ASIAN JOURNAL OF FORESTRY
Volume 10, Number 1, June 2026
Pages: 10
E-ISSN: 2580-2844
https://doi.org/10.13057/asianjfor/r100129

Carbon footprint of teak plantation management in Thailand using life cycle analysis

NALINEE INTIM[1], WIRONGRONG DUANGJAI[2], SAPIT DILOKSUMPUN[2], TOMI KAAKKURIVAARA[3], NOPPARAT KAAKKURIVAARA[3,♥]
[1]Forest Resource Management Office No. 4, Royal Forest Department. 88 Village No. 4, Hua Ro, Phitsanulok, 65000 Phitsanulok, Thailand
[2]Department of Silviculture, Faculty of Forestry, Kasetsart University. 50 Ngamwongwan Rd., Chatuchak, 10900 Bangkok, Thailand
[3]Department of Forest Engineering, Faculty of Forestry, Kasetsart University. 50 Ngamwongwan Rd., Chatuchak, 10900 Bangkok, Thailand.
Tel.: +66-2579-0170, ♥email: ffornrm@ku.ac.th

Manuscript received: 13 November 2025. Revision accepted: 9 April 2026.

Abstract. *Intim N, Duangjai W, Diloksumpun S, Kaakkurivaara T, Kaakkurivaara N. 2026. Carbon footprint of teak plantation management in Thailand using life cycle analysis. Asian J For 10 (1): r100129. https://doi.org/10.13057/asianjfor/r100129.* Greenhouse (GHG) emissions from forest management operations are increasingly scrutinized in the context of climate change mitigation. This study aimed to quantify the carbon footprint of a full rotation teak (*Tectona grandis*) plantation, identifying key direct emission sources in silviculture and harvesting. This study assessed the carbon footprint of teak plantation management in the Mae-Moh Forest Plantation, Lampang Province, Thailand, using a life-cycle emission assessment over a 30-year rotation period. The system boundary covered plantation management activities from site preparation and planting to thinning and final harvesting, following a cradle-to-log-yard framework. Carbon dioxide emissions were calculated using activity data collected during 2023-2024 and emission factors provided by the Thailand Greenhouse Gas Management Organization. The analysis consisted of two major components: silvicultural practices and harvesting operations. The life-cycle emissions of carbon dioxide from silvicultural practices were estimated at 1,726.5 kg CO_2eq ha^{-1}, with annual firebreak construction accounting for 1,176.0 kg CO_2eq ha^{-1}, followed by fertilizer application accounting for 338.0 kg CO_2eq ha^{-1}. The first year of establishment generated the highest emissions owing to the implementation of all silvicultural activities. Harvesting operations resulted in 14.2 kg CO_2eq/m^3 in final felling, with short distance transportation identified as the largest contributor (5.3 kg CO_2eq/m^3). When aggregated over the entire rotation, the total operational carbon footprint was 4,633.4 kg CO_2eq ha^{-1}, with harvesting operations accounting for 62.7% of emissions and silvicultural practices 37.3%. The highest annual emissions occurred during the first thinning at year 15. These results indicate that harvesting logistics, machinery efficiency, and fertilizer management are key drivers of emissions in teak plantation management. Improving equipment efficiency, optimizing nutrient management based on soil conditions, and adopting integrated fertilizer strategies could substantially reduce the carbon footprint of plantation forestry operations.

Keywords: Fuel consumption, greenhouse gases, life cycle assessment, operational efficiency, plantation forestry emissions

INTRODUCTION

Climate change, driven by increasing greenhouse gas (GHG) emissions, remains one of the most pressing environmental challenges of the 21st century (Xu et al. 2025). The forestry sector plays a dual role in this context; it contributes to carbon dioxide emissions through land-use change and management practices, while also providing one of the most effective natural pathways for carbon sequestration (Schmid et al. 2021). Therefore, quantifying the balance between emissions and sequestration is essential for evaluating the climate mitigation potential of forest systems (Gregor et al. 2024).

Approximately 4% of global forest area consists of forest plantations, where intensively managed systems involve repeated cycles of site preparation, establishment, thinning, and harvesting operations (FAO 2020). These activities generate direct carbon dioxide emissions, such as the use of fossil fuels in machinery, and indirect carbon emissions, such as the decomposition of logging residues (Markewitz 2006; Repo et al. 2010). However, plantations also act as long-term carbon sinks by accumulating biomass and storing carbon in harvested wood products (Diao et al. 2022). Thus, a comprehensive assessment of the carbon footprint of rotation time is necessary to inform sustainable management strategies.

