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Long-term dynamics of fire-affected pine-dipterocarp forest in Northern Thailand

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Abstract. *Kantasrila R, Muenrew J, Thammarong W, Sutjaritjai N, Rujichaipimon W, Rakarcha S, Pongamornkul W, Moolla K, Panyadee P. 2026. Long-term dynamics of fire-affected pine-dipterocarp forest in Northern Thailand. Biodiversitas 27 (2): d270211. https://doi.org/10.13057/biodiv/d270211*. Fire disturbance is a critical ecological driver in Southeast Asian tropical forests, yet long-term empirical evidence of repeated fire regime remains limited. This study examined 13-year post-fire dynamics in a pine-dipterocarp forest using a 1-ha permanent plot at Queen Sirikit Botanic Garden, Northern Thailand. Trees with Diameter at Breast Height (DBH) ≥ 4.5 cm were monitored in 2012 and 2025, along with saplings (1.5-4.4 cm DBH) in the latter census. Species richness increased from 40 to 47 species, and basal area rose from 22.52 to 26.06 m^2 ha^{-1}, indicating structural recovery. Recruitment (1.63% yr^{-1}) exceeded mortality (1.15% yr^{-1}), suggesting demographic resilience. While dominant canopy species such as *Pentacme siamensis*, *Quercus kingiana*, *Dipterocarpus obtusifolius*, and *Pinus kesiya* persisted, the sapling layer was dominated by fast-growing deciduous species (*Dalbergia suthepensis*, *Wendlandia tinctoria*, and *Lithocarpus sootepensis*), indicating contrasting regeneration composition between life stages under repeated fire. Aboveground biomass increased from 135.57-159.21 to 148.05-173.62 t ha^{-1} across allometries, with carbon stocks rising from 80.92-95.03 to 88.37-103.63 t C ha^{-1}. These results reflect net accumulation of biomass and carbon between 2012 and 2025 in the fire-affected forest. The study provides the first long-term evidence of demographic and carbon recovery in a fire-prone forest ecosystem in Thailand, underscoring the importance of permanent plot monitoring for adaptive fire management and climate change mitigation.

Keywords: Carbon dynamics, demographic resilience, permanent plot monitoring, repeated fire regime, tropical forest succession

Abbreviations: AGB: Aboveground biomass, DBH: Diameter at breast height, IVI: Importance Value Index, M: Mortality rate, NE: Negative exponential, P: Polynomial, P-DDF: Pine-Deciduous Dipterocarp Forest, QSBG: Queen Sirikit Botanic Garden, R: Recruitment rate, RDO: Relative Dominance, RF: Relative Density, RGR: Relative Growth Rate

INTRODUCTION

Forest fires are a major ecological disturbance affecting tropical forest ecosystems worldwide, altering species composition, successional pathways, and ecosystem functioning (de Andrade et al. 2020; Pati et al. 2024). Fire impacts are largely mediated through changes in soil moisture, light availability, and nutrient dynamics, which can suppress regeneration and increase mortality, particularly in non-sprouting or thin-barked species (Walters et al. 2004; Gosper et al. 2012; Hoffmann et al. 2012; Wanthongchai et al. 2014; Verma et al. 2017; Neeraja et al. 2021; Duangon et al. 2024). Conversely, some species persist in fire-prone ecosystems due to adaptive traits such as thick bark and resprouting ability (Khan and Tripathi 1989; Saha and Hiremath 2003). Understanding these dynamics is essential for predicting forest resilience and guiding post-fire management.

In Thailand and mainland Southeast Asia, forest fires occur mainly during the dry season (December-May) and are largely anthropogenic, driven by activities such as resin tapping, mushroom collection, and agricultural burning (Junpen et al. 2013a, b). In Thailand, forest fires affected more than 112,000 ha between 2007 and 2016 (Forest Fire Control Division 2025). Among fire-prone forest types are Pine-Deciduous Dipterocarp Forests (P-DDF) which occur between 700 and 1,350 m a.s.l. in northern and northeastern Thailand, dominated by *Pinus merkusii* Jungh. & de Vriese and *Pinus kesiya* Royle ex Gordon together with dipterocarps such as *Dipterocarpus obtusifolius* Teijsm. ex Miq. and *Shorea obtusa* Wall. ex Blume (Santisuk 2012). These forests experience frequent surface fires but persist due to the fire-resistant traits of pine species. Pine, Dry Dipterocarp Forests (DDF), and Mixed Deciduous Forests (MDF) in Thailand are especially vulnerable to recurrent burning, often exhibiting reduced regeneration and soil degradation (Wanthongchai et al. 2014; Phumsathan et al. 2022). Similar fire-prone dipterocarp and pine-oak ecosystems occur across Laos, Myanmar, and Cambodia, where repeated fires continue to shape forest structure and regeneration (Pati et al. 2024).

Despite the widespread occurrence of fire in Pine-Deciduous Dipterocarp Forests (P-DDF) and related forest types, systematic long-term assessments of post-fire forest structure, demographic dynamics, and carbon stocks in Thailand and mainland Southeast Asia remain limited. This lack of long-term data constrains our understanding of post-fire successional trajectories and carbon recovery in these fire-prone ecosystems. The forest within Queen Sirikit Botanic Garden (QSBG), Chiang Mai, offers a unique opportunity for continuous monitoring because of its recurring fire history and established permanent plot. This study aimed to (i) describe the 13-year changes in tree species composition and stand structure within a fire-affected pine–dipterocarp forest, (ii) quantify demographic patterns, including recruitment, mortality, and diameter growth between the two census periods, and (iii) estimate aboveground biomass and associated carbon stocks to evaluate temporal trends in carbon accumulation. Rather than inferring causality, the study focuses on documenting observed changes within the permanent plot over time, providing baseline information on forest dynamics under a landscape subjected to recurrent fire events.

