Tree growth, mortality and recruitment of stand dynamics over 10 years (2012-2022) in tropical forests, Phou Khao Khouay National Park, Laos

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Động thái về tăng trưởng, chết và tái sinh của cây rừng nhiệt đới ở Vườn quốc gia Phou Khao Khouay của Lào, giai đoạn 2012-2022

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ABSTRACT

The present study delved into the dynamics of tree communities in a specific area within Phou Khao Khouay National Park in Laos, distinguished by three distinct tropical forest types: Dry Evergreen Forest (DEF), Mixed Deciduous Forest (MDF), and Mixed Coniferous Forest (MCF). Conducted over a decade, from 2012 to 2022, we utilized data from a previous inventory carried out in 32 permanent plots, each measuring 50 m × 50 m. Trees with a diameter at breast height (DBH) ≥ 10 cm were identified, tagged, and measured for various parameters. In 2012, we documented 4,072 stems, amounting to 395 species existing within 155 families across the 32 plots, with a total area of 8 ha. By 2022, the number of stems had increased to 4,402, but the species and family counts had decreased to 311 and 135, respectively. Over the ten years, there was a notable increase in the number of stems, basal area (BA), and aboveground biomass (AGB), accompanied by a reduction in species and families. This study contributes valuable insights that can be utilized to enhance forest management practices. The observed trends provide a nuanced understanding of the dynamic nature of the forest ecosystems in the study area. The findings underscore the importance of considering individual forest types when implementing conservation strategies.

Keywords:
Aboveground biomass, evergreen forest, forest dynamics, Kruskal-Wallis test, permanent plot.

TÓM TẮT

Nghiên cứu này phân tích động thái của các quần xã cây gỗ trong các lâm phần tự nhiên thuộc Vườn quốc gia Phou Khao Khouay ở Lào. Các lâm phần này được chia thành ba loại rừng hỗn loài: cây thường xanh - cây họ Dầu, cây rụng lá theo mùa và cây lá kim. Dữ liệu được thu thập ở năm 2012 và 2022 trên 32 ô tiêu chuẩn cố định (50 m × 50 m). Tất cả cây có đường kính ngang ngực ≥ 10 cm đã được xác định tên, gắn thẻ và đo các chỉ tiêu sinh trưởng. Trong năm 2012, 4072 cây thuộc 395 loài của 155 họ đã được ghi nhận. Ở năm 2022, số cây đã tăng lên 4.402, nhưng số loài và họ giảm xuống còn 311 loài và 135 họ. Trong mười năm, số cây, diện tích mặt cắt

Từ khóa:
động thái rừng, kiểm định Kruskal-Wallis, ô định vị, rừng thường xanh, sinh khối trên mặt đất.

ngang thân cây và sinh khối trên mặt đất có sự gia tăng đáng kể, trong khi số loài và họ lại giảm xuống. Nghiên cứu này đóng góp những hiểu biết có giá trị và có thể được sử dụng để tăng cường thực hành quản lý rừng ở Lào. Các xu hướng quan sát được từ động thái của các lâm phần cung cấp sự hiểu biết sâu sắc về tính chất biến động của các hệ sinh thái rừng trong khu vực nghiên cứu. Những phát hiện này nhấn mạnh tầm quan trọng của việc xem xét từng loại rừng khi thực hiện các chiến lược bảo tồn.

1. INTRODUCTION

Research into the dynamics of tropical forests has played a pivotal role in characterizing and comprehending the diversity and intricacies inherent in plant populations and communities [1]. A crucial prerequisite for delving into tropical forests' diversity and ecological processes is the periodic re-measurement of permanent tree plots, as emphasized by Phillips et al. [2]. Ecological studies often scrutinize population changes by utilizing census information acquired through the meticulous counting and subsequent recounting of a predefined sample, thereby allowing the assessment of survivors, losses, and gains [3]. In tropical forests, changes unfold continuously at individual and population levels, driven by a delicate balance among growth, recruitment, and mortality [4]. Additionally, factors such as local extinction, immigration of new species, and ecological drift contribute to the dynamic nature of these ecosystems [1]. This comprehensive understanding of the dynamics is essential for advancing our knowledge of tropical forest ecosystems and informs conservation and management strategies.