Among the tropical plantation species, teak (*Tectona grandis*) is particularly important because of its high economic value, durability, and widespread use in furniture and construction (IUFRO 2017). Teak plantations cover 4.3 M ha across the world, 83% of which are located in Asia, and are often managed under long rotations ranging from 20 to 40 years (IUFRO 2017). Existing research has tended to focus on the thinning effect and overall carbon storage, while overlooking the cumulative emissions generated by silvicultural practices and harvesting operation inputs during rotation (Chayaporn et al. 2021; Wirabuana et al. 2022). Despite the prominence of teak plantations, there is a significant gap in understanding the complete carbon footprint of teak plantation management when life-cycle carbon emissions from silvicultural practices and harvesting operations, from site preparation to final felling, are missing. Additionally, this information is essential for carbon sequestration balance calculation, whereas several studies have estimated sequestration and storage in teak plantations (Sreejesh et al. 2013; Chayaporn et al. 2021).

Teak has long been recognized as one of the most valuable hardwood species in tropical forests, and Thailand has a significant history of teak plantation development (Royal Forest Department 2013; Meunpong et al. 2026). Following the decline in natural teak forests due to overexploitation, Thailand shifted its focus toward plantation-based management to secure its timber supply and reduce pressure on natural stands (IUFRO 2017). Teak plantations in Thailand are typically established under systematic silvicultural regimes involving site preparation, planting, and intensive maintenance in the early years. During the first two to three years after planting, regular weed control and fertilizer application are essential to support seedling establishment and rapid early growth. Thinning operations are generally scheduled twice within the rotation, first at approximately 15 years and again before 25 years, to reduce stand density, enhance the growth of the remaining trees, and improve log quality. The final harvest usually occurs after 30 years, yielding mature, high-value timber suitable for construction and furniture markets (Royal Forest Department 2013). The Forest Industry Organization (FIO 2005) has played a central role in managing large-scale teak plantations covering up to 100,000 ha in Thailand, where the above-described management is followed. Despite the economic and silvicultural importance of teak plantations, comprehensive assessments of the environmental impacts, particularly the carbon footprint of these management practices across full rotation, remain limited in Thailand. The studied harvesting method aligns with previous research and uses the motor-manual harvesting method in teak harvesting that is common in Southeast Asia; hence, the study is applicable outside Thailand as well (Kaakkurivaara et al. 2022; Borz et al. 2025). However, a holistic understanding of the carbon footprint of teak plantation management over a complete rotation period remains lacking. This knowledge is critical for evaluating the net climate benefits of teak-based forestry and seeking low-carbon management practices for future guidance.

Therefore, this study aimed to define and estimate the direct carbon emissions from teak plantation silviculture practices and harvesting operations. The objectives were to assess the direct carbon dioxide emissions from site preparation, planting, fertilization, maintenance, thinning, and final harvesting over a 30-year rotation. This study omitted the indirect emissions from trees and soils derived from these operations. These results provide information on the carbon dynamics of teak plantations and contribute to broader discussions regarding the role of teak plantation forestry in climate change mitigation and calculation for net carbon balance.

MATERIALS AND METHODS

Study site

The study was conducted in the Mae-Moh Forest Plantation under FIO management. The plantation was located in the Mae-Moh District, Lampang Province, Thailand (Figure 1). The area lies at an elevation of approximately 300-500 m above sea level (masl). The Mae-Moh Forest Plantation covers a total area of 2,252 ha, with teak as the principal cultivated species. Climatically, the site falls within the tropical monsoon zone, experiencing distinct wet and dry seasons, with an average annual temperature of 26-34°C and mean annual rainfall of about 1,100-1,300 mm (Thai Meteorological Department 2023).