MATERIALS AND METHODS

Study area

The study was conducted in a Pine-Dipterocarp Forest (P-DDF) within Queen Sirikit Botanic Garden (QSBG; 18°52′N, 98°52′E), Chiang Mai Province, Northern Thailand (Figure 1). The area lies at elevation between 900-1,100 m asl and experiences a monsoonal climate with a distinct dry season (December-April). Mean annual temperature is approximately 23°C, and mean annual rainfall is about 1,300 mm (Queen Sirikit Botanic Garden Database 2025). Pine-dipterocarp forest constitutes a substantial proportion of the natural forest area within QSBG, occurring mainly on ridges and upper slopes where seasonal drought and fire are recurrent. The permanent plot was established within a representative P-DDF stand that has been repeatedly affected by fire. The site has a history of frequent wildfires, typically of low to moderate intensity, occurring almost every dry season from 2012 to 2025, based on QSBG fire control records and staff observations. Fire events generally occurred between February and April and typically persisted for approximately 2-3 days per event before being fully extinguished through active fire control and natural fire breaks. These fires generally burned through the litter and grass layer without causing canopy-level damage. Although quantitative fire metrics (e.g., scorch height or burn severity index) were not systematically measured, repeated fire disturbance at the site has been consistently documented by local monitoring and visible evidence of fire scars and charred litter layers. The P-DDF here is dominated by *P. kesiya* and *Pentacme siamensis* (Miq.) Kurz, interspersed with deciduous dipterocarps and Fagaceae species.

Site description and data collection

The 1-ha permanent plot was established for this study at elevation of 1,015-1,027 m asl, with gently sloping topography and less than 15 m elevation difference, indicating relatively homogeneous microhabitat conditions. This plot represents the typical stand structure and species composition of fire-prone P-DDF in Northern Thailand and serves as a valuable site for long-term ecological monitoring. To provide context for regeneration under a recurrent fire regime, key environmental variables were measured across the plot. Understory light, air temperature, and relative humidity were recorded using HOBO Pendant Temp/Light Loggers (Model UA-002-64) and HOBO Pro v2 loggers (Part No. U23-001), while soil samples from three random points (0-30 cm depth) were analyzed for macronutrients (N, P, K) and organic matter using standard procedures.

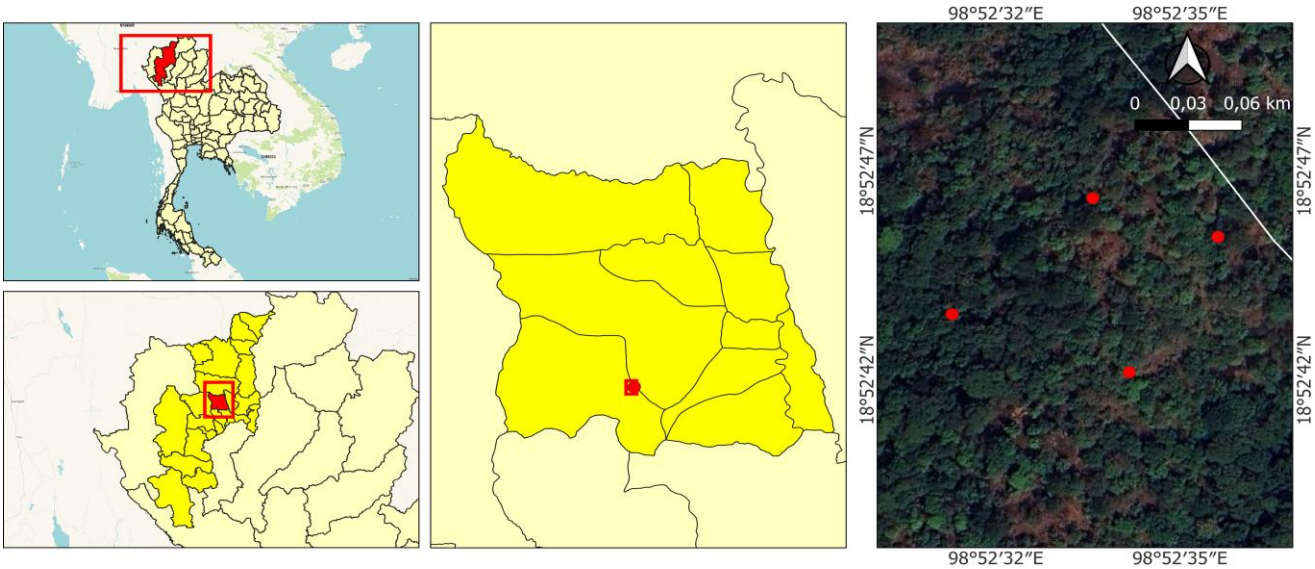

Figure 1. Map indicating the location of study area of P-DDF (18°52'46.0"N 98°52'33.4"E, 18°52'45.2"N 98°52'35.8"E, 18°52'43.6"N 98°52'30.7"E, 18°52'42.4"N 98°52'34.1"E) at Queen Sirikit Botanic Garden, Mae Rim District, Chiang Mai, Thailand

The 1-ha permanent plot was established in 2012 and subdivided into 100 subplots (10 × 10 m each). All trees with DBH ≥ 4.5 cm were tagged with aluminum tags placed at 1.3 m, measured for DBH and height following the standardized protocol of the Center for Tropical Forest Science (CTFS) (CTFS 2004), and identified by QSBG taxonomists using voucher specimens housed in the QBG Herbarium. A detailed stem distribution map was created to record the coordinates of each individual. The plot was resurveyed in 2025 (13 years after the first survey) using the same measurement protocal and height-reference system, with saplings (1.5 ≤ DBH < 4.5 cm) included in the census to characterize current regeneration. Because saplings were not recorded in 2012, all inter-census demographic calculations (mortality, recruitment, and turnover) were based exclusively on stems ≥ 4.5 cm DBH to maintain methodological consistency and avoid biases in regeneration estimates. To ensure measurement consistency, the field team was trained using standardized procedures, and trees were matched between censuses based on tag numbers, species identity, and stem coordinated. For trees with buttresses or irregular stems, alternative measurement points were permanently marked and reused during remeasurement. Measurement errors were minimized by verifying anomalous DBH changes (e.g., negative or implausibly high values) against field notes and the stem map, and corrections followed CTFS (CTFS 2004), with bark-thickening effects evaluated through species-specific growth checks. Species nomenclature follows Plants of the World Online (POWO 2025).

Data analysis

Forest community structure and species composition

Forest structure and species composition of trees and saplings were assessed based on tree density, Basal Area (BA), species diversity and dominant species. Dominant species were identified using the Importance Value Index (IVI), which incorporates Relative Frequency (RF), Relative Density (RD) and Relative Dominance (RDO), calculated following Kent (2011) according to the equation:

$$IVI = RD + RF + RDO$$

Tree species diversity and sapling species diversity were assessed using the Shannon-Wiener Index (H′), as described by Shannon and Weaver (1949), applying the following formula:

$$H' = \sum_{i=1}^{s} P_i \ln P_i$$

Where, *s* is the total number of species in the community and *Pi* is the proportion of individuals that belong to the species *i,* which calculated as the number of individuals of species *i* divided by the total number of individuals of all species.

