Influence of Soil Health on Biodiversity in Community Forests of Northern Thailand

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***Abstract*—In this study, we explored the relationship between soil properties, nutrient availability, and forest ecosystems in Northern Thailand, with the aim of investigating how variations in soil properties and nutrient availability influenced biodiversity in community forests. Specifically, we investigated whether soil health indicators, such as nitrogen, phosphorus, and potassium, impacted forest diversity, density, and tree basal area. Using quantitative analysis and fieldwork, we assessed soil quality indicators, including nitrogen, phosphorus, and potassium ratios. These factors influenced forest variety, density, and tree basal area. We found that the nitrogen, phosphorus, and potassium levels significantly influenced tree species diversity and forest structure, those soils with balanced nutrient ratios supporting greater biodiversity, whereas areas with nutrient imbalances showed reduced ecosystem productivity. These results emphasize the need for targeted nutrient management strategies to enhance forest biodiversity and sustainability. Our findings show that nitrogen, phosphorus, and potassium significantly influence forest diversity, emphasizing the need for balanced nutrients to ensure optimal ecosystem efficiency and strategies for managing nutrient imbalances. In the context of conservation, advocating for soil health measurements in ecological evaluations and conservation plans is essential. This study provides practical guidance for effective conservation strategies through enhancing our understanding of the interactions between soil chemistry and forest ecology.**

***Keywords*—soil health indicators, biodiversity, nutrient management, forest ecosystems, conservation strategies**

I. Introduction

The stability of global ecosystems is closely linked to the dynamic relationship between climate, soil, and biodiversity. This trio forms the foundation of ecosystem health, with diverse and functionally rich ecosystems showing better adaptability to climate variations. By contrast, ecosystems with low functional diversity have reduced resilience. Biodiversity loss undermines ecosystem integrity and diminishes the adaptive capacity of human societies [1]. Global research emphasizes the importance of soil health in sustaining biodiversity across ecosystems like tropical rainforests, temperate forests, and arid landscapes. In tropical forests of South America, studies have shown that soil nitrogen and phosphorus are key drivers of plant diversity and biomass production, while similar patterns are observed in Africa, where balanced soil nutrient profiles enhance ecosystem resilience and carbon sequestration [2].

In Thailand, the interplay between soil health and biodiversity is less extensively studied but remains critical. Past research has demonstrated that organic matter content and soil pH play significant roles in supporting diverse plant species, particularly in the country's agroforestry and community forest systems [3]. Recent investigations have also highlighted the role of traditional forest management practices in influencing soil nutrient dynamics, particularly nitrogen fixation and phosphorus availability, which directly affect species diversity and forest productivity [4].

At the global level, studies in temperate ecosystems emphasize the importance of soil organic matter and nutrient cycling in sustaining forest productivity, while in arid regions, soil properties such as bulk density and moisture content determine plant survival and diversity [5]. These findings collectively reinforce the idea that soil health is a fundamental determinant of biodiversity, influencing ecosystem stability and resilience across environmental gradients. These global perspectives reinforce the significance of soil health as a determinant of biodiversity, aligning with findings from Northern Thailand's community forests. Studies [6, 7] have underscored the vital connection between biodiversity and ecosystem functionality. Well-maintained ecosystems, including diverse agricultural and forest landscapes, are more resilient to climatic fluctuations, unlike biologically impoverished ecosystems, often degraded by human activities.

Our understanding of how biodiversity influences ecosystem processes is still developing. It is widely believed that a basic level of species diversity is essential for ecosystems to function properly, with greater diversity being crucial for their stability against environmental change [8]. While there has been substantial research on the relationship between soil health and biodiversity in various ecosystems globally, studies focusing specifically on community forests, particularly in Northern Thailand, remain limited. Previous research has often centered on either biodiversity or soil health in isolation, without fully exploring the interconnectedness between these two critical factors in community-managed forest systems. For instance, much of the existing literature (e.g., [6, 9]) focuses on tropical rainforests or temperate forests, where the management strategies and environmental conditions differ significantly from those in Northern Thailand's community forests. Moreover, while the role of soil nutrients, such as nitrogen, phosphorus, and potassium, in supporting plant diversity has been well-documented globally, there has been insufficient focus on how these nutrients specifically affect forest structure and diversity in community-based forest management systems, where human activity and traditional practices also influence forest health. Previous studies on Northern Thailand have not adequately addressed how

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nutrient imbalances or soil degradation due to these factors impact ecosystem functioning, particularly in terms of tree species diversity, forest density, and tree basal area. Recent research [10] has indicated that the effect of biodiversity on ecosystem functions is closely related to specific levels of functional diversity. Non-living factors, including climate, topography, and soil characteristics, are critical in affecting the carbon storage in forests. Global warming greatly influences the carbon processes in tropical forests by impacting both the plants and soil health [6, 7], mainly through its effects on photosynthesis and tree biomass accumulation [8]. Although studies have explored the effects of regional climate change [9–12], the specific effects of local climatic conditions at the plot level in tropical areas have often been overlooked. Topography's role in shaping forest formation and composition has been recognized [13], affecting the distribution patterns of biodiversity and, as a result, the dynamics of forest carbon [12, 14]. Additionally, soil properties, such as moisture content, bulk density, pH, and texture, have crucial effects on the habitats of soil microbial communities, with changes in these leading to changes in soil organic carbon dynamics [5, 15].

Soil plays a vital role in enhancing biodiversity and ecosystem stability by serving as a habitat for organisms and acting as a carbon pool. Soil health directly influences biodiversity through interactions between plants and soil organisms, which underpin ecosystem functioning species or acting as a carbon pool [16–19]. Thailand is located at the crossroads between the Indo-Chinese and Malayan regions, giving it a blended biodiversity. The regional plant and animal species populating its habitats—described in detailed botanical proceedings [3, 4, 20]—correspond to the nation's unique biogeography. A transition to community-based forestry measures, as a key strategy in the late 1980s, shifted the management of forest resources toward a comprehensive approach, known today as community forest management. This strategy aligns with Thailand's constitutional policies [21] through promotion of the meaningful participation of local citizens in protecting and managing the forest habitats. Nitrogen (N), phosphorus (P), and potassium (K) were selected as primary indicators because they are critical macronutrients that regulate plant growth, biodiversity, and soil health. In tropical forest ecosystems, these nutrients determine productivity and resilience due to their roles in photosynthesis, root development, and stress tolerance. However, tropical soils often exhibit nutrient imbalances caused by rapid decomposition, leaching, and soil acidification, making N, P, and K particularly relevant for assessing ecosystem health.

This study investigates how soil health indicators influence biodiversity and forest structure in Northern Thailand's community forests. The research aims to identify specific soil factors that enhance biodiversity and ecosystem resilience while providing practical recommendations for sustainable forest management. Through understanding local contexts, we are able to suggest sustainable environmental methodologies that will allow both the exploitation and preservation of forest resources, balancing stewardship and conservation practices. The study tests the following hypotheses:

1) Balanced levels of nitrogen, phosphorus, and potassium (N:P:K) significantly enhance tree species diversity and basal area.
2) Soil organic matter content is positively correlated with biodiversity and ecosystem stability.
3) Sites with nutrient imbalances or lower soil health indicators show reduced biodiversity and forest productivity.

II. Materials and Methods

A. Study Area

We investigated nine community forests across three distinct models in Northern Thailand. Model 1 was community forests recognized at the national level, Model 2 included provincial community forests, and Model 3 involved community forests designated for management process transfer. The classification of these models is outlined in Table 1, which provides a structured overview of the diverse approaches to community forest management in the region.