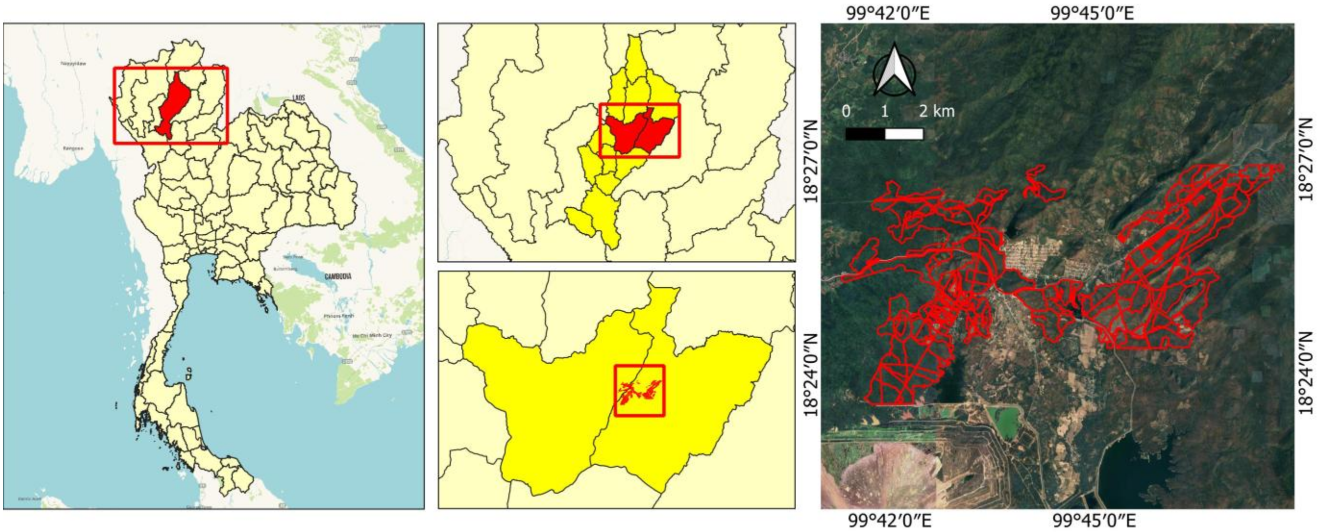

Figure 1. Location of the Mae-Moh plantation in Northern Thailand

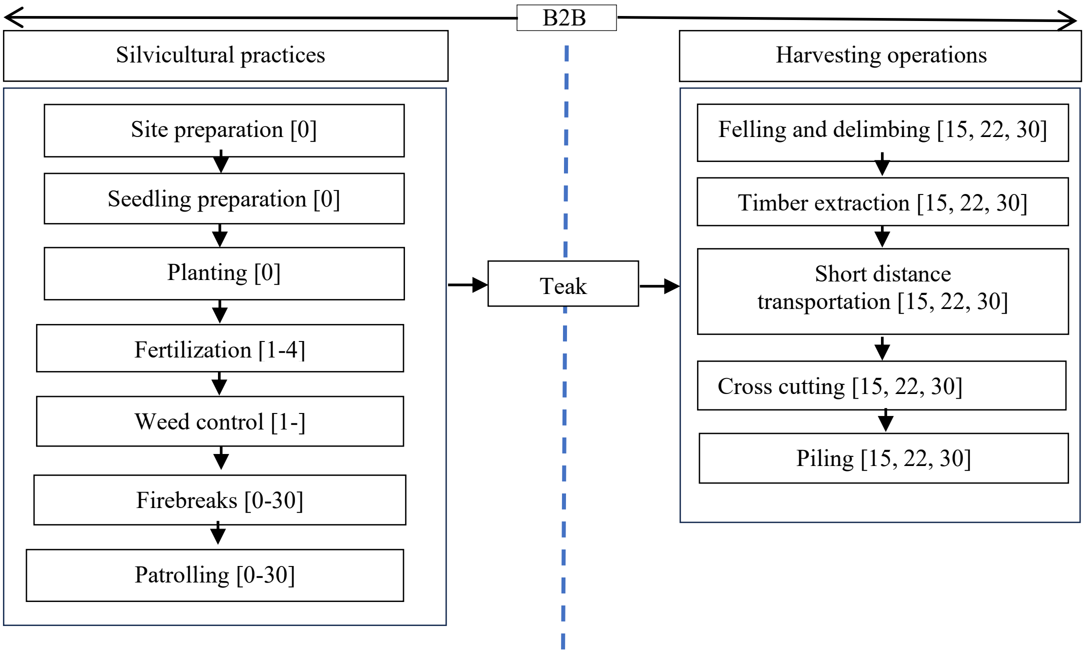

Figure 2. Schematic diagram of activities studied. The numbers in the square brackets indicate the year the activity took place

The soils are generally sandy loam to clay loam with moderate fertility (Land Development Department 2009). Plantation management followed a 30-year rotation cycle that included site preparation, planting, weed control, and fertilization during the first two to three years; two thinning operations, the first at approximately 15 years of age and the second before 25 years; and a final harvest at approximately 30 years. The plantation consisted equally of areas of even size distributed to follow a 30-year rotation time. The initial planting density followed the typical spacing of 625 tree ha^{-1} (spacing 4 × 4 m). Densities were reduced by half in both thinning treatments. These silvicultural practices, together with the harvesting method introduced later, reflect the standard teak silvicultural regimes applied across northern Thailand and make Mae-Moh an appropriate data collection site for assessing the carbon footprint of teak plantation management.