In addition, the balanced distribution of individuals among tree and sapling species was assessed using Evenness (E), as described by Pielou (1966), calculated using the following formula:

$$J' = H'/\ln S$$

Where, J' is the E index and H' is the Shannon-Wiener Index and S is the number of species or species richness.

Differences in Shannon diversity (H′) and basal area between the 2012 and 2025 censuses were re-evaluated using paired permutation tests (9,999 permutations) based on subplot-level values (n = 93). For each subplot, the observed difference between years was calculated, and the null distribution was generated by randomly permuting the sign of paired differences. This non-parametric approach avoids assumptions of normality and is appropriate for ecological diversity indices and structural metrics. All analyses were conducted in R.

The forest dynamics

Mortality rate (M), Recruitment rate (R) and Relative Growth Rate (RGR) of tree species were calculated to characterize the dynamics of the forest ecosystem. The balance between M and R indicated a state of dynamic equilibrium, reflecting the stability and continuity of forest structure over time (Sahunalu 2009). These indices can calculate the following Sheil et al. (1995) as:

$$M(\%) = 100 \times \frac{\ln(N_0) - \ln(N_s)}{t}$$
$$R(\%) = 100 \times \frac{\ln(N_t) - \ln(N_s)}{t}$$

Where, N_0 is the number of trees recorded at the initial survey, N_T is the number at the final survey, and t denotes the duration of the study. The logarithmic transformation assumes that mortality and recruitment follow continuous proportional (exponential) processes. This approach expresses population changes as instantaneous rates, thereby reducing dependency on initial population size and allowing comparisons across census intervals and forest stands (Sheil et al. 1995).

Plant RGR is used as an indicator of ecosystem function and species fitness (Oguchi et al. 2016). RGR exhibits substantial variation among species in response to differing environmental conditions, and is closely linked to physiological traits, morphological characteristics, and biomass distribution (Niklas et al. 2003; Crisóstomo et al. 2007; Xiong et al. 2018). In this study, tree DBH data were used to estimate the RGR index, following the method described by Sherman et al. (2012) as follows:

$$RGR = \frac{\ln(DBH_2) - \ln(DBH_1)}{t_2 - t_1}$$

Where, DBH_2 represents the DBH (cm) measured during the final survey, whereas DBH_1 refers to the measurement taken at the initial survey (Mangiarotti et al. 2008). Log-transformation of DBH was applied because tree growth is a multiplicative process and relative growth rate represents size-standardized growth. This method minimizes bias caused by differences in initial tree size and is commonly used in forest dynamics studies to compare growth performance among species and individuals (Niklas et al. 2003; Sherman et al. 2012).

In addition, regeneration of tree species can be described by DBH distribution (Duangon et al. 2024). The

population structure of all trees was defiled by DBH class distribution, and the growth patterns of dominant tree species were modeled using two types of distributions: Negative exponential (NE; reverse-J) and Polynomial (PO). The size of trees was classified into 4 groups including poles (DBH < 20 cm), small trees (20.1 ≤ DBH ≤ 30 cm), medium trees (30.1 ≤ DBH ≤ 50 cm) and large trees (DBH > 50 cm) following Keren et al. (2018).

Aboveground Biomass (AGB) and carbon storage

To estimate AGB and total biomass, DBH (D, cm) and tree height (H, m) were used in the allometric equations of Ogawa et al. (1965) and Tsutsumi et al. (1983), which are suitable for the mixed-species composition of our pine-dipterocarp forest. These equations have also been applied in previous studies of Thai forests (e.g., Terakunpisut et al. 2007; Senpaseuth et al. 2009), ensuring comparability with earlier work. No local destructive sampling was conducted.

$W_{stem} = 0.0396 \times (D^2 H)^{0.933}$
$W_{branch} = 0.00349\ (D^2 H)^{1.030}$
$W_{leaf} = (28/(W_{Stem} + W_{Branch}) + 0.025)^{-1}$ (Ogawa et al. 1965)

$W_{stem} = 0.0509 \times (D^2 H)^{0.919}$
$W_{branch} = 0.00893 \times (D^2 H)^{0.977}$
$W_{leaf} = 0.0140 \times (D^2 H)^{0.669}$ (Tsutsumi et al. 1983)

$W_{AGB} = W_{stem} + W_{branch} + W_{leaf}$
$W_{root} = W_{AGB} \times 0.27$ (IPCC 2006)
$W_{total} = W_{AGB} + W_{root}$

Where, W_{stem}, W_{branch}, W_{leaf}, W_{root} represent the biomass of the stem, branches, leaves and roots, respectively, expressed in tons.

W_{AGB} represents the total aboveground biomass, expressed in tons.

W_{total} represents the total biomass (including above and belowground components), expressed in tons.

To compare the carbon sequestration potential over a 13-year period, carbon storage was estimated from total biomass using carbon fraction 0.47, following IPCC (2006) guidlines. Carbon stock per hectare (C, tons C ha^{-1}) was calculated as:

$C_{total} = W_{total} \times 0.47$

In addition to tree biomass, litter fall and litter carbon input were measured in 2025 using twenty 1 × 1 m litter traps installed 30–50 cm above the ground (n = 20). Litter fall and litter carbon were not assessed during the initial survey; therefore, these measurements were included in 2025 to establish a baseline for aboveground litter carbon and to enable more comprehensive estimates of total ecosystem carbon stocks for future long-term comparisons. Litter was collected monthly, oven-dried at 65°C to constant weight, and weighed to obtain monthly litter fall biomass. Subsamples were finely ground and analyzed for carbon concentration using the dry combustion method. Annual litter carbon input was incorporated into the carbon stock assessment.

$C_{litter} = B \times fc$

Where B is the litter biomass (t ha^{-1}) and fc is the carbon fraction used to convert biomass to carbon content.

RESULTS AND DISCUSSION

Forest community structure and species composition

Species richness increased modestly over 13 years (40 to 47 species), with concurrent gains in tree density and basal area, reflecting observed changes in forest structure (Table 1). Community diversity and evenness remained stable (H′ ≈ 3.12-3.16; E ≈ 0.82-0.84), consistent with a balanced composition. Dominant canopy taxa persisted, notably *P. siamensis*, *Quercus kingiana* Craib, *D. obtusifolius*, and *P. kesiya* (Table 2).

