysis

The investigation employed an integrated analytical framework combining species–area correlations with rigorous statistical methods to examine the relationship between climatic determinants and forest biodiversity. Specifically, Pearson's correlation analysis was used to identify significant linear associations between climatic parameters (e.g., temperature, precipitation, wind speed) and biodiversity metrics (e.g., species richness, basal area). Subsequently, multiple linear regression analysis was conducted to assess the predictive power of these climatic variables on forest structural attributes and species distribution. This analytical approach has been widely utilized in ecological studies to unravel complex interactions between environmental gradients and biodiversity (Legendre & Legendre, 2012; Dormann *et al*., 2013). These statistical tools are instrumental in capturing both the strength and direction of ecological relationships, thereby facilitating a nuanced understanding of how forest biodiversity responds to climate variability.

Execution of statistical analysis

A statistical examination of the data was conducted meticulously using advanced excel statistical software. The initial descriptive statistical analyses provided a foundational understanding of the characteristics of the dataset. To investigate this further, inferential statistical techniques —specifically, regression and correlation analyses — were employed to rigorously test hypotheses concerning the effects of climatic variables on biodiversity levels.

The fieldwork integral to the data collection was conducted under the official approval and funding support of the relevant research agency, specifically the National Research Council of Thailand (NRCT). The project followed the ethical standards and operational guidelines set forth by the funding institution, ensuring that research activities caused minimal disruption to both natural ecosystems and local communities. All field procedures were conducted with prior informed consent from community forest committees, and with full respect for local knowledge systems and ecological integrity. The study adhered to the principles of environmental research ethics, emphasizing biodiversity preservation and the protection of indigenous rights.The study also transparently addressed its limitations, including the potential for variations in data precision, biases that may arise during species identification, and the inherent challenges associated with fully capturing the complex dynamics of biodiversity in constantly evolving ecosystems.

RESULTS AND DISCUSSION

Analysis of tree species data

Distribution of tree, shrub, and herb species

The survey areas, TP-MH and MKL-TK, exhibited the highest diversity of tree species, indicating a more abundant arboreal population. Conversely, the NLL-UTT area reported the least diversity of tree species, potentially suggesting reduced biodiversity or selective species prevalence due to environmental constraints or anthropogenic influences. The prevalence of shrub species was notably higher in the MKL-TK and PW-UTT regions, implying either a more favourable environment for these species or a reduced impact from biodiversity-limiting factors. The distribution of herb species appeared relatively uniform across all studied regions, suggesting possible resilience or a minimal influence of factors that generally affect the diversity of tree and shrub species (Fig. 2).

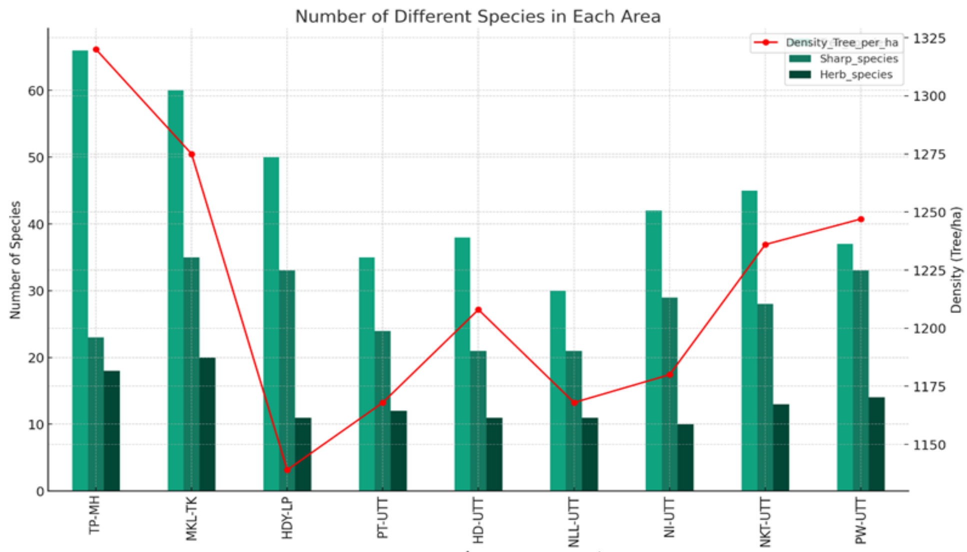

Fig. 2. *Tree species data characteristics across various 9 community forests*

Frequency

The frequency percentage, presumably referring to the presence of certain species or groups of species, varied. MKL-TK and TP-MH demonstrated the highest frequencies, potentially indicating an elevated encounter rate or abundance of specific species, whereas several areas displayed equivalent low frequencies. However, the table does not specify a precise referent for the frequency percentage (Fig. 2).