Data collection

This study evaluated the carbon footprint of teak plantation activities within a business-to-business (B2B) framework in which different actors were involved in activities related to forest management. This study covered the entire management cycle from silvicultural practices to harvesting operations (Figure 2). Both primary and secondary data sources were collected and analyzed to quantify carbon dioxide emissions associated with each activity. Activities excluded from the system boundary of this study included manual labor, worker commuting, animal labor, office-related activities, and nursery management, due to limited research resources and the great variation of practices across Thailand and other countries. The relevance of these factors is noteworthy, but the impact per cubic meter or hectare is minimal during the whole rotation time. All the data used in this study were collected between 2023 and 2024 across the plantations.

Silvicultural practices

Silvicultural practices include land preparation, nursery operations, planting, fertilization, weed control, and firebreak construction. Land was prepared using tractors to plow the plantation area. Seedlings were raised in a nursery using a normal procedure for one year. Seedlings were prepared for delivery by transferring them into 6.5 × 17.5 cm polyethylene bags and later planted in the regeneration area. Planting involved manual labor for pit digging and vegetation clearing around the planting pits. Fertilization during regeneration included three types of input: organic fertilizer (0.1363 kg), urea (46-0-0; 0.0072 kg per pit), and NPK fertilizer (15-15-15; 0.0064 kg per pit), all of which were applied during planting. During the following years (1-4), urea fertilizer was added twice (0.0150 kg and 0.0300 kg per pit) in the first year, and NPK fertilizer was added twice in the second year at 0.0500 kg per pit and once in the third and fourth years at 0.0800 kg per pit in both years. In total, six supplementary fertilizer applications were applied after planting.

Weed control was performed using brush cutters around the planted seedlings and across the plantation area from the first to third years, three times annually, and twice in the fourth year (Figure 3). The brush cutter used was a four-stroke Honda GX35 with a displacement of 36 cm^3 and a power of 1.0 kW. The fuel consumption was measured using the refilling-to-full method, with a plastic measuring cylinder with a scale (Figure 3). Firebreak construction was performed annually between November and December using manual tools to clear understory vegetation and farm tractors to remove larger obstacles. Routine patrolling was conducted using pickup trucks to monitor plantation conditions and prevent illegal logging. Data were collected on fuel consumption, fertilizer inputs, and other material resources, with silvicultural activities scaled per hectare.

Harvesting operations

A final felling harvesting site with a common tree size and age was selected to perform typical teak harvesting operations. The collected emission data were extrapolated to represent thinning operations at the ages of 15 and 22 years, where the available plantation records were indicated as the average ages for thinning operations. Furthermore, exact tree-level data were available for the age groups of these stands. As half of the trees were removed, the average harvested volumes were calculated for both thinning operations to describe a typical silvicultural management situation. When the carbon dioxide emissions per harvested cubic meter and the removed volume were known at the final felling, the carbon dioxide footprint per hectare was calculated to standardize the assessment together with silvicultural practices. Lastly, the carbon dioxide footprint of thinnings (kgCO$_2$eq ha^{-1}) was calculated by multiplying the thinning removals (m^3 ha^{-1}) value by the emission factor (kgCO$_2$eq/m^3). This procedure helps to generalize the measured results of final felling to thinning by avoiding the bias of direct conversion based on cubic meter emissions multiplied by the removal quantity (m^3), which would not describe the relative change in harvesting emissions.