The sapling layer (107 individuals, 27 species, 16 families) showed a different composition from adults, dominated by *Dalbergia suthepensis* Niyomdham, *Wendlandia tinctoria* (Roxb.) DC., and *Lithocarpus sootepensis* (Craib) A.Camus, while canopy dominants remain *P. siamensis*, *Q. kingiana*, *D. obtusifolius*, and *P. kesiya* (Tables 1-3). These layered contrasts highlight potential differences in recruitment composition relative to the adult canopy, without inferring directional shifts over time.

Forest dynamics, resilience and vulnerability in fire-affected pine-deciduous dipterocarp forest ecosystems

The 13-year monitoring data show observed patterns in demographic balance and forest structure in the P-DDF at QSBG, with recruitment slightly exceeding mortality (Table 1). These observations reflect a net positive demographic balance during the study interval (Šumichrast et al. 2023). Environmental conditions across the plot provide context for the observed patterns. Soils were moderately acidic with low salinity, moderate organic matter and nutrient content, and retained moisture well in the rainy season but dried rapidly in the dry season. Seasonal variation in understory light, temperature, and relative humidity further provided a microclimatic context, which may be associated with observed patterns of sapling establishment, species turnover, and biomass recovery under the recurrent fire regime. One species, *Phyllanthus sphaerogynus* Müll.Arg., disappeared from the plot in the latest survey, whereas seven species were newly recorded, including *Anneslea fragrans* Wall., *Gardenia sootepensis* Hutch., *Ilex umbellulata* (Wall.) Loes., *L. polystachyus*, *Pavetta tomentosa* Roxb. ex Sm., *Quercus poilanei* Hickel & A.Camus, and *Quercus* sp. Some of these newcomers, notably *P. tomentosa*, are pioneer species with short life cycles that contribute substantially to tropical forest succession (Albrecht et al. 2017; Gilbertson and Kot 2021).

Table 1. Structure and species composition of the P-DDF at QSBG, Northern Thailand, in 2012 and 2025

Data	Tree (2012)		Tree (2025)	Sapling (2025)
Species number	40	-	47	27
Family number	19	-	21	16
Tree density	398	-	404	107
H′	3.12±0.535a	-	3.16±0.521a	2.83
E	0.84a	-	0.82a	0.86
BA (m^2 ha^{-1})	22.52±12.27a	-	26.06b±12.71 b	0.09
Loss (m^2 ha^{-1})	-	2.82	-	-
Gain (m^2 ha^{-1})	-	0.32	-	-
M (%/year)	-	1.15	-	-
R (%/year)	-	1.63	-	-

Table 2. Dominant tree species in the P-DDF at QSBG, Northern Thailand, based on IVI in 2012 and 2025

Species	Density (2012) (stem ha^{-1})	BA (2012) (m^2 ha^{-1})	IVI (2012) (%)	Density (2025) (stem ha^{-1})	BA (2025) (m^2 ha^{-1})	IVI (2025) (%)
Aporosa wallichii Hook.f.	15	0.17	2.54	20	0.85	4.03
Dalbergia suthepensis Niyomdham	17	0.14	3.13	20	0.18	3.67
Dipterocarpus obtusifolius Teijsm. ex Miq.	31	2.57	9.05	32	3.43	9.52
Helicia nilagirica Bedd.	22	0.25	4.06	21	0.25	4.15
Lithocarpus lindleyanus (Wall. ex A.DC.) A.Camus	21	0.29	3.34	16	0.25	2.63
Lithocarpus sootepensis (Craib) A.Camus	25	0.79	4.58	34	1.07	6.18
Lithocarpus truncatus (King ex Hook.f.) Rehder	15	0.77	3.66	13	0.81	3.21
Pentacme siamensis (Miq.) Kurz	50	3.31	12.19	46	3.68	11.2
Pinus kesiya Royle ex Gordon	14	3.32	7.36	12	4.43	7.75
Quercus kerrii Craib	24	1.57	6.64	22	1.94	6.29
Quercus kingiana Craib	39	1.72	9.27	35	1.97	8.4
Shorea obtusa Wall. ex Blume	21	1.91	6.55	22	2.24	6.47
Tristaniopsis burmanica (Griff.) Peter G.Wilson & J.T.Waterh. var. *rufescens* (Hance) J.Parn. & NicLugh.	20	0.87	4.57	17	0.89	4.23
Wendlandia tinctoria (Roxb.) DC.	9	0.1	1.95	22	0.19	6.18

Table 3. Dominant sapling species in the P-DDF at QSBG, Northern Thailand, based on IVI in 2025, ranked by their IVI values

Species	Density (stem ha^{-1})	BA (m^2 ha^{-1})	Min DBH (cm)	Max DBH (cm)	Mean DBH (cm)	IVI (%)
Dalbergia suthepensis Niyomdham	18	0.0161	1.91	4.46	3.29	17.07
Wendlandia tinctoria (Roxb.) DC.	15	0.0124	1.59	4.30	3.15	13.87
Lithocarpus sootepensis (Craib) A.Camus	12	0.0118	2.55	4.30	3.50	11.77
Pavetta tomentosa Roxb. ex Sm.	11	0.0084	1.91	4.30	3.04	9.93
Dalbergia cultrata T.S.Ralph	5	0.0046	1.59	4.30	3.31	4.80
Croton persimilis Müll.Arg.	5	0.0035	2.07	3.82	2.93	4.41
Helicia nilagirica Bedd.	4	0.0039	3.12	3.82	3.50	3.90
Albizia sp.	4	0.0032	2.07	4.14	3.09	3.66
Gardenia sootepensis Hutch.	4	0.0031	2.23	4.46	3.04	3.63
Castanopsis diversifolia (Kurz) King ex Hook.f.	3	0.0033	3.18	4.23	3.75	3.09
Aporosa villosa (Lindl.) Baill.	3	0.0020	1.91	4.30	2.71	2.61
Vitex pinnata L.	3	0.0018	2.23	3.34	2.76	2.54