Forest dynamics are driven by mechanisms that facilitate ongoing recruitment and the establishment of new individuals and species within the community, even amidst environmental changes triggered by natural or anthropogenic disturbances [5]. The composition and structure of forests, shaped by internal factors like competition for light [6] and external factors such as climate, geological processes, and human-induced changes [1], reflect the intricate interplay of various processes. The persistence of shade-intolerant species and other influences on forest dynamics, such as weak composition leading to a drift in species composition [7], along with recruitment limitation [8], further contribute to the complexity of these ecosystems. Understanding forest dynamics, encompassing the factors governing tree growth, mortality, and growth rates in managed tropical forests, is imperative for their conservation and making informed predictions about their productivity. In this context, a comprehensive understanding of forest dynamics, including shifts in species composition, provides crucial insights for forest managers. This knowledge equips managers with a clearer understanding of the recovery potential of a harvested forest. Armed with precise information about the dynamics of the forest and changes in species composition, managers can make informed decisions that contribute to both conservation efforts and the sustainable production of forests.

Phou Khao Khouay National Park in Laos has faced significant challenges from natural disturbances and human activities. This dual impact has given rise to various consequences affecting forest ecosystems, notably declining forest density and biodiversity. Among the human-induced disturbances, non-timber forest products harvesting, illegal logging, and forest clearing for agricultural purposes stand out, contributing to the overarching issue of biodiversity loss. This loss, in turn, disrupts the entire ecosystem's integrity, functions, and services. In response to these challenges, this article investigated the alterations within the forest structure and tree species composition spanning 2012 to 2022. The study was conducted across 32 permanent plots within three distinct forest types. The primary objective of this research was to discern the intricate patterns associated with tree community dynamics, explicitly focusing on mortality, recruitment, and growth. The study aimed to unravel the evolving dynamics of tropical forests within Phou Khao Khouay National Park in Laos by concentrating on these aspects.

2. RESEARCH METHODS

2.1. Study area

This study was undertaken within the expansive confines of Phou Khao Khouay National Park in Laos, encompassing a total area of 191,942 hectares, as documented by the Government of Lao PDR [9]. Positioned geographically between 18°14'-18°32' N latitude and 102°38'-102°59' E longitude, the national park comprises diverse tropical forest types, primarily categorized as dry evergreen forest (DEF) dominated by the Dipterocarpaceae family, mixed deciduous forest (MDF) characterized by the prevalence of the Fabaceae family, and mixed coniferous forest (MCF) primarily consisting of the Pinaceae family [10].

The elevation profile of the study area exhibits a substantial range, varying from 100 meters to nearly 1,700 meters a.s.l. The national park is characterized by typical tropical red to brown soils, specifically organic acrisols and lithosols, featuring textures ranging from sandy to sandy loam and limited organic matter content [10]. Climatically, Phou Khao Khouay experiences an average annual rainfall of approximately 1,769 mm, distributed across two distinct seasons. The rainy season spans from April to October, with the peak rainfall occurring typically in August at around 494.2 mm. Temperature variations are noticeable, with averages ranging from 16.6°C to 31.8°C during this period. Conversely, the dry season prevails from November to March and is characterized by minimal rainfall, with February recording the lowest precipitation at approximately 2.5 mm. Average temperatures during the dry season fluctuate between 16.8°C and 24.6°C, as the Department of Meteorology and Hydrology reported [11].

2.2. Data collection

Data for this study was obtained from permanent plots established jointly by the Institut Recherche Pour le Development (IRD) in France and the Faculty of Forestry Science (FFS) at the National University of Laos (NUoL) in 2009 , with additional data collected in 2012. Thirty-two plots, each measuring 50 m x 50 m and subdivided into 25 subplots of 10 m x 10 m, were strategically located across three distinct forest types. The first forest type (Dry Evergreen Forest -DEF) comprised 18 plots at an elevation of 569 m, the second (Mixed Deciduous Forest - MDF) encompassed 8 plots at 390 m, and the third (Mixed Coniferous Forest - MCF) comprised 6 plots at an elevation of 816 m. The plots, which are located in the core zone of the national park where human impact is minimal, are strictly protected.

In 2022, data collection involved identifying and measuring individuals with a diameter at breast height (DBH) ≥ 10 cm. The identification process utilized a diameter tape, while tree height was measured using a Blumme-Leiss hypsometer. Tree coordinates and crown diameter were determined using a laser distance measurer (Leica Disto D2) within the designated subplots. Additionally, specimens were systematically collected and forwarded to the herbarium of FFS at NUoL to confirm species identification for suspected cases.