Teak harvesting followed the Tree Length (TL) system in which trees were felled using chainsaws, followed by delimbing and topping, leaving branches and treetops in the stump area. The chainsaw used for tree processing was a new Stihl MS382 (3.9 kW) with a 20-inch-long guide bar, and the farm tractor for skidding was a Massey Ferguson 390 with a 4-cylinder engine (65 kW). This farm tractor was used to extract TL logs from roadside storage at a distance of 380 m from the harvesting stand when the total number of rounds was 47. At this stage, log-level data were recorded, including girth at the end, mid-section, and top, as well as log length, to calculate log volumes expressed on a cubic meter basis. The extraction operation was monitored using data collected on the number of logs per load, skidding distance, and time required. On the roadside, the logs were loaded onto trucks equipped with cable winches, and the number of logs transported, transport distance, and loading time were recorded. The truck used was a Mercedes-Benz L1418 with a six-cylinder engine and a power of 134 kW. Owing to the long length of the logs and short cargo space, the transportation method was similar to a skidding technique, in which log ends dragged the ground during driving (Figure 4). Loading and unloading were performed using a truck-attached cable winch run by a truck engine. Upon arrival at the log yard, workers measured the log dimensions to meet market specifications, and the logs were cut to length using chainsaws (Figure 4). Each log was then stamped with the log ID code, sorted by log dimensions, and stacked into piles with the help of farm tractors for subsequent sales in timber auctions. Data on fuel consumption by chainsaws, farm tractors, and trucks were recorded during different work phases using the refilling method. The vehicles were placed near the log yard from the fuel tank at the plantation headquarters. The shortest transportation distance was 6.3 km per round when the total number of rounds was six.

Harvesting volume data were collected from 53 TL logs of the final felling (Table 1), which represent the typical tree size of 30 years old teak plantation. The girth at the butt, middle, and top sections was measured for each TL log and converted into diameter to calculate the log volume with the help of the total log length. The average log volume was almost half a cubic meter over the bark, with a high variation between 0.120 and 1.128. The average length of the logs was 12.7 m, with minimum and maximum lengths of ±5 m. The total log volume measured from all sampled trees was 25.9 m^3. Similar data collection was performed by cross cutting and piling, which consisted of 16.4 m^3 measured at the log yard after short distance transportation.

Data analysis

There are several international standards for emission factors, without a clear consensus on which one should be implemented for global use. In this study, the focus was to conduct national level survey, and carbon dioxide emissions were calculated using the Emission Factor (EF) approach presented in Table 2, following the most recent guidelines published by the Thailand Greenhouse Gas Management Organization (2016) to ensure compatibility with national carbon accounting practices. Activity data obtained from field measurements, including fuel consumption, fertilizer application, and other material inputs, were multiplied by the corresponding emission factors to calculate the amount of carbon dioxide emissions for each activity. This calculation follows equation 1:

Carbon dioxide emissions = Activity Data × Emission Factor (EF) [1]

Table 1. Tree attributes in a 30-year-old teak plantation (n=53)

Log dimensions	Min	Max	Mean
Diameter (Butt), cm	22.0	56.4	33.5
Diameter (Middle), cm	13.1	31.2	21.8
Diameter (top), cm	11.1	22.3	15.6
Length, m	7.3	17.1	12.7
Volume, m^3	0.120	1.128	0.489

Table 2. Activities and resources used in both forest management processes, with emission factors for emission sources per measured units

Forest management	**Activities**	**Source**	**Unit**	**Emission Factor**
Silvicultural practices	Site preparation	Diesel	L	2.74
	Seedling preparation	Plastics bags	kg	1.52
	Planting	Fertilizer organic	kg	0.11
		Fertilizer Urea	kg	5.53
		Fertilizer NPK	kg	2.05
	Fertilization	Fertilizer Urea	kg	5.53
		Fertilizer NPK	kg	2.05
	Weed control	Gasoline	L	2.19
	Firebreaks	Diesel	L	2.74
	Patrolling	Diesel	L	2.74
Harvesting operations	Felling and Delimbing	Gasoline	L	2.19
		Lubricant	L	0.83
	Timber extraction	Diesel	L	2.74
	Short distance transportation	Diesel	L	2.74
	Cross cutting	Gasoline	L	2.19
		Lubricant	L	0.83
	Piling	Diesel	L	2.74

Figure 3. Control of fuel consumption in weed control practices

Figure 4. Skidding of tree-length logs by truck to the log yard for chainsaw bucking

Where, activity data represent the quantity of input or resource used (e.g., liters of diesel or kilograms of fertilizer per ha) and EF denotes the standardized emission factor expressed as kgCO₂eq per unit of input. For fuel consumption, emission factors accounted for the combustion of diesel and gasoline in machinery and transport vehicles, whereas fertilizer-related emissions included both direct soil emissions and indirect upstream emissions embedded in fertilizer production. The boundary of the analysis covered all operational activities within the plantation management system, excluding human labor and office operations, as specified in the system scope. Each activity was assigned to the specific year(s) of operation and its frequency during the rotation period, allowing emissions to be calculated on an annual basis. Annual emissions from all activities were then aggregated across the 30-year rotation. Harvesting emissions during thinning operations were estimated by back-calculation from final felling data. This approach was adopted because detailed operational records for thinning were unavailable. In Thailand, thinning practices typically remove approximately 50% of standing trees at each thinning event. Therefore, the volume of timber removed during thinning was estimated using the teak growth equation corresponding to different stand ages to approximate the harvested volume at each thinning cycle. Harvesting emissions for thinning were then calculated proportionally based on the estimated timber volume relative to final felling, assuming similar machinery types and operational processes. This method assumes the Thai silvicultural regime to carry out similar thinning densities also in practice, as in guidance forest management recommendations.