Species frequency

The analysis revealed a variance in species frequency, with the MKL-TK and TP-MH regions exhibiting the highest percentages. This observation suggests an increased likelihood of encountering specific species or a higher abundance of certain species in these areas. However, a precise definition of the frequency metric was not elucidated in the data provided (Fig. 2).

Tree density

The HDY-LP area had the highest tree density per hectare, indicating either superior land management practices or naturally favorable conditions. However, this high density suggests potential interspecific competition for resources. In contrast, the HD-UTT area demonstrated the lowest tree density, which could signify either suboptimal growth conditions or intentional management strategies aimed at preventing overcrowding, thereby facilitating larger tree growth or preserving specific ecosystem dynamics (Fig. 2).

Basal area

The basal area, which represents the ground area occupied by tree trunk cross sections, serves as a robust indicator of forest biomass. The TP-MH region exhibited the highest basal area, potentially indicating the presence of larger, possibly older, trees, and thus a more mature forest ecosystem. Conversely, the NKT-UTT and NLL-UTT areas had the lowest basal areas, suggesting either younger forests, forests composed of smaller trees, or areas undergoing thinning or recent logging activities (Fig. 2).

Evaluation of climatic data

The examination of climatic characteristic visualizations across several community forests yields valuable insights and highlights areas that require further investigation. Below is a critical analysis of the findings, along with identified limitations and recommendations for further exploration: Annual Rainfall. The analysis reveals a relatively stable annual rainfall pattern across the surveyed locations, albeit with minor fluctuations. The observation of two distinct rainfall levels, 1,200 mm and 1,300 mm, may suggest underlying regional climatic patterns or the impact of geographical features on precipitation levels. A gradual increase in average temperature was noted across the community forests. This trend may indicate a temperature gradient from one location to another as arranged in the dataset. Specifically, elevated temperatures in areas such as the Uttaradit could result from factors such as geographical positioning, elevation, and localized environmental conditions. Average Relative Humidity: There is an apparent declining trend in relative humidity across the forests, particularly in areas such as Uttaradit, which also exhibit higher average temperatures. This observation aligns with the physical principle that warmer air can hold more moisture, potentially leading to a decrease in relative humidity if not accompanied by a proportional increase in moisture availability. Wind speed exhibits a variable trend, initially increasing, followed by stabilization. This pattern suggests that factors beyond geographical location, including terrain and forest density, may significantly influence the wind dynamics in these regions.