2.3. Data analysis

2.3.1. Mortality and recruitment

The growth of trees with DBH ≥10 cm was assessed by analyzing diameter frequency data collected during the initial census in 2012 and the recensus in 2022. This comprehensive approach allowed for a detailed examination of growth patterns over the specified period.

In this context, mortality was defined as either the death or disappearance of trees. Trees' demise was categorized into four distinct modes: cut, uprooted, standing dead, and trunk snapped off. To quantify the mortality rate (m) of stems with a DBH of 10 cm or more, the following equation, as proposed by Nascimento et al., was applied [12]:

$$m = 1 \quad [(N_o \quad N_m)/N_o]^{1/t} \qquad (1)$$

In re-enumerating trees, particular attention was given to individuals entering the ≥10 cm DBH class and their recruitment was duly recorded (r). The stand turnover time, denoting the duration required for all initially inventoried trees to reach the end of their life cycle, was determined by employing the following equations, as outlined by Nascimento, Barbosa et al. [12]:

$$r = 1 \quad [(N_o \quad N_r)/N_o]^{1/t} \qquad (2)$$

where,

N_o is the number of individuals at the first measurement;

N_m is the number of dead trees;

N_r is the number of recruited stems;

and t is time duration = 10 years.

Equations 1 and 2 effectively estimated the annual mortality rate and recruitment rate concerning Basal Area (BA) and Aboveground Biomass (AGB). In this context, N_o represents the initial BA and AGB of all stems recorded during the first measurement. N_m stands BA and AGB of deceased stems. N_r signifies BA and AGB of stems recruited during the observation period.

The parameters m (mortality rate) and r (recruitment rate) were estimated separately for each plot. Subsequently, the mean values were computed by aggregating all plot-specific estimates.

2.3.2. Aboveground biomass

AGB was estimated across three distinct forest types by utilising allometric regression models, as proposed by Chave et al. [13]. The methodology is outlined as follows:

$$AGB_{est} = 0.0673 \times (\rho D^2 H)^{0.976} \qquad (3)$$

where,

D is DBH (cm);

H is height (m), and p is wood density in (g cm^3). Wood density (WD) data were compiled from published sources [14].

2.4. Statistical analysis

Differences among the three forest types in various variables such as individuals, species, family, DBH, BA, and AGB for the years 2012 and 2022 were assessed through a nonparametric test, specifically the Kruskal-Wallis test. Before the test, assumptions of normality and equal variances were thoroughly verified. The Mann-Whitney test scrutinised further differences between 2012 and 2022 within each forest type. The statistical analyses were executed using IBM SPSS version 20 software. Additionally, comparisons of means about the number of stems, BA, BA increment (BAI), AGB, and AGB increment (AGBI) among DBH classes were conducted through analysis of variance analysis. Meanwhile, pairwise comparisons were applied to investigate differences between two censuses and recruited and deceased stems.

3. RESULTS

3.1. Tree diversity dynamics in 2012 and 2022

In 2012, a comprehensive survey of the 32 permanent plots within the three distinct forest types, namely DEF, MDF, and MCF revealed a total of 4072 individuals with DBH ≥ 10 cm. The corresponding count increased to 4402 individuals in 2022. These individuals represented a diverse ecological landscape, encompassing 395 species and 155 families in 2012 and 311 species and 135 families in 2022, as summarized in Table 1.

Focusing on the DEF, the 18 plots exhibited 2365 individuals in 2012, with an average density of 131±35 trees per hectare. This population comprised 248 species (34±10) and 64 families (22±5). In 2022, the DEF plots recorded a total of 2463 individuals (137±38), 134 species (27±7), and 51 families (20±4).

Similarly, in the MDF, 1189 individuals were observed in 2012, with an average density of 149±45 trees per hectare. This population included 199 species (43±14) and 56 families (24±6). In 2022, the MDF plots recorded 1309 individuals (164±43), 125 species (36±13), and 50 families (24±8).

For the MCF, six plots documented 518 individuals in 2012, with an average density of 68±34 trees per hectare. This population represented 77 species (20±8) and 35 families (14±5). In 2022, the MCF plots recorded 630 individuals (105±34), 52 species (16±5), and 34 families (13±4), showcasing the dynamic nature of the forest ecosystem over the study period, as detailed in Table 1.