RESULTS AND DISCUSSION

Silvicultural management

The total carbon dioxide emissions from silvicultural practices are presented in Table 3, with a detailed breakdown of emissions by activity. The carbon dioxide footprint was estimated to be 1,726.5 kgCO$_2$eq ha^{-1} over the whole 30-year rotation period, where firebreak construction was the highest source of emissions. Among all activities, fertilizer application during years 1-4 represented the second largest source of emissions at 338.0 kgCO$_2$eq ha^{-1}, over eleven-fold greater than the fertilizer emissions at planting. The third largest sources, producing similar amounts, were weed control (62.6 kgCO$_2$eq ha^{-1}) and site preparation (58.7 kgCO$_2$eq ha^{-1}), followed by patrolling activities (54.0 kgCO$_2$eq ha^{-1}).

The share of carbon dioxide emissions by origin among silvicultural practices is presented in Figure 5. The figure highlights firebreaks as the primary contributor of emissions, contributing 68.1%, which consisted of annual firebreak construction work before the dry season. Fertilizer on planting (1.7%) and fertilization (19.6%) during years 1-4, two types of fertilizers were used: urea and NPK. Of these, NPK fertilizer accounted for the majority of fertilizer emissions, 245.1 kgCO$_2$eq ha^{-1}, while urea contributed 92.9 kgCO$_2$eq ha^{-1}. Fuel-based emissions came from two sources: gasoline used for weed control, contributing 3.6%, and diesel for site preparation, firebreaks, and patrolling, contributing a total of 74.6%.

Timber harvesting

The total carbon dioxide emissions from harvesting operations were estimated at 14.2 kgCO$_2$eq/m^3 (Table 4). A detailed breakdown of emissions by activity revealed that three activities were responsible for the highest emissions: short distance timber transportation by winch truck (5.3 kgCO$_2$eq/m^3; 37.3%), extraction by farm tractor (4.2 kgCO$_2$eq/m^3), and log piling using farm tractor (4.1 kgCO$_2$eq/m^3). In contrast, the lowest emissions were associated with felling and delimbing using a chainsaw, which accounted for only 0.19 kgCO$_2$eq/m^3.

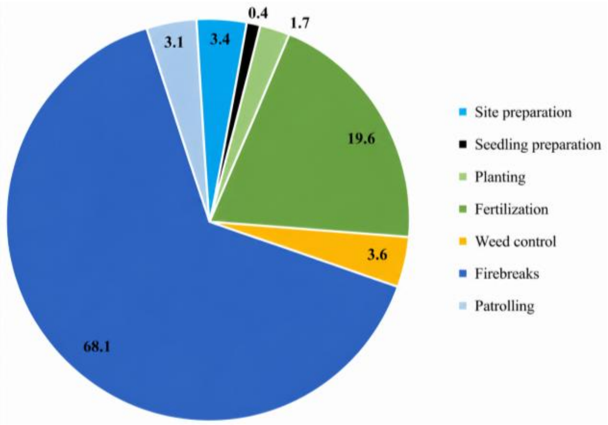

Figure 5. Percentage contribution of emission sources in silvicultural practices during the 30-year rotation. Colors represent emission sources: fertilizers (green), diesel fuel (blue), gasoline (yellow), and plastics (black)

Table 3. Carbon dioxide emissions of silvicultural practices during rotation time

Activity	Observed area (ha)	Observed consumption	Consumption /ha	Carbon footprint kgCO$_2$eq/ha
Site preparation	27.60	590.00 L	21.38	58.7
Seedling preparation	0.32	1.00 kg	3.13	7.5
Planting:				
Organic Fertilizer	0.32	27.25 kg	85.16	
Fertilizer Urea	0.32	1.44 kg	4.50	
Fertilizer NPK	0.32	1.28 kg	4.00	
Planting total				30.2
Fertilization:				
Fertilizer Urea	0.32	9.00 kg	28.13	
Fertilizer NPK	0.32	52.00 kg	162.50	
Fertilization total				338.0
Weed control	32.24	83.81 L	2.60	62.6
Firebreaks	1.40	20.00 L	14.29	1,176.0
Patrolling	2,229.44	1,425.60 L	0.64	54.0
Total				1,726.5

Note: Carbon footprint calculated by equation 1

As shown in Figure 6, the three activities with the highest emissions, short distance transportation, skidding, and log piling, accounted for a total of 96.6% of emissions. These activities rely on diesel fuel consumption by heavy machinery, particularly winch-equipped trucks and tractors. Timber handling caused by these machines results in substantially higher carbon dioxide emissions compared with tree felling and stem processing with a chainsaw, which contributed only marginal emissions of 3.4%.