Table 1. Summary of the locations of the community forest sites

Model 1	Model 2	Model 3
Ban Tor Phae (BTP) Community Forest, Tor Phae Subdistrict, Khun Yuam District, Mae Hong Son Province	Ban Pak Thap (BPT) Community Forest, Village No. 7, Pha Luat Subdistrict, Tha Pla District, Uttaradit Province	Ban Na In (BNI) Community Forest, Moo 6, Na In Subdistrict, Phichai District, Uttaradit Province
Ban Mae Kut Luang (BMKL) Community Forest located at Moo 1, Mae Kasa Subdistrict, Mae Sot District, Tak Province	Hua Dan (HD) Community Forest, Moo 8, Wang Daeng Subdistrict, Tron District, Uttaradit Province	Ban Na Khan Tung (BNKT) Community Forest, Village No. 6, Saen Tor Subdistrict, Nam Pat District, Uttaradit Province
Ban Dong Huay Yen (BDHY) Community Forest, Village No. 14, Ban Hong Sub-district, Ban Hong District, Lamphun Province	Ban Na Lap Lang (BNLL) Community Forest, Moo 5, Pa Khai Subdistrict, Fak Tha District, Uttaradit Province	Ban Pang Wua (BPW) Community Forest, Moo 7, Khun Fang Subdistrict, Mueang Uttaradit District, Uttaradit Province

B. Data Collection

Data for this comprehensive analysis of community forests in northern Thailand were collected through a multi-pronged approach to ensure accuracy and completeness.

1) Soil sampling and soil chemical and physical analyses

Nine pits were dug, each to a depth of 200 cm. The selection of soil sampling locations in each forest was by the topography, which can significantly affect soil moisture, nutrient distribution, and organic matter content. Each forest was divided into different vegetation zones (e.g., areas of dense trees, mixed shrubs, and open canopy) to capture the influence of different plant communities on soil health. This was to help us understand how varying levels of canopy cover and plant diversity affected the soil properties. In terms of proximity to water sources, sites near streams or other water bodies were included to assess the impact of soil moisture and water availability on nutrient cycling and soil organic matter content. These locations were compared to drier areas to evaluate differences in their soil health. Sampling locations were also chosen to represent the impact of human activity, including both areas that had experienced minimal human disturbance and areas that were closer to community-managed activities. This provided insights into how different levels of human interaction with the forest affected soil properties and biodiversity. To ensure accessibility and sampling safety, locations in extreme terrain were avoided, although the sample design still aimed to represent the full range of forest conditions.

The soils were cored at 13 distinct depth intervals and grouped based on length—short (<5 cm), slightly tall (5–10 cm), moderately tall (10–20 cm), tall (20–30 cm), very tall (30–40 cm), and extremely tall (40–60$^+$ cm). The main reason for building up those samples as to be able to determine the soil texture using a hydrometer (i.e., the sedimentation method) and the bulk density using the cores method. The pH of the soil, organic matter concentration, total nitrogen and all the effects associated with the use of phosphorus, potassium, calcium, magnesium, and extractable sodium were analyzed. We also obtained an estimate of the mass of the soil per unit area, which was key to calculating the ability of the soil to store carbon and other nutrients.

The hydrometer and core methods were employed to determine soil texture and bulk density, respectively, due to their suitability for tropical forest soils and their ability to provide reliable, quantitative data. The hydrometer method is particularly effective for assessing the proportions of sand, silt, and clay in soils with varying organic matter content, which is critical for understanding soil water retention and aeration in these ecosystems. Despite its sensitivity to factors such as temperature and organic matter aggregation, this method allows for a detailed analysis of soil texture, which directly influences nutrient cycling and root development.

The core method was selected for bulk density measurement due to its precision in capturing soil compaction and porosity, key indicators of soil health. Bulk density affects water infiltration, root penetration, and carbon storage potential, making it a critical parameter for evaluating soil quality in tropical forest ecosystems. Although rocky or compacted soils can introduce sampling challenges, pre-treatment and multiple replicates were applied to mitigate these issues and ensure data accuracy.

Notwithstanding their utility, both techniques exhibit limitations that may potentially introduce bias. The hydrometer method is particularly susceptible to the presence of organic matter and particle aggregation, which may result in inaccurate soil texture classification, especially in forest soils with high organic content. Furthermore, extrinsic factors such as temperature can influence the outcomes.

With the core's method, soil compaction during sampling can lead to an overestimation of the bulk density, and the procedure does not deal well with the variability in rocky soils. To mitigate these issues, the samples were pre-treated and temperature controlled, and multiple samplings were performed to improve the accuracy of the analysis and thus the results. Although some biases might still have persisted, our strategies ensured reliable, representative data, supporting robust conclusions about soil health and forest ecology across the community forests studied.

2) Forest structure and other environmental variables

Sample plots, each measuring 40×40 m^2, were established in a tiered arrangement, consisting of three plots in one tier and nine plots in the other, culminating in a total of 27 plots. This structured approach allowed a comprehensive assessment of the forest structure and ancillary environmental variables. Each community forest was observed and divided into different zones or strata based on visible changes in vegetation, topography, and environmental features, such as proximity to water sources or areas of human activity. The sample plots were then randomly placed within these strata, ensuring that different types of habitats in the forest were represented. This method was chosen in order to avoid biases and to make sure the plots reflected the true diversity of the forest environment, including both the more densely vegetated areas and the more open, less densely populated ones. Recognizing that a single plot might not fully capture the ecological complexity of the forest, multiple 40×40 m^2 plots were established across each community forest. By spreading the sample plots across different parts of the forest, we were able to account for spatial differences in the forest structure and species composition. This helped to paint a more accurate and complete picture of the overall biodiversity. For example, plots were positioned in areas of both higher and lower elevation, in more and less moist regimes, near paths that might see more human activity and in secluded, less disturbed areas. The choice of plot location was also guided by the need to include a variety of ecological conditions. This meant setting up plots in areas with dense canopy cover, in regions where the forest was more open, and in sections where different levels of human activity might have affected the vegetation. By doing this, we were able to capture the influence of environmental gradients and human interactions on the biodiversity. For instance, regions in proximity to water sources typically exhibited higher plant diversity, while those adjacent to frequently utilized community pathways often displayed evidence of anthropogenic impact. By incorporating sample plots from these diverse environments, a more comprehensive understanding of the forest's biodiversity was obtained. Including plots from these varied environments provided us with a more holistic view of the forest biodiversity. The selection of the 40×40-m^2 plot size was also informed by reviewing previous studies on similar ecosystems, these dimensions having been used in tropical and community-managed forests, which would allow for effective data comparisons. In this way, we ensured that our findings would contribute to the larger body of ecological research, helping to build a more comprehensive understanding of how soil health and biodiversity interact in community forests. The study assessed nitrogen, phosphorus, and potassium as soil quality indicators due to their direct influence on biodiversity and forest structure. Nitrogen is essential for chlorophyll production and protein synthesis, while phosphorus supports energy transfer and root growth. Potassium regulates water balance and plant resilience. These macronutrients were chosen because their availability and balance significantly impact tropical forest ecosystems, where nutrient cycling and soil fertility are critical determinants of biodiversity and forest health.