3.2. Stem abundance and growth parameters in 2012 and 2022

In 2012, the 18 plots within the DEF exhibited a range of individual counts from 76 to 228 (with an average of 131±35). The species richness varied from 16 to 50 (34±10), and the number of families ranged from 12 to 32 (22±5). By 2022, the DEF plots recorded a shift in these parameters, with individual counts ranging from 86 to 212 (averaging 137±38), species ranging from 17 to 41 (27±7), and families ranging from 12 to 27 (20±4). The mean DBH across the plots exhibited variability, ranging from 12.8 to 30.0 cm in 2012, with an average of 23.3±6. These variations in the number of stems and DBH contributed to differences in BA and AGB. In 2012, BA ranged from 2.29 to 11.49 m²/ha, averaging 7.1±3, while AGB ranged from 9.79 to 147.51 Mg/ha, averaging 61.0±38. In 2022, the mean DBH ranged from 14.2 to 30.7 cm (23.0±5), BA ranged from 2.50 to 12.43 m²/ha (7.7±3), and AGB ranged from 12.64 to 255.60 Mg/ha (91.3±65) (Table 1).

In the MDF, data from eight plots were documented in 2012, revealing a range of individual counts from 49 to 194 (averaging 149±45). The observed species richness varied from 16 to 54 (33±14), and the number of families ranged from 12 to 31 (24±6). In 2022, the MDF plots displayed a shift in these metrics, with individual counts ranging from 75 to 211 (averaging 164±43), species ranging from 13 to 48 (36±13), and families ranging from 11 to 31 (24±8). The mean DBH across the MDF plots ranged from 15.3 to 23.7 cm in 2012, with an average of 20.1±3. In the same year, BA values ranged from 2.26 to 8.61 m²/ha (averaging 6.4±2), and AGB ranged from 11.98 to 95.74 Mg/ha (averaging 53.2±31). In 2022, the mean DBH across the plots ranged from 16.3 to 24.3 cm (averaging 19.7±3), while BA values ranged from 3.0 to 9.7 m²/ha (averaging 6.5±2), and AGB ranged from 20.0 to 96.2 Mg/ha (averaging 53.4±29) (Table 1).

In 2012, data from six plots within the MDF revealed a range of individual counts from 49 to 136 (averaging 86±34). The observed species richness varied from 9 to 29 (20±8), and the number of families ranged from 7 to 20 (14±5). In 2022, the MDF plots exhibited changes in these metrics, with individual counts ranging from 67 to 141 (averaging 105±34), species ranging from 9 to 20 (16±5), and families ranging from 7 to 18 (13±4). The mean DBH across the MDF plots ranged from 12.8 to 30.0 cm in 2012, with an average of 23.3±6. In the same year, BA values ranged from 2.06 to 9.35 m²/ha (averaging 5.4±3), and AGB ranged from 11.19 to 69.37 Mg/ha (averaging 61.0±38). In 2022, the mean DBH across the plots ranged from 19.6 to 27.1 cm (averaging 23.3±3), while BA values ranged from 2.63 to 10.06 m²/ha (averaging 6.3±3), and AGB ranged from 16.66 to 99.21 Mg/ha (averaging 55.1±32) (Table 1).

Table 1. General parameters of three forest types between 2012 and 2022 of study area