Annual and rotation time emissions

The emissions from the silvicultural practices and harvesting operations are presented in Tables 3 and 4, respectively. Based on these results, the annual carbon footprints of both activities are illustrated in Figure 7, where the carbon dioxide emissions are summed for each year of rotation time. To assess the life-cycle carbon footprint, the total emission was calculated to be 4,633.4 kgCO_2eq ha^{-1} in the studied teak plantation, whereas silvicultural practices accounted for 1,726.5 kgCO_2eq ha^{-1} (37.3%), while harvesting operations contributed a larger share of 2,906.9 kgCO_2eq ha^{-1} (62.7%). Annual mean emissions were 154.45 kgCO_2eq ha^{-1} for the studied rotation period, resulting in 347,821.4 kgCO_2eq annual emissions for the whole Mae-Moh plantation, on the assumption that all teak compartments are undergoing similar silviculture management processes.

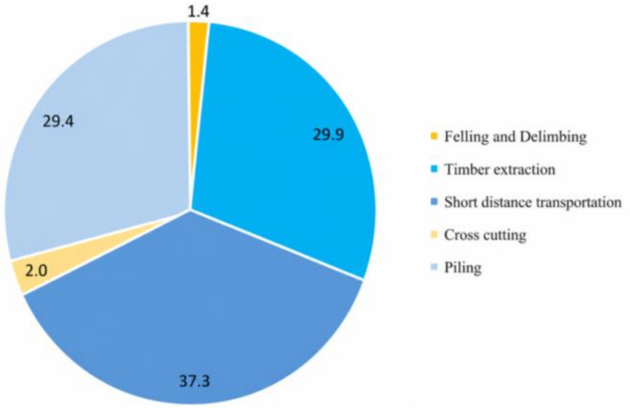

Figure 6. The share (%) of carbon dioxide emissions from the final felling is divided between activities. Each color represents a different emission source: blue for diesel, and yellow for gasoline and lubricant

Table 4. Carbon dioxide emissions of the teak harvesting operation on final felling

Activity	Observed volume, m^3	Observed consumption, L	Consumption, l/m^3	Carbon footprint, kgCO2eq/m^3
Felling and delimbing:				
Gasoline	25.9	2.12	0.08	
Lubricant	25.9	0.43	0.02	
Felling and delimbing total				0.19
Timber extraction	25.9	40.00	1.54	4.24
Short distance transportation	25.9	50.00	1.93	5.30
Cross cutting:				
Gasoline	16.4	1.90	0.12	
Lubricant	16.4	0.66	0.04	
Cross cutting total				0.29
Piling	16.4	25.00	1.50	4.13
Total				14.20

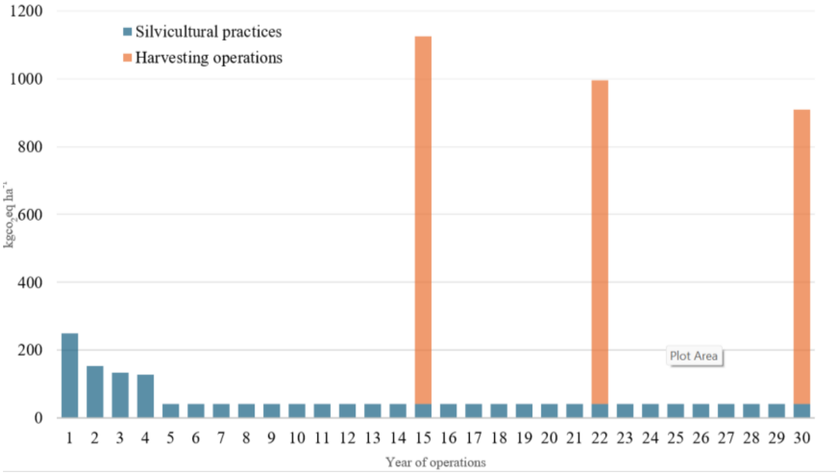

Figure 7. Annual carbon footprint (kgCO_2eq ha^{-1}) from silvicultural practices and harvesting operations over a 30-year rotation in teak plantation