3) Climate data collection

Climate data were gathered on a daily basis, aligned with the Julian calendar. Parameters, such as rainfall, temperature, moisture, wind speed and direction, and solar radiation were systematically recorded. These data came from automatic meteorological 3 stations located close to the research site, ensuring their precision and relevance to the study. To address potential discrepancies in the climate data from the automatic meteorological stations, we verified the readings with data from multiple nearby stations to ensure consistency. Portable weather-monitoring devices were also deployed in the study plots to capture microclimatic variations, such as the differences caused by vegetation cover or topography. These localized readings allowed adjustments to be made to the regional climate data, ensuring it accurately reflected the conditions in the plots. Statistical calibration was applied to align the coarser climate data with more-local observations, and seasonal data were collected to account for the temporal variability. This comprehensive approach ensured that the climate data used in the study accurately represented the conditions affecting the soil health and biodiversity, thus enhancing the reliability of the research findings.

4) Engagement with community members

Members of the local community were interviewed, fostering a dialogue for obtaining insights into the intersection of human and ecological narratives in the study area. This process was instrumental in grounding the research in local contexts and perspectives.

C. Statistical and Analytical Framework

Various statistical and analytical techniques were used to interrogate the data:

1) Descriptive statistics

We used the mean, median, and standard deviation to summarize the features of the ecological and climate-related data. These descriptive statistics provided a fundamental understanding of the datasets.

2) Correlation analysis

We applied correlation analysis to reveal the interdependencies between the environmental parameters, such as rainfall, temperature, humidity, and wind speed, and the ecological attributes, including species diversity and soil quality. We also calculated the Pearson's correlation coefficient to elucidate the magnitude and direction of these interrelations.

3) Regression analysis

Multiple linear regression models were used to quantify the effects of the climatic variables on the biodiversity (i.e., species diversity and tree density) and soil-quality properties (e.g., pH, organic matter content, and nutrient levels). Stepwise regression was employed to simplify the models by retaining only the most significant variables, reducing the risk of overfitting. Diagnostic tests ensured assumptions of linearity, independence, homoscedasticity, and normality were satisfied, with a variance inflation factor analysis addressing multicollinearity among the predictors. Generalized linear models were applied in cases where the data did not meet normal distribution assumptions, accommodating nonlinear relationships. Additionally, Spearman's rank correlation was used to validate the associations, particularly for non-parametric data. To further enhance model reliability, k-fold cross-validation was applied, ensuring the predictive power remained consistent and not overly dependent on specific data subsets. This rigorous statistical approach provided a robust understanding of the key soil properties that sustain biodiversity in Northern Thailand's community forests.

Albeit with certain constraints, this analysis elucidated the interactions between climate, soil, and biodiversity in the community forests of Northern Thailand, thus enriching our understanding of these crucial ecosystems and their adaptive mechanisms to environmental shifts.

III. Results and Discussion

A. Geographic Characterization

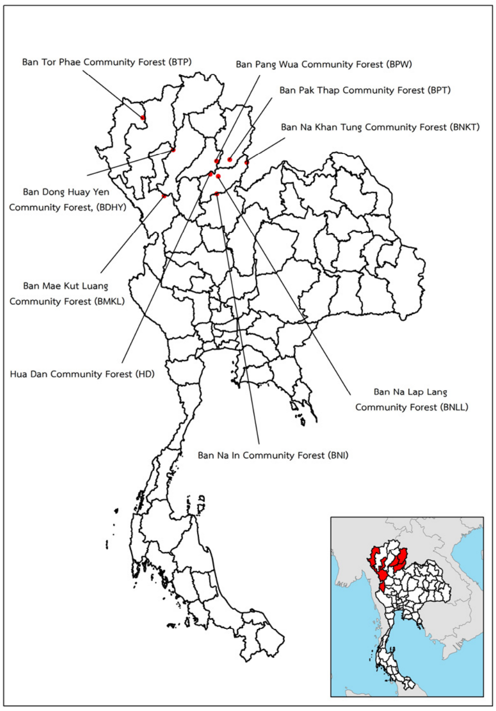

Fig. 1. Map showing the geographic distribution of the study sites across Northern Thailand.

The geographic analysis of the nine community forests (location details and acronyms given in Table 1) revealed diverse topographic features. Location TP was at 500–1,000 m above sea level (a.s.l.) and had a uniform 30% slope from north to south, being part of an undulating landscape of hills and plains. Location BMKL lay at 300–800 m a.s.l., with an average 20% slope and a pronounced upward tilt, being surrounded by a complex hill system in the northeast and west. Location BDHY was at 300–1,000 m a.s.l. and featured a 25% slope from north to south, representing a terrain of hills and adjacent lowlands. Location BPT ranged from 50–500 m a.s.l. in elevation, with a 20% mean gradient, sharing the north–south slope orientation with a mix of hilly and plain landscapes. Location HD was at 50–300 m a.s.l., with a relatively steep 33% average slope, and characterized by alternating hills and plains in the northeast and west. Location BNLL was situated at 50–200 m a.s.l. and had a 31% average slope. Location BNI, situated at 50–400 m a.s.l., exhibited a 30% slope. Location BNKT ranged from 50 to 300 m a.s.l. in altitude, with a 25% slope, with Location BPW having a similar elevation and gradient. These properties, along with the average temperatures and relative humidity, are presented in Table 2. To provide a clearer understanding of the topographic variations between the studied community forests, Fig. 1 includes a series of maps illustrating the geographic features of each study site. These maps show the elevations, slope gradients, and aspects of the forests, allowing a visualization of the differences between the landscapes and how they could influence the soil and forest ecology.

Table 2. Geographical characteristics of the nine community forest area

Study site	Latitude (N)	Longitude (E)	Elevation (m a.s.l.)	Slope (%)	Average temperature (℃)	Relative humidity (%)	annual average rainfall (mm)
BTP	18º 48' 59. 25"	97º 91' 83. 05"	720	30	25.9	45–50	1,350
BMKL	16º 47' 37.54"	98º 64' 39.50"	550	20	26.8	50–55	1,280
BDHY	18º 17' 33.52"	98º 78' 17.5"	580	25	24.5	45–50	1,330
BPT	17º 44' 04.39"	100º 42' 95.92"	350	20	29.5	50–55	1,220
HD	17º 52' 16.79"	100º 13' 58.26"	380	33	28.5	50–55	1,270
BNLL	17º 50' 01.83"	100º 25' 64.10"	150	31	30.2	30–35	1,260
BNI	17º 23' 31.14"	100º 24' 02.81"	350	5	29.5	30–35	1,220
BNKT	17º 42' 57.47"	100º 69' 10.58"	250	10	29.5	30–35	1,200
BPW	17º 43' 10.09"	100º 23' 38.71"	150	20	29.5	30–35	1,290

Table 3. Physical geography and characteristics of the study site

Study Site	Province	Height above sea level (m)	Average slope (%)	Aspect	Physical geography
BTP	Mae Hong Son	500–1,000	30	North South	Hills with plains in between
BMKL	Tak	300–800	20	North East West	Complex hills
BDHY	Lamphun	300–1,000	25	North South	Complex hills
BPT	Uttaradit	50–500	20	North South	Hilly plain
HD	Uttaradit	50–300	33	North East West	Hilly plain
BNLL	Uttaradit	50–200	31	North East West	Hilly plain
BNI	Uttaradit	50–400	5	South West South	Lower plain area
BNKT	Uttaradit	50–300	10	North South	Complex hills
BPW	Uttaradit	50–300	20	North South	Hilly plain

1) Forest community analysis

Fig. 2 contains a graphical representations of tree species per study site, with BTP being at the top in terms of tree species diversity, followed by BMKL and BDHY. It also shows tree density (trees per hectare), with BDHY having the most densely populated forest, but most sites also having relatively high densities, except for BPW, which has a notably lower density. The basal area per unit area (square meters per ha) is also provided in Fig. 2, and shows BTP, BMKL, and BDHY as leading in this aspect, suggesting forest maturity, with either larger individual trees or a higher cumulative cross-sectional area of trees per unit of land, whereas BPW has a low basal area, indicating either smaller trees or sparser tree coverage.