Forest types	Plots No.	2012						2022					
		No. Stems plot^{-1}	No. Species plot^{-1}	No. Families plot^{-1}	DBH (cm)	BA (m^2 ha^{-1})	AGB (Mg ha^{-1})	No. Stems	No. Species	No. Families	DBH (cm)	BA (m^2 ha^{-1})	AGB (Mg ha^{-1})
	1	127	45	25	33.4	10.31	62.24	125	29	22	30.06	12.42	113.94
	2	141	40	24	27.4	9.51	48.84	161	29	22	24.95	10.81	111.01
	5	139	40	19	22.5	6.73	59.96	131	34	23	22.70	7.64	85.09
	6	91	39	27	25.7	6.52	74.23	108	32	23	25.43	8.24	100.57
	7	76	22	16	20.3	2.59	13.10	91	17	14	17.35	2.50	12.64
	8	108	29	20	24.5	6.44	50.58	111	22	17	24.66	6.67	70.08
	9	109	23	16	30.0	11.29	147.51	104	21	15	30.68	11.61	225.60
	10	104	29	19	26.0	8.47	88.47	139	24	16	25.66	12.43	200.20
	11	151	50	32	23.3	8.00	77.69	151	41	26	24.68	8.83	82.55
DEF	12	160	49	29	20.6	7.41	74.18	154	34	27	21.51	7.05	63.48
	23	228	36	22	15.9	6.84	18.18	212	35	24	18.74	6.64	51.03
	24	145	29	22	13.8	2.31	10.60	209	29	22	15.56	4.66	26.30
	25	169	16	15	12.8	2.29	9.79	190	16	12	14.22	3.30	18.63
	26	157	37	23	16.7	4.83	31.42	123	29	19	17.55	3.73	30.96
	27	123	36	22	23.2	6.48	52.89	104	23	19	21.66	5.05	51.59
	29	97	33	19	27.8	7.87	79.17	86	24	16	24.69	5.90	66.94
	31	118	16	12	26.3	9.07	69.82	148	19	14	23.22	8.95	119.45
	32	122	35	25	29.8	11.49	129.04	116	29	21	30.47	11.93	213.27
	Mean	*131*	*34*	*22*	*23.3*	*7.1*	*61.0*	*137*	*27*	*20*	*23.0*	*7.69*	*91.3*
	SD	*35*	*10*	*5*	*6*	*3*	*38*	*38*	*7*	*4*	*5*	*3.2*	*65*
	15	155	51	31	23.1	8.61	95.74	153	37	27	24.3	9.69	87.34
	16	144	51	26	20.8	7.04	54.88	167	48	31	20.7	7.90	75.44
	17	189	54	25	15.3	4.99	31.84	211	48	29	16.9	5.66	37.50
	19	194	38	24	16.0	6.18	30.08	207	40	28	16.3	4.95	30.09
MDF	20	139	52	27	23.7	8.46	89.96	166	40	26	22.3	9.73	96.22
	22	160	52	29	20.3	8.15	78.82	183	41	27	18.9	6.84	53.18
	28	159	27	17	18.6	5.17	32.57	147	21	13	17.7	4.21	27.24
	30	49	16	12	23.3	2.26	11.98	75	13	11	20.2	2.99	20.03
	Mean	*149*	*43*	*24*	*20.1*	*6.4*	*53.2*	*164*	*36*	*24*	*19.7*	*6.5*	*53.4*
	SD	*45*	*14*	*6*	*3*	*2*	*31*	*43*	*13*	*8*	*3*	*2*	*29*
	3	136	29	20	25.3	9.35	69.37	141	20	18	23.89	9.63	99.21
	4	113	23	16	23.8	6.38	40.92	127	19	15	22.34	6.84	60.27
	13	49	9	7	20.4	2.06	11.19	68	9	7	19.60	2.63	16.66
MCF	14	92	27	16	20.1	3.50	16.95	92	20	14	21.96	4.10	34.25
	18	54	13	11	27.3	3.70	19.86	67	13	10	25.11	4.36	36.70
	21	74	18	14	31.2	7.16	42.73	135	14	12	27.09	10.06	83.35
	Mean	*86*	*20*	*14*	*24.7*	*5.4*	*33.5*	*105*	*16*	*13*	*23.3*	*6.3*	*55.1*
	SD	*34*	*8*	*5*	*4*	*3*	*22*	*34*	*5*	*4*	*3*	*3*	*32*

3.3. Recruitment and mortality in 2012 and 2022

Over ten years in the DEF, data from 18 plots revealed dynamic patterns in the recruitment and mortality of stems. The number of recruited stems ranged from 18 to 86 stems/ha, averaging 34±17. The BA of recruited stems varied from 0.39 to 3.85 m^2/ha, averaging 1.8±1.1. The AGB of recruited stems ranged from 2.60 to 67.45 Mg/ha, with an average of 20.3±19.9. Concurrently, the number of dead stems in DEF plots ranged from 11 to 53 stems/ha, averaging 29±12. The BA of dead stems ranged from 0.29 to 3.11 m^2/ha (1.5±0.8), and the AGB of dead stems varied from 1.30 to 38.50 Mg/ha, with an average of 13.4±10.6.

In the context of the MDF, data from 8 plots indicated a range of recruited stems from 24 to 75 stems/ha, averaging 46±14. The BA of recruited stems ranged from 0.97 to 3.70 m^2/ha (2.0±0.8), and the AGB of recruited stems varied from 5.29 to 35.74 Mg/ha, with an average of 16.3±9.4. The number of dead stems in MDF plots ranged from 14 to 62 stems/ha (31±17). The BA of dead stems varied from 0.38 to 1.83 m²/ha (1.1±0.5), and the AGB of dead stems ranged from 1.60 to 15.55 Mg/ha, averaging 8.3±4.3.