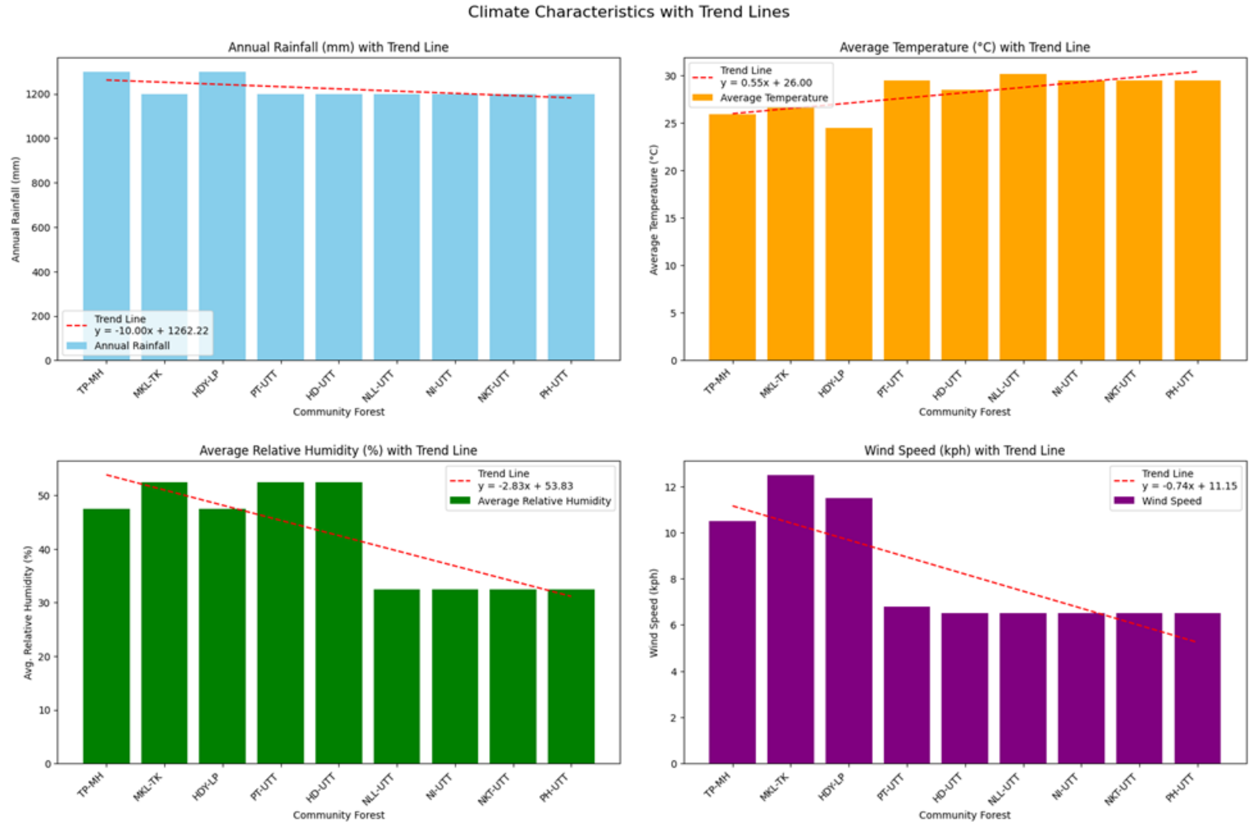

Fig. 3. *Analyzing and critiquing the results from the visualizations of climate characteristics across various 9 community forests*

The methodology of using bar graphs to represent continuous data, such as temperature and rainfall, may not adequately capture the complexities or trends within the data. Alternative graphical representations, such as line graphs or scatter plots with trend lines, can provide more precise insights into the continuous nature and correlations of climatic variables. Furthermore, the simplicity of trend lines, while offering an initial visual indication of patterns, fails to encapsulate the intricate variability of climate data, including seasonal fluctuations, extreme weather events, and the influence of geographical diversity.

The present dataset presents an introductory perspective on the climate attributes of various community forests, highlighting the general trends in temperature, rainfall, humidity, and wind speed. However, a more granular approach to data that incorporates temporal variations and a broader spectrum of geographical and environmental factors is essential for comprehensive analysis and deriving actionable insights. Future research could enhance these observations by juxtaposing local climate data with broader regional or global climatic trends, thereby gaining a more comprehensive understanding of the climatic impacts, as illustrated (Fig. 3).

Species-Area Relationship (SAR) analysis

The Species-Area Relationship (SAR) is a fundamental ecological concept that elucidates the increase in species richness with the expansion of the surveyed area. This relationship is mathematically represented by the equation S = cAz, where S denotes the species count, c and z are empirical constants that vary across habitats, and A represents the area under consideration. In our analysis, the SAR was determined using the formula S = cAz, where the count of tree species served as a surrogate for the number of species (S) and 'density' acted as a proxy for area (A). The utilization of 'density' as a proxy for area is a novel approach aimed at adapting the SAR formula to the specific data characteristics of this study.

The resulting coefficients from this computation were as follows: the constant c, representing the y-intercept on a log-log plot, was approximately 3.18, whereas the constant z, denoting the slope on the same plot, was found to be approximately 0.68. These values indicate that, within this dataset, species richness increases with area, or 'density,' as operationalized here, at a rate characterized by these coefficients. Notably, the value of z is particularly informative; within the field of island biogeography, it is established that z typically ranges from 0.2 to 0.35 for islands and from 0.1 to 0.15 for continental areas. The derived values in our study suggest a more pronounced increase in species richness with area expansion relative to these established parameters.

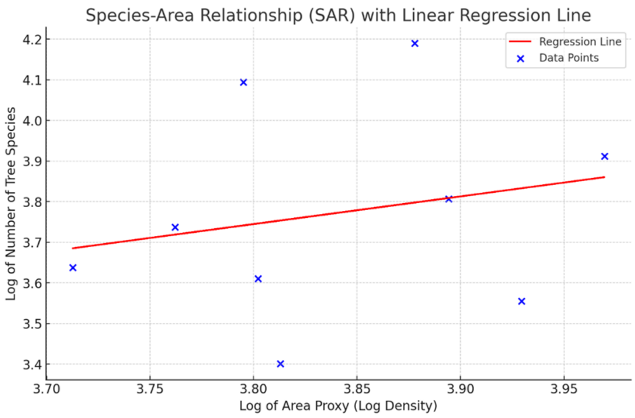

Fig. 4. *Species-Area Relationship (SAR) of various 9 community forests*

Nevertheless, it is essential to recognize that the substitution of 'density' for 'area' in this analysis presupposes that density can adequately represent an area's function in Species-Area Relationship (SAR) assessments. This approximation may not fully capture the multifaceted nature of species-area dynamics, thereby introducing a degree of simplification to the complex ecological relationships inherent in these dynamics (Fig. 4).

The species–area relationship (SAR) is a fundamental ecological concept that elucidates the relationship between species richness and the extent of the surveyed area. This relationship was mathematically expressed as S = cAz, (Eq.1)

where S signifies the species count, c is a constant representing the y-intercept in a log-log graphical representation, z indicates the slope of the graph, denoting the rate at which species richness increases with area, and A represents the area under consideration.