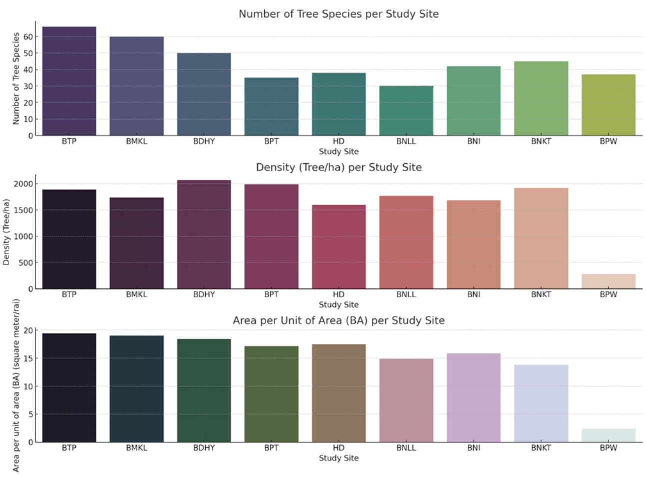

Fig. 2 Graphical representation of tree species richness, tree density, and basal area across study sites. BTP has the highest species richness, followed by BMKL and BDHY. BDHY shows the highest tree density, while BPW has the lowest. BTP, BMKL, and BDHY also lead in basal area, indicating greater forest maturity, whereas BPW has the lowest, suggesting smaller trees or sparser coverage.

Biodiversity encompasses the spectrum of species in a given ecosystem. A variability in tree species across the study locations was noted, with BTP having the highest species richness, contrasting with BNLL and BPW, which had relatively lower diversities. This variation in diversity highlights differences in the ecological conditions or developmental stages of the forests. Locations BDHY and BNKT had the highest tree densities, whereas BPW had a significantly lower density, indicating a potentially younger forest, a region of recent ecological disturbance or the application of a unique forest management strategy.

The basal area analysis revealed that mixed forest sites, such as BTP, BMKL, and BDHY, generally had larger basal areas, whereas deciduous forests, particularly BPW, had smaller basal areas. The size and maturity of the trees influences this measure, with larger or older trees usually contributing to higher basal area measurements, underscoring the structural complexity of these ecosystems (Fig. 3).

Biodiversity plays a critical role in bolstering ecological stability and resilience, offering pivotal ecosystem services, such as carbon sequestration, and aiding in climate change mitigation through species diversity [22]. Tree density and basal area are crucial indicators of forest health and have implications for understory development and overall biodiversity. Environmental gradients further modulate diversity and productivity in these. While anthropogenic activities and natural disturbances can alter forest structure, effective management practices can enhance vegetation diversity, thereby supporting broader species populations [23]. Forests hosting diverse species compositions are better equipped to adapt to climate change and to preserve essential ecological functions. Anthropogenic activities, such as selective logging and farming near forest edges, significantly alter soil properties and biodiversity, with varying short- and long-term impacts.

Selective logging involves removing specific trees, which reduces canopy cover and alters microclimatic conditions, such as soil temperature and moisture. The increased exposure to sunlight can accelerate soil drying, reduce organic matter decomposition rates, and disrupt nutrient cycling, particularly nitrogen and phosphorus availability. Additionally, the heavy machinery used in logging often compacts the soil, decreasing porosity and permeability, which limits root penetration and water infiltration. The resulting habitat fragmentation can lead to a decline in tree diversity and the proliferation of opportunistic or invasive species, reducing overall biodiversity.

Farming near forest edges introduces significant disturbances to soil structure and fertility. Conversion of forested land into agricultural plots leads to a loss of topsoil through erosion, especially on sloped terrains. The removal of vegetation reduces organic matter inputs into the soil, lowering its fertility over time. Pesticides and fertilizers commonly used in farming can leach into adjacent forest soils, altering soil pH and disrupting microbial communities essential for nutrient cycling. Furthermore, edge effects—such as increased light penetration and wind exposure—promote the growth of edge-adapted plant species, which can outcompete native species and decrease biodiversity. These changes often extend into the forest interior, creating cascading effects on both soil health and ecosystem functionality.

Both practices disrupt the balance of soil nutrients, such as nitrogen, phosphorus, and potassium, directly impacting plant growth and species diversity. Over time, these changes reduce the forest's ability to sequester carbon, regulate water cycles, and maintain habitat connectivity. Effective management strategies, such as reforestation, buffer zones, and sustainable farming practices, are critical to mitigating these impacts.

The mixed forests were characterized by their superior diversity, enhanced density, and more substantial basal areas than the deciduous forests, indicating potentially greater maturity or minimal disturbance. Regionally, each location exhibited distinct characteristics, highlighting the necessity for conservation and management approaches that are tailored to the unique conditions of each forest. Enhancing conservation efforts involves prioritizing sites that have significant biodiversity and structural complexity, and particularly those exhibiting elevated tree density and basal area.

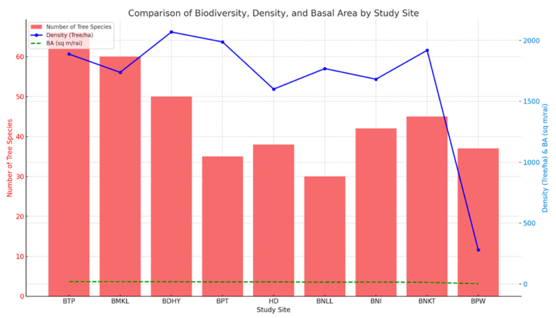

Fig. 3. Tree species richness (red bars), tree density (dashed green line), and basal area (blue line) across study sites. BTP and BMKL show the highest species richness, while BPW has the lowest. Tree density is relatively high across most sites but significantly lower at BPW. Basal area varies, with BTP, BMKL, and BDHY showing higher values, suggesting greater forest maturity.

2) Soil characteristics analysis

The soil had an average bulk density of 1. The density of profile was 41 g/cm³, with the primary spread ranging from 1.33 to 1.48 g/cm³. This indicates that the degree of compactness of the soil was approximately the same at all locations. The soil pH fluctuated from slightly acidic (5.65) to somewhat acidic to slightly alkaline (6.55), with an average of almost neutral (5.996), suggesting a moderate pH across the region. In slightly acidic soils (pH 5.5–6.5), nitrogen availability tends to be optimal due to the enhanced activity of nitrogen-fixing bacteria. These microorganisms thrive in this pH range, converting atmospheric nitrogen into forms that plants can readily absorb. However, in more acidic soils, nitrogen can become less available, leading to nutrient deficiencies that may affect forest productivity and tree diversity. Phosphorus is notoriously sensitive to pH fluctuations. In slightly acidic soils (around pH 5.5–6.5), phosphorus availability is reduced because it binds to aluminum and iron compounds, making it less accessible to plants. In near-neutral soils, phosphorus becomes more soluble and available to plants, promoting root development and overall plant health. The pH values observed in this study suggest that the phosphorus availability might be slightly restricted in some locations, which could limit plant growth and biodiversity in those areas. Potassium tends to be more stable across a wide range of pH levels. In the pH range found in this study, potassium is likely to be readily available for plant uptake, supporting water regulation, enzyme activation, and overall plant resilience. The pH levels across the study sites ranged from slightly acidic (5.65) to near-neutral (6.55), which can have important implications for nutrient availability. Soils with a pH in this range generally favor the availability of macronutrients, such as nitrogen, phosphorus, and potassium. However, slight deviations in pH can significantly alter nutrient dynamics.