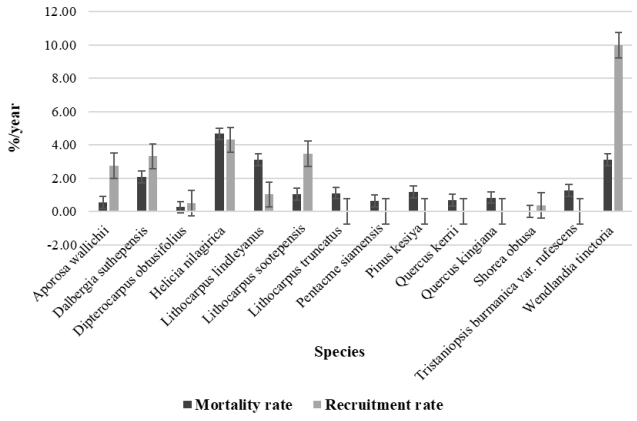

Figure 2. Mortality (M) and Recruitment rate (R) of the 14 most dominant tree species in P-DDF at QSBG, Northern Thailand, over a 13-year period (2012-2025)

Distinct patterns of recruitment and mortality were observed among the dominant species (Figure 2). Six species: *Lithocarpus truncatus* (King ex Hook.f.) Rehder, *P. siamensis*, *P. kesiya*, *Q. kingiana*, *Quercus kerrii* Craib, and *Tristaniopsis burmanica* (Griff.) Peter G.Wilson & J.T.Waterh. var. *rufescens* (Hance) J.Parn. & NicLugh.- experienced mortality without any recruitment and may gradually decline in dominance. Large trees such as *P. kesiya* experienced higher mortality; these individuals were located in areas exposed to repeated fires, although the influence of fire cannot be confirmed. In contrast, *A. wallichii*, *D. suthepensis*, *L. sootepensis*, and *W. tinctoria* exhibited recruitment exceeding mortality, reflecting observed differences in recruitment and mortality. *Helicia nilagirica* Bedd. and *Lithocarpus lindleyanus* (Wall. ex A.DC.) A.Camus showed slightly higher mortality than recruitment but still displayed limited regeneration, whereas *S. obtusa* continued to recruit without recorded mortality, indicating a stable population.

Relative Growth Rate (RGR) was used as an indicator of growth performance and resource-use efficiency (Pommerening and Muszta 2015). The mean RGR was 1.54 % yr^{-1} over the 13-year period. *Dalbergia suthepensis* had the highest mean RGR (3.77 % yr^{-1}). Among dominant species (Figure 3), *D. suthepensis* exhibited the highest RGR, followed by *A. wallichii*, *W. tinctoria*, *H. nilagirica*, *L. sootepensis*, *L. lindleyanus*, *D. obtusifolius*, *Q. kingiana*, *P. kesiya*, *Q. kerrii*, *L. truncatus*, *S. obtusa*, *P. siamensis*, and *T. burmanica* var. *rufescens*.

Table 4. The biomass and carbon storage of P-DDF in QSBG, Northern Thailand

Component	2012		2025		Allometry equation
	Biomass (ton ha^{-1})	Carbon stock (ton C ha^{-1})	Biomass (ton ha^{-1})	Carbon stock (ton C ha^{-1})	
Stem	106.73	50.16	116.41	54.71	Ogawa et al. (1965)
Stem	118.39	55.64	128.99	60.63	Tsutsumi et al. (1983)
Branch	26.35	12.38	28.97	13.62	Ogawa et al. (1965)
Branch	38.33	18.01	41.95	19.72	Tsutsumi et al. (1983)
Leave	2.49	1.17	2.66	1.25	Ogawa et al. (1965)
Leave	2.50	1.17	2.68	1.26	Tsutsumi et al. (1983)
AGB	135.57	63.72	148.05	69.58	Ogawa et al. (1965)
AGB	159.21	74.83	173.62	81.6	Tsutsumi et al. (1983)
Root	36.60	17.2	39.97	18.79	Ogawa et al. (1965)
Root	42.99	20.2	46.88	22.03	Tsutsumi et al. (1983)
Total	172.17	80.92	188.02	88.37	Ogawa et al. (1965)
Total	202.2	95.03	220.49	103.63	Tsutsumi et al. (1983)

Table 5. Biomass and carbon stock of litter components of P-DDF in QSBG, Northern Thailand, with carbon fraction determined in the laboratory

Component	Biomass (t ha$^{-1)}$	% of total litter C	Carbon fraction	Carbon stock (t C ha^{-1})
Leaves	4.03	67.05	0.379	1.53
Branches	1.12	18.64	0.376	0.42
Flower	0.24	3.99	0.382	0.09
Fruits	0.62	10.32	0.387	0.24
Total	6.01	100	-	2.28

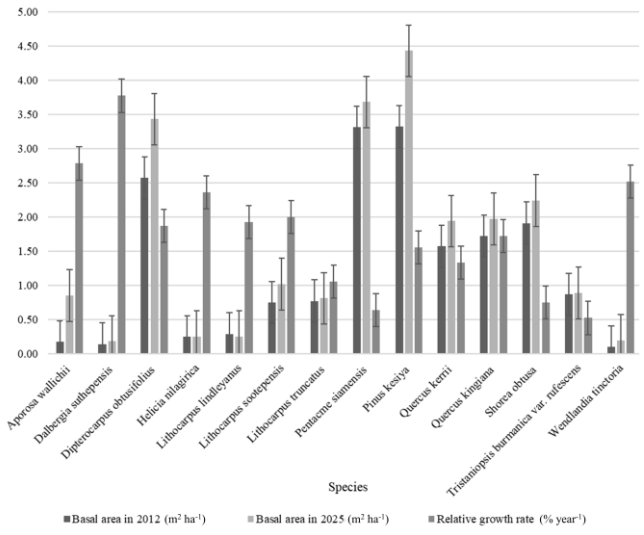

Figure 3. Comparison of Basal Area and Relative Growth Rate of dominant species in P-DDF at QSBG, Northern Thailand, between 2012 and 2025. Notes: error bars indicate Standard Errors (SE)

Demographic patterns and regeneration dynamics

Regeneration patterns of dominant tree species with more than 20 individuals were assessed using diameter-class distributions (Figure 4). The resulting distributions revealed contrasting population structures, consistent with species-specific demographic strategies in this disturbance-prone environment. Five species: *D. obtusifolius*, *H. nilagirica*, *L. sootepensis*, *Q. kerrii*, and *W. Tinctoria* exhibited negative exponential (reverse-J) patterns, consistent with observed recruitment patterns. In contrast, *P. siamensis*, *Q. kingiana*, and *S. obtusa* displayed unimodal (polynomial) distributions, showing peaks in intermediate size classes. Most reverse-J species were characterized by numerous small and pole-sized individuals but few large trees, whereas unimodal species had peaks in medium size classes with limited recruitment of smaller stems. Overall, these patterns indicate diverse regeneration dynamics among dominant species in this fire-prone forest, highlighting differences in size-class structure among dominant species.