Meanwhile, within the MCF, data from 6 plots showed a range of recruited stems from 27 to 66 stems/ha, averaging 38±15. The BA of recruited stems ranged from 1.15 to 4.46 m²/ha (2.2±1.1), and the AGB of recruited stems varied from 7.05 to 35.14 Mg/ha, averaging 18.1±10.3. The number of dead stems in MCF plots ranged from 5 to 38 stems/ha (19±13). The BA of dead stems varied from 0.28 to 2.10 m²/ha (0.9±0.7), and the AGB of dead stems ranged from 1.25 to 12.71 Mg/ha, averaging 5.5±4.4 (Table 2).

Table 2. Recruited stems and dead stems of three forest types recorded in 2022

Forest types	Plots No.	Recruited stems			Dead stems		
		No. Stems $plot^{-1}$	BA (m^2 ha^{-1})	AGB (Mg ha^{-1})	No. Stems	BA (m^2 ha^{-1})	AGB (Mg ha^{-1})
DEF	1	28	2.71	20.23	30	2.10	23.52
	2	31	3.22	35.70	11	0.31	2.53
	5	22	0.71	7.02	30	1.80	15.58
	6	30	1.14	9.79	13	1.24	16.23
	7	33	0.94	4.80	18	0.40	1.81
	8	29	1.56	16.80	26	1.57	12.33
	9	20	1.59	21.99	25	3.11	38.50
	10	51	3.80	65.11	16	1.25	12.93
	11	30	1.86	17.33	30	1.94	21.19
	12	27	1.03	9.35	33	1.32	10.11
	23	31	0.80	5.80	47	0.83	2.73
	24	86	1.98	11.92	22	0.29	1.30
	25	59	1.21	7.93	38	0.49	1.80
	26	19	0.39	2.60	53	1.54	10.07
	27	20	0.82	6.50	39	1.80	13.10
	29	18	1.08	11.56	29	2.10	18.28
	31	43	3.15	44.39	13	1.12	6.57
	32	36	3.85	67.45	42	3.05	32.34
	Mean	*34*	*1.8*	*20.3*	*29*	*1.5*	*13.4*
	SD	*17*	*1.1*	*19.9*	*12*	*0.8*	*10.6*
MDF	15	24	1.40	14.98	26	1.33	15.55
	16	48	2.20	20.17	25	1.83	9.20
	17	51	1.51	11.33	29	0.65	5.19
	19	75	1.79	9.99	62	1.33	9.01
	20	45	3.70	35.74	18	0.63	4.97
	22	45	2.55	20.41	22	1.01	10.82
	28	38	0.97	5.29	50	1.68	9.79
	30	40	1.72	12.10	14	0.38	1.60
	Mean	*46*	*2.0*	*16.3*	*31*	*1.1*	*8.3*
	SD	*14*	*0.8*	*9.4*	*17*	*0.5*	*4.3*
MCF	3	43	2.13	19.75	38	2.10	12.71
	4	32	2.32	23.12	17	1.17	7.62
	13	28	1.20	7.05	9	0.28	1.25
	14	29	1.15	9.47	29	1.07	6.35
	18	27	1.72	13.93	14	0.67	3.39
	21	65	4.46	35.14	5	0.30	1.51
	Mean	*38*	*2.2*	*18.1*	*19*	*0.9*	*5.5*
	SD	*15*	*1.2*	*10.3*	*13*	*0.7*	*4.4*

3.4. Stand increment in 10 years duration (2012 to 2022)

Over ten years, the increment and decrement stand dynamics were analyzed for the number of stems, species, families, BA, and AGB across different forest types. Within the 18 plots of the DEF, there was an increase in the number of stems by 98 stems/ha (averaging 5±3), BA by 9.9 m^2/ha (0.6±0.4), and AGB by 545.6 Mg/ha (30.3±26.8). However, the number of species and families decreased by 114 species/ha (7±3) and 13 families/ha (2±1), respectively.

In the eight plots of the MDF, the stand increment involved an increase in the number of stems by 120 stems/ha (15±2), BA by 1.1 m^2/ha (0.1±0.3), and AGB by 1.2 Mg/ha (0.1±2). On the contrary, the number of species and families was reduced by 74 species/ha (7±2) and six families/ha (0±1), respectively.