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Potassium tends to be more stable across a wide range of pH levels. In the pH range found in this study, potassium is likely to be readily available for plant uptake, supporting water regulation, enzyme activation, and overall plant resilience. The variation in pH levels across the study sites suggests that certain areas might experience nutrient imbalances. For instance, in more acidic soils (pH around 5.65), phosphorus and calcium availability could be limited, leading to stunted plant growth and reduced tree diversity. These areas may require soil amendments, such as lime, to raise the pH levels and improve nutrient availability.

Contrastingly, soils with a near-neutral pH (around 6.55) are likely to support healthier nutrient cycles, with a more balanced availability of key nutrients, such as nitrogen and phosphorus. These areas may exhibit higher levels of biodiversity and more stable forest ecosystems. Soil pH is a crucial indicator of soil health because it influences the microbial activity responsible for organic matter decomposition and nutrient cycling. In this study, the pH values indicate a relatively healthy range for sustaining forest ecosystems, although targeted nutrient management could further optimize conditions. Maintaining a balanced pH is essential for supporting both soil microbial communities and plant species diversity, which in turn enhances ecosystem resilience and productivity.

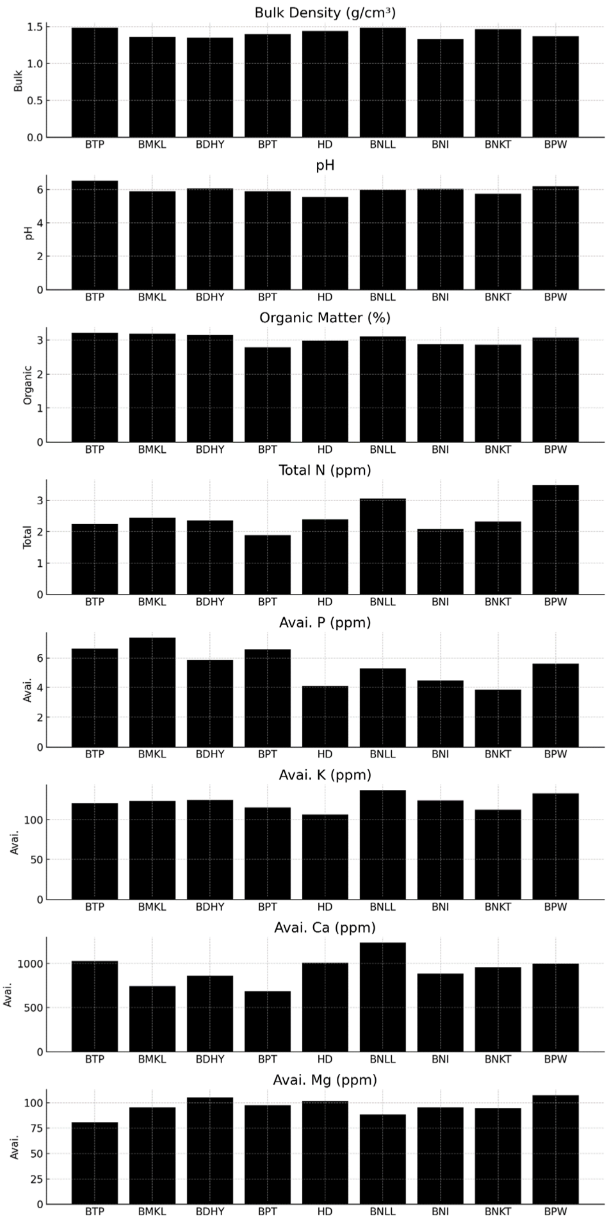

Fig. 4. Key soil properties across study sites, including bulk density (g/cm³), pH, organic matter (%), total nitrogen (ppm), available phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). Variations in these properties reflect differences in soil fertility, structure, and nutrient availability, which can influence vegetation growth and ecosystem function.

The average organic matter content had a 3.02% volatility rate over the last 10 years. The range of this rate between 2000 to 2010 was 2.78% to 3%. This means that the amount of organic material favorable to the growth of new forest was present at a generally healthy level, indicated by its percentage of 21%.

The total nitrogen also showed variation, ranging from 1.89 to 3. The average carbon dioxide concentration was 48 ppm, with a maximum of 2 giving an indication that there was variability in the soil fertility among the sites. While the levels of phosphorus, potassium, calcium, and magnesium—all essential nutrients—fluctuated, calcium especially had a highly unstable trend (from 687.34 to 1,236.89 ppm). These variations underscore the differences in nutrient compositions between the sites (Fig. 4).

Certain locations—notably BNLL and BPW—were characterized by higher levels of key nutrients, such as potassium, calcium, and magnesium, suggesting these soils might support a wider array of plant species. In addition, there was a variation in soil texture—from clay loam to sandy clay loam—between the different sites, which would have impacted water retention and aeration, potentially influencing forest health and type. This diversity in soil texture may have contributed to the noted differences in forest biodiversity and structural configuration, underscoring the complex interplay between soil characteristics and forest ecology.

The relationship between a soil and a forest is most productive when the soil has a bulk density mean of between 1.33 and 1.48 g–the density optimal for root growth, water infiltration, and soil aeration, meaning better forest viability [24]. Also, a soil pH of 5.55 to 6.55 affects the probability of nutrient and microorganism availability, and thus the specific plant species and yields [25]. The optimum variable studied was the soil organic matter content, which was 2.78%–3.21%, which supports local diverse microbial populations and transports sufficient nutrients to the plant roots [26]. A total nitrogen range of 1.89–3.48 ppm is an index of soil fertility––an essential factor in forest management [27]. Consequently, the fluctuation in nutrient availability at the study sites, especially calcium, indicates the need for nutrient management in order to maintain the forests. Our findings stress the role of soil factors as a basis for developing management strategies for the forests in order to increase ecosystem stability [28]. Maintaining healthy developing soils, by applying adequate amounts of nutrients, is fundamental for forest yields and biodiversity, which in turn provide ecosystem services [29].

A heatmap analysis (Fig. 5) revealed a correlation between the soil properties (organic matter content, total nitrogen, and available phosphorus, potassium, calcium, and magnesium) and ecological factors (tree species, shrub species, and herb species), with a notable positive relationship between percentage of organic matter and herb diversity (0.57) and tree species (0.58), suggesting a higher organic matter content fosters increased plant diversity, albeit with a slight inverse relationship with sharp species (–0.24), indicating divergent ecological needs or adaptations. The total nitrogen showed a strong positive correlation with available potassium (0.67) and a moderate one with available calcium (0.60), although these relationships do not significantly relate to the ecological factors measured. The available phosphorus correlated strongly with herb species (0.69), but negatively with sharp species (–0.30), reinforcing its importance for herb species. The available potassium, although closely linked with total nitrogen (0.67), lacked a significant relationship with the plant diversity metrics, hinting at the dominance of other ecological factors in the species distribution. The available calcium and magnesium showed moderate relationships with total nitrogen (0.60) and a positive relationship with sharp species (0.52), respectively, with no strong links to plant diversity, suggesting other ecological interactions taking precedence. Tree species exhibited a strong positive relationship with both organic matter content (0.58) and herb species (0.77), indicating that areas rich in organic matter and herb species tended to exhibit greater tree diversity. Conversely, sharp species demonstrated a slight positive relationship with tree species (0.34) and a moderate negative one with available calcium (–0.50), pointing to specific soil preferences or sensitivities, while herb species displayed a very strong positive relationship with tree species (0.77), suggesting potential shared habitat requirements or mutual facilitation that enhanced biodiversity.