Carbon dynamics and comparative forest performance

Total biomass increased slightly between 2012 and 2025 under both allometric equations in this fire-prone forest. The Ogawa et al. (1965) model estimated an increase from 172.17 to 188.02 t ha^{-1}, while the Tsutsumi et al. (1983) equation yielded higher values, rising from 202.2 to 220.49 t ha^{-1} (Table 4). The modest increase reflected gradual diameter and height growth over the 13-year period, while mortality was observed in some fire-affected individuals. Stems accounted for the largest share of total biomass, followed by roots, branches, and leves, confirming their role as the primary biomass reservoir. Trees in the 29-46 cm DBH class contributed most to biomass accumulation, with large trees (>46 cm DBH) representing nearly half (47.9%) of total AGB, underscoring their importance in ecosystem carbon storage.

Among species, *P. kesiya* had the highest AGB, followed by *P. siamensis*, *D. obtusifolius*, and *S. obtusa*. Carbon stock showed a corresponding increase, rising from 80.92 to 88.37 t C ha^{-1} (Ogawa et al. 1965) and from 95.03 to 103.63 t C ha^{-1} (Tsutsumi et al. 1983), paralleling the increase in AGB. Although the gain was modest, these results indicating ongoing biomass accumulation and carbon storage in this fire-prone forest, suggesting that the P-DDF retains substantial storage capacity even where fires occur recurrently.

In addition, the carbon stock in litter measured in 2025 was 2.28 t C ha^{-1}, with leaves contributing the largest fraction (67.1%), followed by branches (18.6%), fruits (10.3%), and flowers (4.0%) (Table 5). Although litter carbon was only measured in 2025, this pool represents an additional component of ecosystem carbon storage and highlights the potential contribution of forest floor debris to overall carbon sequestration in the P-DDF.

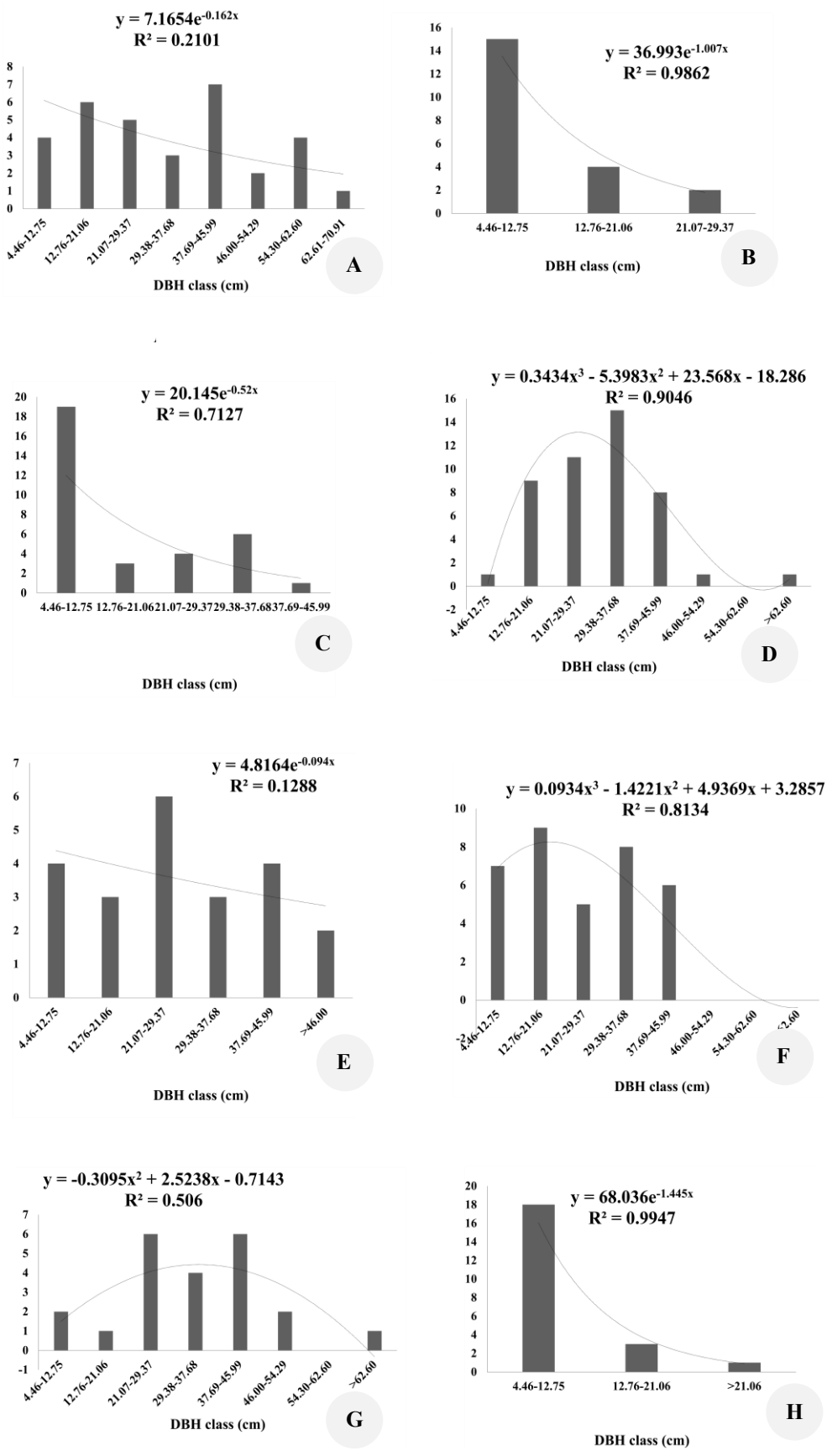

Figure 4. Frequency distribution of dominant tree species (n > 20) by DBH class. Bars represent the number of individuals per diameter class (cm), and curves indicate the fitted model (logarithmic or polynomial) describing population structure. A. *Dipterocarpus obtusifolius*, B. *Helicia nilagirica*, C. *Lithocarpus sootepensis*, D. *Pentacme siamensis*, E. *Quercus kerrii*, F. *Quercus kingiana*, G. *Shorea obtusa*, H. *Wendlandia tinctoria*

Discussion

Forest community structure and species composition

Between 2012 and 2025, the P-DDF at QSBG showed modest increases in species richness and tree density, suggesting ongoing regeneration and structural recovery during a period of recurrent low-to moderate-intensity fires recorded nearly every dry season from 2012 to 2025. Although Basal Area (BA) rose slightly, the balance between gains and losses may reflects the influence of recurrent fire and past selective logging on stand structure and biomass retention. The relatively stable Shannon-Wiener (H′) and Evenness (E) Indices fall within the range reported for natural pine-dipterocarp dry dipterocarp forest types in Northern Thailand (Seramethakun et al. 2013), which encompass stands with varying forest condition. This suggests that compositional diversity at QSBG has been maintained at levels comparable to other regional pine–dipterocarp forests despite recurrent fire.