Within the six plots of the MCF, there was an increase in the number of stems by 112 stems/ha (averaging 19±0), BA by 5.5 m^2/ha (0.9±0.4), and AGB by 129.4 Mg/ha (21.6±10). Simultaneously, the number of species and families decreased by 25 species/ha (4±3) and one family/ha (1±1), respectively.

3.5. Kruskal-Wallis and Mann-Whitney test of three forest types

The results obtained from the Kruskal-Wallis test conducted on three distinct forest types between in 2012 and in 2022 revealed statistically significant differences ($p < 0.05$) in specific parameters. Specifically, in 2012, significant differences were observed in the number of individuals (Chi-square = 8.866, Sig. = 0.012 < 0.05), number of species (Chi-square = 10.376, Sig. = 0.006 < 0.05), and number of families (Chi-square = 9.205, Sig. = 0.010 < 0.05). However, parameters such as DBH, BA, and AGB did not exhibit significant differences ($p > 0.05$).

In 2022, the Kruskal-Wallis test demonstrated significant differences ($p < 0.05$) in the number of individuals (Chi-square = 6.934, Sig. = 0.031 < 0.05), number of species (Chi-square = 12.501, Sig. = 0.002 < 0.05), and number of families (Chi-square = 10.199, Sig. = 0.006 < 0.05). However, similar to the 2012 findings, parameters such as DBH, BA, and AGB did not exhibit significant differences ($p > 0.05$) (Table 3).

Table 3. Kruskal-Wallis test of three forest types between in 2012 and in 2022

Properties	2012			2022		
	Chi-Square	Asump. Sig.	p-value	Chi-Square	Asump. Sig.	p-value
Individuals	8.866	0.012*	0.05	6.934	0.031*	0.05
Species	10.376	0.006*	0.05	12.501	0.002*	0.05
Families	9.205	0.010*	0.05	10.199	0.006*	0.05
DBH (cm)	3.523	0.172	0.05	4.631	0.099	0.05
BA (m^2/ha)	2.600	0.272	0.05	1.172	0.557	0.05
AGB (Mg/ha	1.890	0.389	0.05	2.427	0.297	0.05

The results of pair comparisons using the Mann-Whitney test for three forest types over the period spanning from 2012 to 2022 were conducted on six ecological properties, namely individuals, species, families, DBH, BA, and AGB. The test outcomes revealed that the properties of individuals, families, and DBH exhibited no significant differences between 2012 and 2022 ($p > 0.05$) for all three forest types.

On the other hand, significant differences ($p < 0.05$) were observed in the properties of species, BA, and AGB for the DEF during the same period. In particular, species (Sig. =

0.033 < 0.05), BA (Sig. = 0.000 < 0.05), and AGB (Sig. = 0.000 < 0.05) revealed statistical significance.

Within the MDF forest, individuals, species, families, and DBH showed no significant differences (p > 0.05) between 2012 and 2022. However, BA (Sig. = 0.001 < 0.05) and AGB (Sig. = 0.001 < 0.05) demonstrated significant differences.

Similarly, in the MCF, indicators like individuals, species, families, and DBH presented no significant differences (p > 0.05) between 2012 and 2022. However, BA (Sig. = 0.004 < 0.05) and AGB (Sig. = 0.004 < 0.05) showed significant differences (Table 4).

Table 4. Mann-Whitney test of forest types between 2012 and 2022

Forest types	Properties	2012-2022		
		Mann-Whitney	Asump. Sig.	p-value
DEF	Individuals	152.500	0.764	0.05
	Species	95.000	0.033*	0.05
	Families	127.000	0.273	0.05
	DBH (cm)	153.000	0.776	0.05
	BA (m^2/ha)	0.000	0.000*	0.05
	AGB (Mg/ha)	0.000	0.000*	0.05
MDF	Individuals	23.000	0.345	0.05
	Species	18.000	0.140	0.05
	Families	27.500	0.635	0.05
	DBH (cm)	29.000	0.753	0.05
	BA (m^2/ha)	0.000	0.001*	0.05
	AGB (Mg/ha)	0.000	0.001*	0.05
MCF	Individuals	12.500	0.378	0.05
	Species	13.000	0.421	0.05
	Families	14.000	0.520	0.05
	DBH (cm)	14.000	0.522	0.05
	BA (m^2/ha)	0.000	0.004*	0.05
	AGB (Mg/ha)	0.000	0.004*	0.05