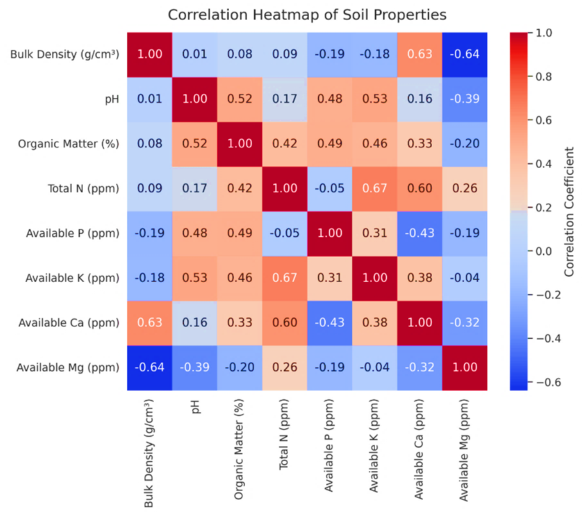

Fig. 5. Heatmap based on the concentration of key soil nutrients across the different study sites, with each cell representing the average nutrient level at each site. Blue—low concentration, red—high concentration.

The heatmap analysis highlights the intricate relationships between soil characteristics and plant diversity, indicating sophisticated ecological interactions, notably, the positive correlations between organic matter content and herb and tree species diversity. This suggests that soils enriched in organic matter produce greater plant diversity, as previously posited by [30], who found that soil organic matter plays a crucial role in enhancing nutrient availability, thus nurturing diverse plant ecosystems. Conversely, the slightly negative correlation with shrub species may reflect unique ecological preferences or adaptations peculiar to shrub species favoring environments with a lower organic matter content. This aligns with the hypothesis proposed by [31] that distinct plant functional types exhibit specific nutrient needs and tolerance levels, thereby influencing their distribution and abundance in varying soil conditions.

The pronounced correlation between total nitrogen and available potassium, coupled with its moderate linkage with available calcium, but a poor direct influence on plant diversity indicators, underscores the complicated interplay between nutrients and their subtle impacts on ecological variables. This nuanced network of nutrient interactions, and their consequential effects on plant community structures, resonates with the insights provided by [32], who elaborated on the pivotal role of nitrogen in plant development, while also highlighting its complex interactions with other soil nutrients, which can lead to diverse outcomes for plant community composition.

The marked positive correlation between available phosphorus and herb species diversity, juxtaposed with its negative relationship with shrub species, underscores the critical influence of phosphorus in favoring specific plant functional groups, a phenomenon described by [33], who demonstrated that phosphorus availability plays a significant role in determining plant species richness, especially among herbaceous communities. This relationship suggests that phosphorus not only serves as a vital nutrient, but also as a selective force in shaping plant community structures by differentially supporting various functional groups. The absence of significant correlations between available potassium and plant diversity, despite its strong association with total nitrogen, hints at the critical role of potassium in plant physiological processes, but also suggests that its influence on plant species distribution and diversity may be overshadowed by other ecological determinants, as discussed by [34]. This observation implies that, while potassium is vital for plant growth, broader ecological variables may have a more pronounced impact on the biodiversity and distribution of plant species. The moderate connection between available calcium and magnesium with total nitrogen, along with their distinct associations with ecological factors, underscores the subtle yet impactful roles these nutrients play in structuring plant communities. These effects may stem from their influence on the soil pH and cation exchange capacity, which, in turn, affects plant nutrient absorption, as noted by [35]. The robust positive correlation between tree species diversity and both organic matter and herb species diversity highlights the complex interplay within forest ecosystems. This relationship suggests that organic matter not only nurtures a diverse understory, but also plays a crucial role in sustaining overall tree diversity, echoing the findings of [36], who explored the connections between soil biodiversity and plant diversity in ecosystems. Conversely, shrub species exhibit particular soil preferences or sensitivities, evidenced by a slight positive correlation with tree species and a moderate negative correlation with available calcium. This pattern indicates that certain shrub species may select for, or avoid, specific soil conditions—a phenomenon examined by [37] in their study on plant interactions and soil characteristics. Furthermore, the exceptionally strong positive relationship between herb and tree species points to a potential mutual facilitation or shared habitat preferences, contributing to enhanced biodiversity. This concept was previously posited in [38], who investigated the ways in which plant diversity underpins ecosystem functionality through varied plant interactions.

The variability in soil pH and organic matter content across the sites has significant ecological implications for tree species diversity. Slightly acidic soils (pH 5.5–6.5) enhance nutrient availability and microbial activity, supporting greater biodiversity. By contrast, slightly alkaline soils (pH 7.5–8.0) can limit the availability of nutrients, such as phosphorus and iron, potentially reducing species diversity.

A high organic matter content improves soil fertility, water retention, and carbon sequestration, fostering diverse and resilient plant communities. Sites with lower organic matter contents may face challenges with poor soil structure and reduced biodiversity. Overall, acidic soils with high organic matter contents are more conducive to diverse forest ecosystems, while alkaline soils may require targeted soil management to enhance biodiversity.

B. Soil Quality Index

The soil quality index (SQI) had an average value of approximately 0.485 across the investigated sites, with a standard deviation of 0.166, reflecting a degree of variation in soil quality among these locations. The SQI values ranged from a minimum of approximately 0.253 to a maximum of approximately 0.751. Half the studied sites fell between the 25th percentile situated around 0.320 and the 75th percentile at approximately 0.579, illustrating the span of soil quality. Notably, BPW had the highest SQI score, suggesting it possessed the best soil quality among the sites, based on the chosen indicators and method of normalization. By contrast, BNKT had the lowest SQI score, signifying it having the least favorable soil quality. Meanwhile, BDHY, BMKL, and BNLL had SQI scores above the average, implying their soil quality was comparatively superior compared to the other locations. Conversely, BPT, HD, and BNI had SQI scores below the median, indicating relatively inferior soil quality (Fig. 6).

The SQI is a pivotal instrument for identifying locales that could benefit from the implementation of management practices dedicated to augmenting their soil quality. The locations marked by elevated SQI scores indicate more robust ecological frameworks, potentially supporting enhanced ecosystem services, such as nutrient cycling and water regulation. Conversely, the sites with lower SQI scores warrant additional scrutiny to determine the shortcomings of those particular soils and to formulate appropriate corrective measures.

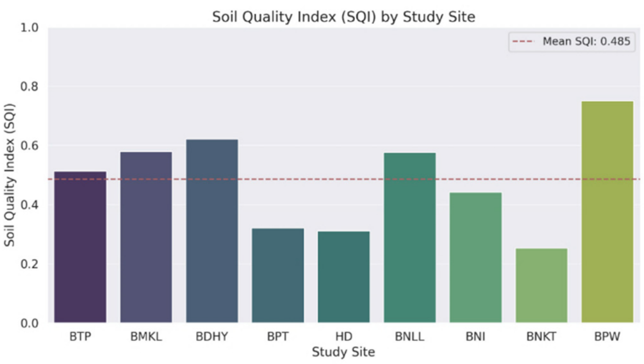

Fig. 6. Soil Quality Index (SQI) values across study sites. The red dashed line represents the mean SQI value (0.485), providing a reference for comparing soil quality among sites.