In this analysis, the number of tree species was used to represent S, signifying overall species richness, whereas tree density was employed as a proxy for A, to measure the area. This method yielded coefficients of approximately 3.18 for c and 0.68 for z, indicating a substantial increase in species diversity correlated with an increase in area (or, in this case, density). The calculated z-value exceeded the typical values observed in island biogeography, indicating an unusually high correlation between species richness and area in the forests under study. However, it is essential to acknowledge the potential limitations of using tree density as a surrogate for actual areas, which may not accurately reflect the complexities and variations within ecosystems. Nevertheless, employing density as an area surrogate offers valuable insights into the dynamics between species numbers and environmental conditions within specific ecosystems.

The implementation of SAR analysis through scatter plots and linear regression effectively illustrates the positive association between species richness and area (or density), providing both visual and quantitative evidence of spatial autocorrelation in the dataset. This analysis highlights the utility of SAR in ecological research, enabling the discovery of biodiversity patterns, informing conservation strategies, and predicting the impact of environmental changes on species richness. The divergence of the observed z-value from conventional ranges underscores the unique characteristics of the forests examined and highlights the necessity for context-specific ecological investigations. The significant SAR observed suggests a higher-than-typical rate of species accumulation with increasing area, which is atypical for both island and mainland ecosystems. This anomaly suggests that unique ecological attributes within the studied forests are fostering enhanced biodiversity. While employing density as a proxy for area introduces a novel perspective for understanding SAR in certain contexts, it also necessitates careful consideration of its limitations and the assumptions involved. The species-area relationship is pivotal in conservation biology, as it aids in predicting biodiversity responses to habitat alterations. Thus, the findings of this study can inform conservation policies by emphasizing the importance of preserving large, contiguous habitats for biodiversity maintenance. This exploration of species richness trends within specific forests not only yields significant insights, but also illuminates the complexities and nuances of applying SAR in ecological research. Future studies should aim to refine the area measurement methodologies, explore the effects of various ecological variables on SAR parameters, and leverage these insights to bolster conservation efforts. Advancing our understanding of biodiversity patterns through these methods will significantly contribute to the development of effective ecological conservation and management practices.

Correlation analysis of climate and forest biodiversity

The investigation into the correlations among various climatic and environmental variables—specifically, average rainfall, average temperature, wind speed, tree density, and basal area—reveals a complex and intricate interrelationship that is significantly influenced by the geographical and climatic settings of the forests. A review of the existing literature offers several key insights.

There appears to be a potential negative correlation between the average rainfall and temperature in specific locales, although this relationship is not universally observed. This variability suggests that the interplay between rainfall and temperature may be influenced by additional regional factors or by complex ecological dynamics that are not captured by a simple linear relationship. The analysis also indicated a lack of strong correlations between average rainfall and both wind