The slight rise in species richness and BA, coupled with a minor decline in evenness, points to a gradual, orderly recovery trajectory typical of fire-affected tropical pine-dipterocarp forests (Bunyavejchewin et al. 2016). Dominant canopy taxa: *P. siamensis*, *Q. kingiana*, *D. obtusifolius*, *P. kesiya*, *Q. kerrii*, *S. obtusa*, *L. sootepensis*, *W. tinctoria*, and *T. burmanica* var. *rufescens* remain characteristic of northern Thai P-DDFs (Santisuk 2012). In contrast, the prevalence of *D. suthepensis*, *W. tinctoria*, *L. sootepensis*, and *P. tomentosa* in the sapling layer (Phumphuang et al. 2018) suggests ongoing compositional shifts in early recruitment stages. The persistence of *L. sootepensis* and *W. tinctoria* across both strata highlights their strong regeneration capacity and ecological resilience, consistent with the adaptive regeneration patterns observed in other fire-prone tropical forests (Pausas and Keeley 2019).

Forest dynamics, resilience and vulnerability in fire-affected pine-deciduous dipterocarp ecosystems

The 13-year monitoring data indicate that the P-DDF at QSBG exhibited moderate resilience during a period of repeated fire disturbances, with recruitment slightly exceeding mortality, reflecting a net positive demographic balance over the study interval (Šumichrast et al. 2023). The disappearance of *P. sphaerogynus* and the appearance of seven new species, including pioneer taxa such as *P. tomentosa*, underscore the dynamic nature of community composition and succession. Pioneer species with short life cycles play important roles in facilitating regeneration and accelerating structural recovery in tropical forests (Albrecht et al. 2017; Gilbertson and Kot 2021).

The absence of recruitment in several dominant species: *L. truncatus*, *P. siamensis*, *P. kesiya*, *Q. kingiana*, *Q. kerrii*, and *T. burmanica* var. *Rufescens* points to long-term vulnerability and a potential compositional shift. Repeated fires have particularly affected large individuals of *P. kesiya*, emphasizing the sensitivity of pine to sustained burning. In contrast, species such as *A. wallichii*, *D. suthepensis*, *L. sootepensis*, and *W. tinctoria* showed recruitment exceeding mortality, reflecting strong regeneration capacity under repeated fire. These contrasting responses are consistent with an ongoing shift from pine dominance toward a mixed deciduous assemblage, consistent with patterns reported in other tropical fire-affected forests (Staver et al. 2011; Pausas and Keeley 2019).

The mean Relative Growth Rate (RGR) of 1.54% yr^{-1} indicates moderate growth performance among species in the P-DDF. Fast-growing taxa such as *D. suthepensis*, *A. odoratissima*, and *D. suthepensis* exhibited the highest RGRs, suggesting strong colonization ability in post-fire environments (Pommerening and Muszta 2015). The high RGR observed in *A. odoratissima* and *D. suthepensis*, both Fabaceae species, may be associated with mycorrhizal symbioses that enhance nutrient, particularly nitrogen, acquisition (Liang et al. 2022).

Dominant species with high RGRs, including *D. suthepensis* and *A. wallichii*, represent early-successional strategists that contrast with slower-growing climax taxa such as *S. obtusa* and *P. siamensis*. These differing growth strategies reflect the coexistence of pioneer and late-successional components, a hallmark of transitional forest communities following disturbance (Liu et al. 2010). Generally, species with higher RGRs exhibit greater competitiveness under resource-limited post-fire conditions (Grime 1977; Berendse and Elberse 1990; Poorter and Garnier 2007).

Although these patterns suggest that repeated fire may influence species composition over time, the two-point census design (2012 and 2025) limits detection of interannual variability in recruitment, mortality, and biomass dynamics. More frequent or periodic remeasurements, together with detailed fire-severity data, would provide a stronger basis for robust demographic modeling and a more complete understanding of forest responses to recurrent fire. The observed demographic differentiation may reflect a gradual shift toward fast-growing, fire-tolerant deciduous taxa over pines and slower-growing canopy dominants, although these trajectories cannot be confirmed with the current dataset.

Demographic patterns and regeneration dynamics

The diameter class distributions of dominant tree species revealed contrasting population structures, which may reflect species-specific responses to disturbance, including repeated fire. Five species: *D. obtusifolius*, *H. nilagirica*, *L. sootepensis*, *Q. kerrii*, and *W. Tinctoria* exhibited reverse-J distributions, typical of pioneer and early-successional taxa in Thailand (Duangon et al. 2024), suggesting ongoing regeneration, a pattern often observed in disturbance-tolerant taxa. In contrast, *P. siamensis*, *Q. kingiana*, and *S. obtusa* displayed unimodal (polynomial) distributions, a pattern often associated with late-successional species that typically show slower recruitment and may depend on specific microsite conditions for regeneration.

These species-specific patterns illustrate the influence of fire frequency and microenvironmental constraints on population dynamics. For instance, the limited recruitment of *D. obtusifolius* may be associated with microsite factors such as light availability and soil moisture, although these mechanisms were not directly measured for seedling establishment, while *H. nilagirica* and *L. sootepensis* demonstrate successful regeneration despite wildfire impacts,

consistent with their adaptive tolerance to repeated burning (Bunyavejchewin et al. 2003; Marod et al. 2004; Dávila-Hernández et al. 2025). The dominance of pole-sized individuals in *L. sootepensis* suggests delayed maturation but sustained recruitment under disturbance. Meanwhile, *P. siamensis*, *Q. kingiana*, and *S. obtusa* show recruitment mainly in intermediate size classes, reflecting the slower recovery typical of climax species (Duangon et al. 2024). *W. tinctoria*, maintaining a strong reverse-J pattern, exemplifies pioneer behavior with rapid regeneration following fire (Luo et al. 2017).