An examination of the SQI values across the diverse studied locations reveals a complex array of soil health, with fluctuations in the SQI scores delineating varying tiers of soil quality. This variation accentuates the pivotal role of soil management strategies in the preservation and augmentation of ecosystem services. As an aggregate metric, the SQI combines several soil properties to provide a comprehensive evaluation of soil health in both natural and managed ecosystems. This encompasses sustaining floral and faunal productivity, conserving or improving water and air purity, and fostering human wellbeing and habitation, as previously articulated by [39]. The range of SQI scores, from 0.253 to 0.751, with an average of approximately 0.485 and a standard deviation of 0.166, underscores a pronounced variation in soil quality across the surveyed sites. This variance represents a continuum of soil health conditions, from sites exemplified by BPW, which has the highest SQI score and thus optimal ecosystem services conditions, such as nutrient recycling, water purification, and biodiversity support, to the site with the lowest SQI score, BNKT, which represents potential soil function challenges that are detrimental to the ecological balance and productivity. Those locations with SQI scores above the average, including BDHY, BMKL, and BNLL, have relatively enhanced soil quality, potentially signifying a heightened capacity for sustaining vigorous ecosystems and providing superior services, such as nutrient cycling and water regulation. Conversely, those sites with SQI scores below the mean, such as BPT, HD, and BNI, pinpoint areas where the soil quality might be a limiting factor in ecosystem efficiency and the provision of services. The SQI is thus an indispensable instrument for determining sites that could benefit from targeted soil management interventions aimed at ameliorating soil health. Implementing strategic soil-quality improvement measures can foster more-dynamic ecological systems that can offer augmented ecosystem services. This strategy aligns with the perspectives of [40], who saw sustainable soil management practices as critical for preserving soil functionality and boosting ecosystem services. For those locations with relatively low SQI scores, comprehensive soil evaluations are needed to identify their precise requirements. Remedial strategies could include the augmentation of organic matter, erosion mitigation, and/or nutrient management—practices that [41] demonstrated as being efficacious in elevating soil quality and ecosystem services. In essence, the differences in SQI scores across the study areas highlighted the pivotal role of soil quality in underpinning functioning ecosystems and delivering services. Utilizing the SQI as a diagnostic tool would allow land stewards and researchers to determine those locations requiring soil enhancement and focus management practices toward improving soil health and ecological robustness.

C. Nutrient Ratios

Nutrient ratios play a crucial role in determining the availability of essential nutrients in plants, which directly affects plant health and productivity. Typically, an optimal nitrogen: phosphorus: potassium ratio of 3:1:2 is considered sufficient for most plant species, although this ratio can vary depending on the specific needs of different plant species or their growth stages.

Fig. 7 shows the nutrient ratios (nitrogen, phosphorus, and potassium) across the different study sites. The nitrogen: phosphorus ratio was lower than the other ratios at all sites, indicating a relative scarcity of nitrogen in relation to phosphorus, and suggesting that nitrogen may be a limiting nutrient in these ecosystems. Conversely, the phosphorus: potassium ratio was lower than the potassium ratio across the study sites, indicating that potassium was more abundant than phosphorus. Similarly, the nitrogen: potassium ratio also showed variability between the sites, but remained lower than the nitrogen ratio, reinforcing the idea that potassium was more available relative to nitrogen.

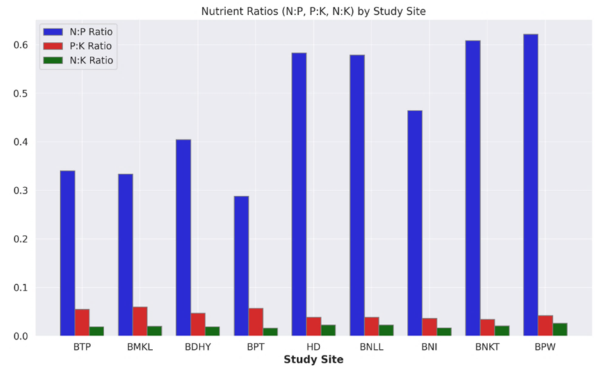

Fig. 7. Bar chart comparing nutrient ratios across the study sites.

The data in Fig. 7 show that the nitrogen ratios generally fall below an optimal threshold of 3:1, which is ideal for most plants. This trend suggests a comparative surplus of phosphorus or a deficiency of nitrogen in the studied soils. By contrast, the consistently low phosphorus ratios across all sites reflect a relative abundance of potassium in relation to phosphorus. Likewise, the low nitrogen ratios suggest that potassium was more available than nitrogen, reinforcing the idea that potassium is not a limiting nutrient in these ecosystems. These findings have important implications for soil management and fertilization strategies. In soils with low nitrogen ratios, nitrogen supplementation may be required to balance the surplus phosphorus and promote optimal plant growth. Additionally, the widespread abundance of potassium, as indicated by the low phosphorus ratios, may be beneficial for certain plants, but may require monitoring to prevent excessive potassium accumulation. Customizing fertilizer applications based on these nutrient ratios can optimize plant growth while minimizing environmental impacts. The variations in nutrient ratios across different study sites highlight the complexity of soil nutrient dynamics. The scarcity of nitrogen, as indicated by the lower nitrogen ratios, suggests that nitrogen is likely the limiting nutrient in these ecosystems. Nitrogen is essential for various plant processes, including amino acid and protein synthesis, as well as chlorophyll production. This aligns with the findings of [42], who noted that nitrogen often acts as a controlling factor in terrestrial ecosystems, influencing both productivity and species diversity. The phosphorus ratio confirms the superior availability of potassium compared to phosphorus at most sites. Potassium plays a critical role in various plant processes, such as water balance, enzyme activation, and photosynthesis. However, an imbalance in the phosphorus ratios may require adjustments to the phosphorus or potassium levels to ensure that the nutrient needs of the plants are met. The nitrogen: potassium ratios suggest that potassium was more readily available than nitrogen, reinforcing the importance of considering nutrient proportions when designing fertilization strategies. As emphasized by [43], nutrient proportions should be carefully considered to meet the specific needs of the plants. The variations in nutrient ratios observed across the different study sites underscore the need for site-specific soil management practices that take into account the unique nutrient requirements of the plants and the developmental stages of the plant species [44], further emphasizing the importance of understanding the soil nutrient dynamics in relation to plant growth. A focus on nutrient proportions, rather than absolute quantities, provides a more nuanced understanding of soil fertility and its compatibility with different plant species. This approach facilitates sustainable agricultural practices by ensuring that the soil nutrient profiles are optimized to meet the specific nutritional demands of the plants, leading to more efficient resource use and minimized environmental impacts.

D. Soil Health Indicators

The SMAF methodology, which combines various soil attributes in a singular SQI, is a sophisticated strategy for assessing soil health across diverse locations. Simplified Soil Management Assessment Framework (SMAF) scores (Fig. 8) can significantly enhance soil management practices by pinpointing those locations requiring interventions to ameliorate their soil health. When these scores are analyzed in conjunction with nutrient ratios, they contribute to the development of more-precise nutrient management strategies. For an in-depth and accurate evaluation, it is imperative to employ a detailed scoring function for each soil attribute, grounded in empirical data, and to apply a refined weighting system to the indicators, in line with the exhaustive methodology of the full SMAF approach. The range of SMAF scores observed here, from the highest at BPW (0.751) to the lowest at BNKT (0.253), highlights the variability in soil health conditions and the opportunity for tailored soil enhancement initiatives. The SMAF is thus an indispensable tool for identifying sites where the soil health can be bolstered through specific management interventions, with the goal of augmenting ecosystem services and agricultural outputs. This perspective is in reflected in the views of [39], who underscored the pivotal role of soil quality in upholding ecological processes. Additionally, the association between the nutrient ratios and SMAF scores suggests that a combined analysis of these elements can provide more-insightful and efficacious soil management practices, as advocated by [40]. A comprehensive evaluation necessitates adopting a detailed approach [45] that involves precise scoring functions for each soil property. This level of assessment is essential to accurately gauge soil health and direct the application of management practices that elevate soil function and sustainability [41, 42] as being critically importance in preserving soil quality for ecosystem resilience.