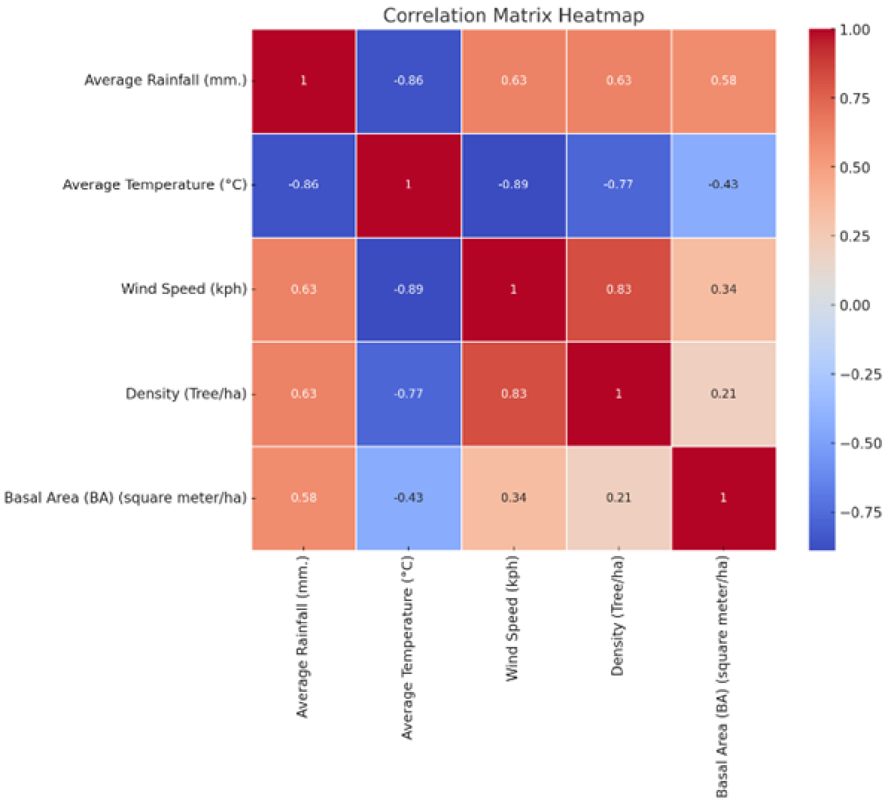

Fig. 5. *Heat map correlation between climate on forest biodiversity*

speed and tree density as well as between average temperature and these variables. This outcome suggests that the relationships among these environmental factors are likely governed by more complex interactions than straightforward causal influences. The absence of direct correlations suggests that other, possibly non-linear, relationships or external influences could be at play, mediating the interactions between climatic conditions and forest characteristics. A noteworthy finding was the positive correlation between tree density and basal area. This observation aligns with ecological principles, positing that forests with higher tree densities are expected to have larger basal areas. This correlation is illustrated in Figure 5, underscoring the ecological rationale that denser forests, often resulting from favourable environmental conditions, exhibit larger basal areas due to the accumulation of biomass and the structural complexity of the forest stand.

These findings highlight the complexity of the relationship between climatic variables and forest biodiversity. The observed correlations and lack thereof underscore the nuanced nature of these interactions, suggesting that the specific geographical and climatic contexts of the study areas significantly shape them. Such insights underscore the importance of a detailed and context-sensitive approach in ecological research, particularly when examining the impacts of climatic variables on forest ecosystems. This nuanced understanding is crucial for developing informed conservation strategies and management practices tailored to the specific ecological dynamics and climatic influences of different forest regions (Fig. 5).

Impact of climate on forest biodiversity: An analytical synopsis

The investigation into the intricate relationships between climatic and environmental variables—specifically, average rainfall, average temperature, wind speed, tree density, and basal area—reveals a complex and nuanced interplay that is significantly influenced by the geographical and climatic contexts of the studied regions. The synthesis of findings from the existing body of research indicates the following.

There is a nuanced potential for a negative correlation between average rainfall and temperature in certain locales, although this relationship is not universally consistent. The absence of strong correlations between average rainfall, wind speed, and tree density, as well as between average temperature and these variables, suggests that the interactions among these environmental factors may be governed by more complex mechanisms than direct mutual influence. A discernible positive correlation exists between tree density and basal area, aligning with ecological theories that posit denser forests typically exhibit a larger basal area (Fig. 5).

This discourse underscores the pivotal role of local contextual nuances in understanding the dynamics between environmental variables. The variability observed across different regions and studies highlights the complex nature of environmental systems and the challenges inherent in generalizing these interconnections. There is a pronounced need for region-specific research to delineate the exact dynamics at play, which could substantially inform conservation efforts and land management strategies and enhance our overall understanding of ecological systems.

Moreover, the interconnectedness and variability among these environmental factors indicate critical areas for future research, particularly in elucidating how climate change may alter these relationships. These interrelations are likely to shift with the progression of climate change, potentially bearing significant implications for ecosystems and human societies. Continuous monitoring and research are indispensable for effectively navigating these changes, ensuring that conservation and management approaches remain robust and adaptable in response to the evolving dynamics of the natural environment.

Despite the inconclusiveness of research findings—wherein certain regions exhibit an inverse relationship between increased precipitation and decreased temperatures, and others do not demonstrate significant correlations—the inquiry into these phenomena remains vital. For instance, the study by Wu *et al*. (2006) highlights inconsistencies in model-predicted correlations between rainfall and temperature across different geographical areas, suggesting that these relationships may vary by location. Additionally, the literature provides limited evidence of significant links between rainfall and wind speed or tree density, indicating that these variables may operate independently or be mediated by complex, site-specific factors.

Similar uncertainties pertain to the relationship between temperature and forest structural variables such as wind speed and tree density, where past research has shown limited direct impact. However, recent studies have advanced this discourse by uncovering more nuanced interactions. For example, Yu *et al*. (2023) found that tree-ring maximum latewood density (MXD) strongly correlates with summer temperatures in high-latitude zones, while precipitation plays a minor role. In contrast, Battipaglia *et al*. (2023) demonstrated that rising annual temperatures increase intra-ring density variability (IADF) in trees growing in bimodal growth climates, indicating region-specific growth sensitivities. Similarly, studies in semi-arid China reveal that MXD tracks hydroclimate—especially precipitation and drought—more closely than temperature, underscoring the dominance of water availability in growth dynamics (Yang *et al*., 2023). These observations are further supported by Song *et al*. (2020), who noted a reversal in tree growth response along precipitation gradients in the Tibetan Plateau.