4. DISSCUSSION

Over ten years (2012 to 2022), we extensively monitored tree dynamics across 32 permanent plots in three distinct forest types, DEF, MDF, and MCF, within the tropical forest areas of Phou Khao Khouay National Park in Laos. Our observations revealed fluctuations in the quantities of individuals, species, families, DBH, BA, and AGB. The parameters of tree growth, mortality, and recruitment across individuals, species, families, DBH, BA, and AGB exhibited considerable variation among these plots, as detailed in Table 1. Despite the topographical similarities within the study site, our findings indicated notable discrepancies compared to previous studies. For instance, the current study documented a higher count of species (311 species; 135 families) compared to previous records: 145 species, 62 families [15]; 123 species, 47 families [16]; and 76 species, 42 families [17]. Across other tropical forest sites, varying species and family counts were reported: 151 species, 49 families in Vietnam [18]; 72 species [19]; 67 species [20]; 177 species, 43 families [21]. In Thailand, 306 species and 73 families were recorded [22]. In India, reports included counts such as 78 species, 36 families [23]; 43 species, 24 families [24]; 46 species, 24 families [25]; 270

species, 55 families [26]; and 129 species, 44 families [27]. In China, counts were 94 species, 24 families [28]. These counts notably surpass those found in other tropical forests, with an exception noted in Lucas's study conducted at the same site but in a different year, reporting 395 species and 155 families [10].

Tree mortality surpassing recruitment was observed across three forest types in the study sites of Phou Khao Khouay National Park, primarily attributed to illegal logging and land clearing for agriculture. Our study revealed notable dynamics in tree stands: for DEF, stem count increased from 131 to 137 stems/ha, BA increased from 7.1 to 7.7 m^2/ha, and AGB increased from 61.0 to 91.3 Mg/ha; for MDF, stem count increased from 149 to 164 stems/ha, BA increased from 6.4 to 6.5 m^2/ha, and AGB increased from 53.2 to 53.4 Mg/ha; for MCF, stem count increased from 68 to 105 stems/ha, BA increased from 5.4 to 6.3 m^2/ha, and AGB decreased from 61.0 to 55.1 Mg/ha. Comparisons with other tropical forests yielded exciting insights. In Japan, density decreased from 779 to 510 stems/ha, BA increased from 33.23 to 42.13 m^2/ha, and AGB increased from 131.70 to 180.64 Mg/ha [29]. Density decreased from 510 to 515 stems/ha in China, while BA increased from 36.19 to 46.53 m^2/ha [30]. Vietnam exhibited an increase in density from 522 to 557 stems/ha, BA increased from 34.4 to 42.2 m^2/ha, and AGB increased from 298.2 to 384.2 Mg/ha [18]. India showcased a decrease in density from 1,229 to 1,032 stems/ha, BA increased from 14.6 to 14.9 m^2/ha, and AGB increased from 3,754.53 to 3,829.51 kg/ha. Density increased from 832 to 978 stems/ha, BA decreased from 28.9 to 27.0 m^2/ha, and AGB increased from 2,756.71 to 3,074.16 kg/ha [31]. Recognizing the necessity for long-term data collection on tropical tree growth, mortality, and recruitment is crucial for enhancing our understanding of forest functioning. It is imperative to adhere to a standardized and unbiased protocol for collecting and processing data from long-term permanent plots, as emphasized by Sheil [32].

5. CONCLUSION

The immediacy to assemble exhaustive data on tropical forest tree dynamics, centering on growth, mortality, and recruitment, cannot be addressed. This stems from understanding how forest degradation and habitat fragmentation primarily contribute to biodiversity loss. Therefore, it is critical to intensify conservation efforts and protect reserve forests in Laos, particularly those within the Phou Khao Khouay National Park. The long-standing formation of these preserves accentuates their pivotal role in biodiversity conservation.

The prevailing degree of protection for these reserves demands enhancement, which requires a further commitment to their safeguarding. Illegal logging presents a significant hurdle in most reserve forests, and addressing this demands legislative measures and active community involvement. This collective strategy guarantees a more sustainable and robust solution.

Our study, encompassing 32 permanent plots and focusing on three unique forest types—DEF, MDF, and MCF—symbolic of the Phou Khao Khouay National Park in Laos, is significant. These forest areas have witnessed disturbances stemming from human activities, primarily modifications by local communities, leading to shifts in forest abundance. Insights from this study are poised to significantly contribute towards forest health improvement, biodiversity augmentation, and ecosystem services enhancement offered by forests for future generations.

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