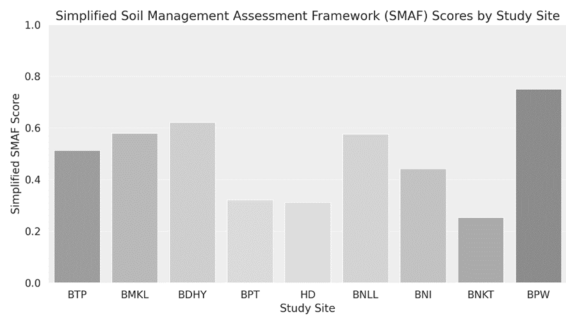

Fig. 8. Bar chart illustrating the simplified Soil Management Assessment Framework (SMAF) scores for each study site.

Soil health and biodiversity are intimately connected, both being crucial in supporting ecosystem services, such as nutrient cycling, carbon sequestration, and plant productivity. Healthy soils provide a habitat for a diverse array of microorganisms, which in turn help maintain the fertility and structure of the soil. Conversely, biodiversity depends on soil health because plants and soil organisms interact in complex ways to support the functioning of ecosystems [46]. A recent study has emphasized the importance of soil biodiversity, especially belowground organisms, in maintaining these ecosystem functions [47], highlighting that belowground biodiversity is essential for nutrient cycling and ecosystem resilience, stressing that the loss of soil biodiversity can severely compromise ecosystem services. Moreover, mycorrhizal fungi, which form symbiotic relationships with plant roots, have been shown to enhance soil structure and nutrient availability [48]. These fungi not only help plants absorb essential nutrients, but also improve soil aggregation, thereby increasing soil stability and water retention. This interaction underpins the critical link between soil health and biodiversity, demonstrating how soil organisms contribute to overall ecosystem productivity. A significant body of recent research has focused on the role of soil health in climate change mitigation, with [49] discussing the potential of soil carbon sequestration as a means of removing greenhouse gases from the atmosphere, underscoring how healthy soils can store carbon efficiently. This process is crucial for maintaining global biodiversity because climate change poses a major threat to ecosystems worldwide. Similarly, it has been emphasized [50] that enhancing soil health can help mitigate climate change impacts, suggesting that sustainable soil management practices not only support biodiversity, but also strengthen ecosystem resilience. In the context of tropical and subtropical regions, including community forests, much of the existing literature has not fully integrated soil health and biodiversity research. Previous studies, such as that of Vieilledent *et al.* [51], have focused primarily on nutrient cycling or plant diversity in isolation, often overlooking the synergistic effects of these factors on ecosystem health. However, understanding how soil health influences biodiversity is particularly important in community-managed forests, where traditional practices and local management play a significant role in shaping the ecological landscape.

E. Management Implications and Recommendations

The variations in biodiversity and forest structure across the different sites, particularly the lower diversity and density at locations such as BPW, highlight several key areas for targeted management. Based on our findings, the following recommendations can be proposed to improve forest health and sustainability.

1) Restoration of degraded areas

Sites with a history of land-use disturbances, such as BPW, would benefit from active restoration efforts. This could include reforestation with native species, soil rehabilitation, and the introduction of practices to reduce soil erosion and compaction. Planting a mix of fast-growing pioneer species alongside slower-growing, late-successional species could help accelerate the recovery process and enhance biodiversity.

2) Soil health improvement

Addressing soil nutrient imbalances is crucial for supporting plant growth and sustaining biodiversity. Management practices, such as adding organic matter, using biochar, or applying natural fertilizers, could help restore nutrient levels and improve soil structure. Regular soil testing should be implemented to monitor soil health and guide appropriate interventions.

3) Control of invasive species

Effective management strategies are needed to control or remove invasive species that may be reducing native biodiversity. This could include mechanical removal, controlled burns, or the introduction of biological control agents. Ensuring that invasive species do not outcompete native plants is essential for maintaining a diverse ecosystem.

4) Microclimate enhancement through canopy management

Managing the canopy cover can help create favorable microclimates that support diverse plant and animal species. In areas with lower canopy density, selective planting of shade-tolerant species could help improve soil moisture retention and temperature regulation. This approach would support the establishment of a more stable and resilient forest ecosystem.

5) Community engagement and sustainable use

Engaging local communities in conservation efforts can help reduce the impact of human activities, such as illegal logging or overgrazing, on forest ecosystems. Promoting sustainable land-use practices and providing alternative livelihoods can minimize the pressure on forests and encourage the preservation of biodiversity. Education and outreach programs are crucial to building awareness and fostering community-led conservation.

6) Long-term monitoring and research

Establishing long-term monitoring programs to track changes in biodiversity, forest structure, and soil health are critical for assessing the effectiveness of management practices. Continued research can help identify new threats and develop adaptive management strategies to address these, ensuring the sustainability of community forests.

To enhance the soil nutrient balance and biodiversity in community forests, several targeted management interventions could be implemented.

a) Organic amendments

Applying compost, manure, and green mulch can replenish essential nutrients and improve soil structure. Community-based composting programs could be established to encourage local participation.

b) pH adjustment

Lime can be used to raise the pH in overly acidic soils, while sulfur can lower the pH in alkaline areas, improving nutrient availability. Regular soil testing can guide precise application rates, coordinated by community managers.

c) Nitrogen-fixing plants

Integrating nitrogen-fixing species, such as legumes, can naturally enrich soil nitrogen levels, reducing the need for synthetic fertilizers. Agroforestry practices could help incorporate these plants effectively.

d) Controlled fertilizer use

When needed, mineral fertilizers should be applied based on soil tests, with careful management to avoid their overuse and environmental impact. Community guidelines could promote responsible application.

e) Mulching

Mulching with leaf litter or plant residues can enhance soil moisture retention and add organic matter. Communities could adopt this practice through demonstration plots showing its benefits.

f) Agroforestry systems

Combining trees with crops or livestock improves nutrient cycling, biodiversity, and ecosystem resilience. Training in agroforestry principles could help communities integrate these systems effectively.

IV. Conclusion

The findings demonstrate the critical relationship between soil health and biodiversity in Northern Thailand's community forests. Nutrient balance, particularly nitrogen, phosphorus, and potassium level, significantly influences tree species diversity and ecosystem productivity. The Soil Quality Index (SQI) effectively highlighted areas requiring targeted nutrient management to sustain biodiversity and ecosystem functionality.

These results emphasize the importance of integrating soil health assessments into conservation strategies to enhance ecosystem resilience. By incorporating soil management into ecological evaluations, this study offers practical approaches to preserving biodiversity and ensuring forest stability in the face of environmental challenges.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Chattanong Podong conducted the entire research, data analysis and writing process. Krissana Khamfong, Supawadee Noinamsai and Sukanya Mhon-ing facilitated the research, validated the data; all authors had approved the final version.

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