Wind speed has also been shown to influence both climate measurements and forest microclimates. Rácz (2023) emphasized that wind-induced precipitation undercatch can distort rainfall estimates, particularly in windy regions, while Nicolas and Boos (2025) quantified the positive relationship between cross-slope wind speed and orographic rainfall in tropical mountains. At the ecosystem scale, Li *et al*. (2023) found that increased wind speed can reduce the localized cooling effect of trees but extend its influence farther downwind. Moreover, Bytebier *et al*. (2022) revealed that tree density and wood density traits are co-regulated by temperature and moisture availability, with varying sensitivity across ecological zones. These findings collectively reinforce earlier global perspectives, such as those by Schultz and Halpert (1993), who examined NDVI–climate correlations worldwide and concluded that complex interactions among multiple climatic variables shape vegetation responses. Thus, while overarching patterns exist, specific environmental conditions and regional climate regimes remain critical in determining forest responses to climate drivers.

Investigating the effects of climatic variables on forest biodiversity

Understanding the impacts of climatic variables on forest biodiversity requires a sophisticated understanding of the interactions between environmental factors and forest ecosystem attributes. Statistical methodologies, including correlation analysis and multiple linear regression, play a crucial role in delineating and quantifying these interrelations. The correlation coefficient, denoted as r, is a pivotal measure for assessing both the magnitude and direction of the linear relationship between two distinct variables. The value of this coefficient ranges from -1, signifying a perfect negative correlation, to +1, indicating a perfect positive correlation. A coefficient of 0 suggested the absence of a linear association between the variables.

The linear regression equation is formulated as

$$y=mx+b \quad \text{(Eq. 2)}$$

where y represents the dependent variable, which, in this case, is Density (Trees per hectare),

x denotes the independent variable, in this scenario, Wind Speed (km/h),

m stands for the slope of the regression line, reflecting the correlation coefficient and indicating the extent of change in y for a unit change in x,

b is the y-intercept that represents the predicted value of y when x is zero.

Through the application of these statistical tools, the Pearson correlation coefficient (r) between Wind Speed (km/h) and Tree Density (Trees/ha) was determined to be approximately 0.336. This calculation revealed a moderate positive correlation, suggesting that as the wind speed increased, there was a corresponding increase in tree density to some extent. Consequently,

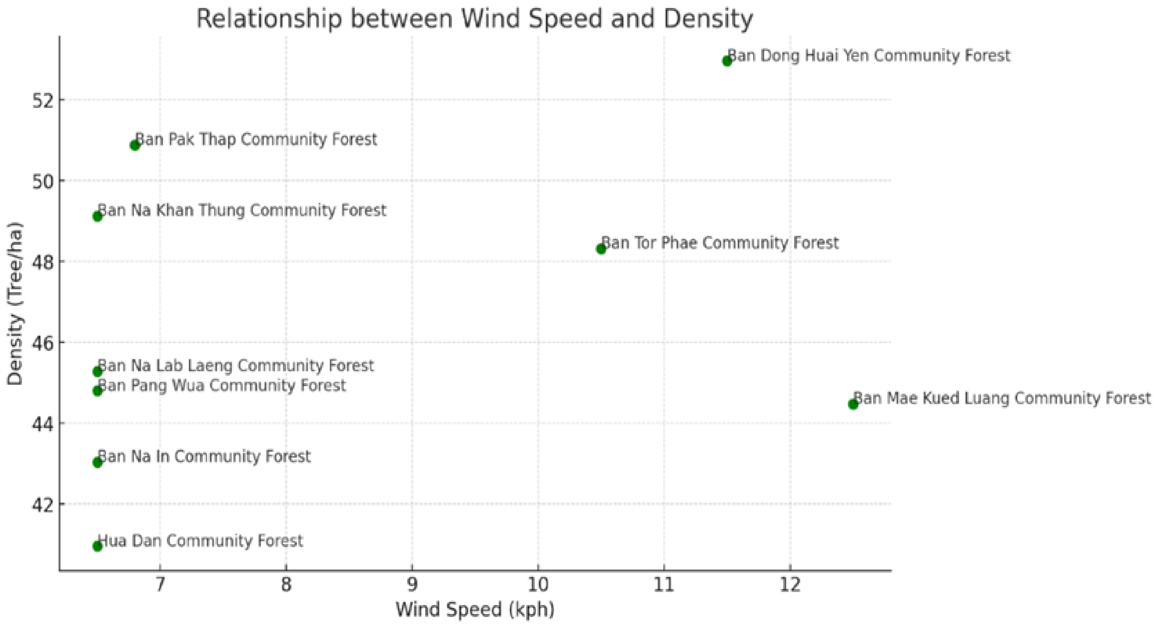

Fig. 6. *Forest characteristics with respect to environmental factors*

the derived equation for the correlation line is

Tree Density (Trees/ha)=0.519×Wind Speed (km/h)+42.395Tree Density (Trees/ha)=0.519×Wind Speed (km/h)+42.395 (Eq. 3)