Collectively, these demographic trends portray a forest undergoing dynamic structural change, where fast-growing species dominate lower size classes while late-successional taxa persist at larger diameters. This coexistence of contrasting regeneration strategies underlines the ecological balance between resilience and vulnerability in fire-affected P-DDF ecosystems. Maintaining mixed regeneration strategies may help support structural diversity and long-term ecosystem stability in disturbance-prone P-DDF systems.

Biomass and carbon stock dynamics

The modest increases in total biomass and AGB from 2012 to 2025, consistently detected by both allometric equations, indicate steady biomass accumulation under recurrent low- to moderate-intensity fires at QSBG. Despite fire-induced mortality, incremental gains in tree diameter and height supported continued carbon sequestration, reflecting ecosystem resilience rather than recovery from a single disturbance (Fatimah et al. 2024). Stem biomass remained the dominant component, consistent with its role as the primary carbon reservoir, while the strong contribution of medium-to-large trees highlights their importance in maintaining long-term carbon storage (Zhang et al. 2016).

Species-level patterns showed that *P. kesiya* contributed the highest AGB, followed by *P. siamensis*, *D. obtusifolius*, and *S. obtusa*, confirming that dominant canopy species strongly influence forest carbon dynamics. The rise in total carbon stock mirrored AGB trends across both equations, suggesting that natural regeneration processes continue to enhance carbon accumulation under repeated burning. The 2025 AGB estimate (~148 t ha^{-1}, Ogawa et al. 1965) aligns with values reported for secondary and fire-affected forests in mainland Southeast Asia (110-160 t ha^{-1}; Hashimoto et al. 2012; Baker et al. 2017).

Litter carbon assessed in 2025 was dominated by foliar material, with smaller contributions from branches, fruits, and flowers, reflecting typical nutrient return patterns in P-DDF. While incorporating litter improves estimates of forest floor carbon pools, the absence of soil organic carbon and belowground biomass measurements still limits comprehensive ecosystem-level carbon accounting.

However, recurrent wildfires, insect outbreaks, and droughts can reduce biomass and carbon stocks by increasing tree mortality and limiting regeneration (Jiang et al. 2023; Dye et al. 2024). Frequent burning, in particular, alters stand structure, species composition, and the abundance of large trees, thereby constraining long-term carbon retention (Jiang et al. 2023). These findings highlight the need for proactive fire management and conservation strategies aimed at protecting large individuals and promoting mixed-species regeneration to sustain biomass accumulation and optimize carbon storage in fire-prone landscapes.

Management implications for fire control and restoration

The findings provide direct guidance for fire management and biodiversity conservation in pine–deciduous dipterocarp forests. The maintenance of overall stand structure and gradual biomass recovery suggest that complete fire suppression is neither necessary nor ecologically desirable. Instead, management should aim to modify the fire regime by: (i) reducing anthropogenic ignition during critical recruitment periods (December-May), and (ii) implementing assisted regeneration programs for recruitment-limited species such as *P. kesiya* and several Fagaceae taxa. selected based on their eco-physiological traits related to fire tolerance, drought resistance, and post-fire recovery capacity. Trait-based restoration approaches emphasizing eco-physiological adaptations to disturbance can enhance long-term ecosystem resilience (Fiqa et al. 2025) and are particularly relevant for pine-dipterocarp forests experiencing recurrent fire. These measures would support a modified fire regime while maintaining the ecological functions of low-intensity burns.

This adaptive management approach aligns with regional strategies in Southeast Asia, where permanent sampling plots are increasingly recognized as effective tools for tracking forest diversity and dynamics over time. Integrating the present results with regional long-term monitoring networks could improve understanding of tropical forest responses to changing fire regimes and climatic variability. Such collaborations would also facilitate the development of predictive frameworks for fire-resilient forest management across mainland Southeast Asia.

The coexistence of traditional land uses and conservation objectives requires careful negotiation. Engaging local communities-particularly resin collectors, mushroom foragers, and shifting cultivators-in participatory fire management can reduce anthropogenic ignition while maintaining cultural practices. Establishing zoned fire management systems, ranging from full protection areas to zones of controlled burning, would balance ecological restoration with local livelihood needs. These strategies will be increasingly vital as climate change extends dry seasons and intensifies wildfire risks in Northern Thailand and neighboring regions.

Study limitations and future research directions

Several critical limitations constrain interpretation of our findings. The reliance on a single 1-hectare permanent plot limits spatial representativeness, as P-DDF ecosystems exhibit substantial variation across topographic gradients, soil types, and disturbance histories. The absence of quantitative fire history documentation, including burn severity, return intervals, and seasonal timing, prevents establishment of causal relationships between fire characteristics and ecological responses.

Methodological gaps include lack of systematic soil and microclimate monitoring, which limits mechanistic understanding of repeated fire regime processes. The

exclusion of understory vegetation and seedling dynamics provides an incomplete picture of regeneration processes. Additionally, the 13-year monitoring period may be insufficient to capture full recovery cycles for long-lived canopy species, as many tropical trees exhibit episodic recruitment tied to multi-year climatic cycles.

Because the study is based on a single permanent plot with two census years, multivariate ordination analyses were not applied; instead, changes in community composition were evaluated through species turnover, demographic rates, dominance structure, and size-class distributions.

Future research should prioritize: (i) establishing replicated plots across fire exposure gradients and forest types, (ii) implementing standardized fire monitoring including burn severity mapping, (iii) extending monitoring periods to 25-30 years for complete demographic assessment, and (iv) integrating understory vegetation and seedling monitoring, alongside soil analyses, to better understand the mechanistic drivers of forest recovery.

In conclusion, this 13-year permanent plot study provides the first long-term assessment of pine-deciduous dipterocarp forest dynamics under repeated fire regimes in Northern Thailand. The results suggest moderate resilience, as indicated by sustained species diversity, positive demographic balance, and ongoing carbon recovery. However, recruitment failure among several dominant taxa, including the typically fire-adapted *P. kesiya*, exposes demographic vulnerabilities that may drive gradual compositional shifts toward communities dominated by deciduous species with greater fire tolerance, although these patterns are associational rather than causal given the absence of quantified fire metrics and environmental covariates. These findings highlight the importance of large, mature trees for maintaining carbon storage and ecological stability, while underscoring that repeated fires, although not entirely destructive, limit optimal forest function. Adaptive fire management that reduces anthropogenic ignition, safeguards recruitment-limited species, and integrates long-term monitoring will be essential to sustain biodiversity and ecosystem services under future climate change scenarios. This study contributes valuable baseline evidence for regional fire ecology and management in Southeast Asia.

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