Understanding the interplay between climatic variables and forest biodiversity requires a sophisticated analysis of the interrelations among environmental factors and forest attributes. The application of statistical methodologies, particularly correlation coefficients and multiple linear regression analyses, is crucial for delineating these complex relationships. The correlation coefficient, denoted as r, serves as a measure of the magnitude and direction of the linear association between two distinct variables. This coefficient ranges from -1, which symbolizes a perfect negative correlation, to 1, which indicates a perfect positive correlation. A coefficient of zero signified the absence of a linear correlation. The linear correlation model is represented by the equation y=mx+b, where y represents the dependent variable (in this context, Tree Density per hectare), x is the independent variable (here, Wind Speed in kilometers per hour), m denotes the slope of the line, reflecting the correlation coefficient and indicating the rate at which y varies with x, and b signifies the y-intercept of the line or the value of y when x is zero. The Pearson correlation coefficient (r) between Wind Speed (kph) and Tree Density (trees/ha) was calculated to be approximately 0.336. This culminates in the following equation: Tree Density (trees/ha)=0.519×Wind Speed (kph)+42.395Tree Density (Trees/ha)=0.519×Wind Speed (kph)+42.395.

This formula not only provides a quantitative basis for predicting tree density based on wind speed but also highlights the complex interplay between climatic variables and forest biodiversity. Such insights are crucial for advancing our understanding of forest ecosystem dynamics and informing targeted conservation and management strategies in the face of evolving climatic conditions. The detection of a positive correlation coefficient between Wind Speed and Tree Density indicates a subtle positive linear relationship, suggesting that increments in Wind Speed are slightly associated with higher Tree Density. However, this relationship is modestly pronounced. To further explore the connections between environmental factors (Average Rainfall, Average Temperature, Relative Humidity, Wind Speed) and forest traits (Tree Species, Shrub Species, Herb Species, Frequency, Density, Basal Area), multiple linear regression analysis is essential. This approach allows the investigation of the influence exerted by variations in independent variables (environmental factors) on dependent variables (forest characteristics), thereby uncovering the intricate dynamics that govern these relationships. Research into the impact of climatic variables on forest biodiversity has revealed a complex interaction between environmental conditions and forest characteristics. Numerous studies have highlighted various factors that affect forest biodiversity, emphasizing the significant role of climate change, ecosystem properties, and ecological responses. Moreover, human activities, coupled with climatic variables, have profoundly altered tropical forests, significantly impacting their biodiversity and ecological functions. Practices such as intensive agriculture, logging, and broader effects of climate change pose serious threats to these ecosystems. The call for “development without destruction” remains a pressing priority in safeguarding forest biodiversity against the escalating threats of climate change. Preserving old-growth forests is particularly vital, as they act as ecological strongholds for species sensitive to climatic fluctuations. These forests regulate local microclimates and enhance ecosystem stability by supporting rich species assemblages and long-term carbon sequestration (Huang *et al*., 2017). Recent studies have confirmed that mixed-species forests are more productive than monocultures, especially in regions with higher precipitation, thereby reinforcing the importance of biodiversity in buffering ecosystems against climate variability (Jactel *et al*., 2018). In fact, climate change may alter the biodiversity–productivity relationship itself, depending on regional conditions, being positive in dry climates but more complex in humid zones (Fei *et al*., 2018). The role of net primary production (NPP) in assessing climate impacts is also gaining prominence. While global NPP has shown increases where water is not limiting, climate-induced disturbances, such as droughts and pest outbreaks, are starting to offset these gains, especially in the extremes of Europe (Tijerín-Triviño *et al*., 2025). Therefore, conservation efforts must extend beyond productivity metrics alone and account for species turnover and resilience mechanisms under changing climate conditions (García-Valdés *et al*., 2020). Models, such as Species Distribution Models (SDMs), remain essential tools for projecting future habitat suitability and informing adaptive strategies. However, forest governance and planning must now internalize biodiversity values into economic models to align conservation incentives with societal welfare (Augustynczik *et al*., 2020). In conclusion, integrating habitat quality, biodiversity–productivity dynamics, and climate adaptation strategies is key to ensuring the resilience of forest ecosystems in an era of accelerating climate change.

Initiating meticulous data cleaning and exploratory data analysis (EDA) are indispensable for developing an in-depth comprehension of the interconnections among various variables. This initial phase involves an exhaustive review and methodical organization of the data columns, with a particular focus on variables directly relevant to the study's objectives. The key variables under scrutiny can be broadly categorized as follows.

1. Environmental Factors: This group comprises variables such as average rainfall, Average Temperature, and Wind Speed. These factors are integral for assessing the influence of climatic conditions on the dynamics and health of forest ecosystems.

2. Forest Characteristics: Under this category, crucial variables such as Tree Species, Shrub Species, Herb Species, and their respective frequencies, densities, and basal areas are listed. These variables are crucial for understanding the composition and structural attributes of forests, providing valuable insights into biodiversity and the functioning of ecosystems.

Upon completion of the data preparation, the EDA phase begins by employing visual methods to thoroughly scrutinize the dataset. This step is crucial for understanding the distributions of the variables and identifying potential relationships between them. Scatter plots have emerged as particularly invaluable tools during this exploration, illuminating the variations in forest characteristics in response to environmental factors. Through this preliminary investigation, researchers gained foundational insight into which variables may exhibit notable correlations or associations, as depicted in Fig. 6. This process sets the stage for more detailed statistical analyses and hypothesis testing, guiding the research towards meaningful ecological insights and conclusions.

Data purification and exploratory data analysis (EDA) are fundamental components for examining the intricate network of interdependencies within forest ecosystems. These methodological approaches are essential for elucidating the distributions of various variables and identifying potential correlations, particularly between forest attributes and environmental conditions. The literature synthesis emphasizes the efficacy of these techniques, which are categorized into environmental factors and forest characteristics. Environmental Factors, the utilization of remote sensing technologies, and machine learning algorithms are crucial for monitoring and managing forest ecosystems in the context of climate change. Notably, Nitoslawski *et al*. (2021) asserted the critical role these tools play in adapting forest management strategies to the changing climate landscape. The Impact of Agroforestry on ecosystem services is significant, as the incorporation of trees within agricultural landscapes —a practice known as agroforestry —enhances ecological resilience. This approach fosters a symbiotic relationship between agriculture and forestry, thereby augmenting benefits such as carbon sequestration and biodiversity enhancement, as described by Brown *et al*. (2018). This exemplifies the significant impact of environmental conditions on the effectiveness of agricultural and forestry practices. Forest Characteristics, Data Mining, and Machine Learning Applications: The emergence of data mining and machine learning has transformed the analysis of air pollution's impacts on forests. Bellinger *et al*. (2017) demonstrated the potential of utilizing big data in environmental studies to elucidate complex interactions among numerous factors. Moreover, the incorporation of metrics, such as mature tree prevalence and canopy coverage, into forest management plans highlights the importance of assessing forest composition and structure to ensure sustainability, as noted by Cosovic *et al*. (2020). Exploratory factor analysis (EFA) is recognized in psychological and environmental research for its utility in validating studies, particularly for identifying underlying patterns among variables, including environmental perceptions (Izquierdo *et al*., 2014). The integration of digital technologies, machine learning, and advanced data analysis techniques in the domain of forest ecosystem studies has elucidated the intricate relationships between environmental variables and forest characteristics. Through the application of advanced methodologies, such as remote sensing and agroforestry practices, coupled with rigorous EDA, a more comprehensive understanding of these interrelations was achieved. This enhanced comprehension is instrumental in developing more effective forest management and conservation strategies, reflecting the collective insights derived from the highlighted research endeavours. Thus, the integration of data purification, exploratory data analysis (EDA), and visualization tools enhances our understanding and management of forest ecosystems in an era characterized by climate and environmental transformations. The insights derived here carry broad implications, informing not only conservation efforts aimed at safeguarding species diversity but also community-based forest management policies. Ultimately, this research underscores the vital importance of environmental stewardship for both ecological preservation and the well-being of local communities, thereby paving the way for sustainable forest governance in Northern Thailand.

Conclusion

In conclusion, this study elucidates the profound and complex relationship between climatic factors and forest biodiversity in Northern Thailand. The present findings revealed that variables such as temperature and precipitation significantly influence the diversity and spatial distribution of species in community forests, highlighting the susceptibility of these ecosystems to the effects of climate change. The intricate interplay between climatic conditions and biodiversity highlights the need for adaptive conservation strategies that mitigate the adverse impacts of global warming on these vital ecosystems. Furthermore, our study advocates the continuation of detailed, region-specific research to deepen our understanding of the interactions between climate and biodiversity. This knowledge is imperative for formulating effective conservation policies and practices. The integration of indigenous ecological knowledge with modern scientific inquiry offers a promising avenue for developing innovative approaches to preserving the biodiversity of community forests in Northern Thailand and beyond. It is essential for stakeholders at every level, from local communities to international organizations, to collaborate in implementing sustainable forest management and conservation strategies. These strategies must be grounded in empirical research and tailored to address the distinct needs and conditions of each forest ecosystem. Through coordinated and decisive actions, it may be able to protect the world's forest biodiversity against the effects of an ever-evolving climate.

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Conflict of interest

The authors declare that they have no conflict of interest.

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