When considering only silvicultural practices, the highest silvicultural emissions were recorded in year 1, amounting to 250.2 $kgCO_2eq\ ha^{-1}$ (14.5%). This was followed by year 2 with 152.3 $kgCO_2eq\ ha^{-1}$ (8.8%) and year 3 with 133.6 $kgCO_2eq\ ha^{-1}$ (7.7%). The total emissions during year 1 can be attributed to the implementation of all silvicultural activities, including site preparation, planting, and initial fertilization. In years 2-4, the emissions remained relatively similar, primarily because of the application of NKP fertilizer. During years 5-30, emissions of 41 $kgCO_2eq\ ha^{-1}$ (2.4%) were attributed to fire break construction and patrolling.

For harvesting operations, the highest emissions occurred in year 15 during the first thinning, reaching 1,084.7 $kgCO_2eq\ ha^{-1}$ (37.3%). The second thinning in year 22 contributed 954.5 $kgCO_2eq\ ha^{-1}$ (32.8%), whereas final felling in year 30 generated 867.7 $kgCO_2eq\ ha^{-1}$ (29.9%). These results highlight the strong influence of thinning and harvesting activities on the overall carbon footprint of teak plantations. The year with the highest combined emissions from both silvicultural practices and harvesting operation was year 15, corresponding to the first thinning, with emissions of 1,125.6 $kgCO_2eq\ ha^{-1}$, representing about one fourth of total emissions during the whole rotation period.

Discussion

Silvicultural practices involve all the necessary activities to secure seedling survival and tree growth. These activities are commonly used in Thailand and in other parts of the world (IUFRO 2017; Nero and Boateng-Boye 2025). The greatest emission source mainly consisted of diesel fuel from firebreak construction, together with almost over two-thirds of the silvicultural practices, which were carried out using the same outdated farm tractor as some tasks in harvesting operations. The annual amount of emission was not large, but the cumulative amount over a 30-year rotation time resulted in the highest impact compared to other silvicultural activities. About one-fifth of carbon dioxide emissions from silvicultural practices originated from the use of fertilizers in our study. Teak plantations contribute to carbon sequestration and long-term storage of harvested wood products (Sreejesh et al. 2013; Chayaporn et al. 2021). Review of previous study results has given mixed results regarding the effect of fertilization in Latin America and Asia-Africa, where positive responses were most likely observed in low fertility stands, where chemical fertilization can increase the stand volume by 30-50 % (IUFRO 2017). In light of this, the use of fertilizer should be based on the detection of low-nutrient soils, where the amount of fertilizer should be optimized to correspond to actual needs. Thus, overfertilization would be minimized in areas where it is not necessary to mitigate the negative impacts on soil properties and water bodies (Asigbaase et al. 2024). The optimization of fertilization would benefit the total assessment of the carbon footprint, where emissions of silvicultural practices and harvesting operations during the rotation period are considered as the net removal of carbon dioxide at the end of the rotation time. Focusing on the use of chemical fertilizers is essential when monitoring GHG emissions, instead of carbon dioxide emissions. It is important to note that, in addition to NPK fertilizer, urea fertilizer, which has a high nitrogen content, was used in our study. Nitrogen fertilizer use is associated with nitrous oxide (N_2O) emissions, which have a global warming potential 298 times greater than that of carbon dioxide (IPCC 2007). Consequently, a higher nitrogen content in fertilizers directly results in greater GHG emissions, together with carbon dioxide.

Mitigation strategies for reducing GHG emissions in silvicultural practices can be divided into two primary strategies. The first strategy involves reducing emissions from fuel consumption during field operations. This may be achieved by renewing machinery with engine power appropriate to the work demand, adopting renewable or synthetic fuels, scheduling firebreaks at optimal times, and ensuring regular maintenance of machinery to maximize fuel efficiency. Together, these measures can significantly improve operational efficiency while reducing the overall carbon footprint of silvicultural practices. The second focuses on optimizing fertilizer use, as compound fertilizers of both NPK and urea remain essential inputs for promoting healthy tree growth and ensuring satisfactory yield. Therefore, emission reduction should emphasize appropriate application methods, including soil analysis, to guide nutrient requirements and apply only the necessary quantities. An integrated nutrient management approach that combines chemical fertilizers with organic amendments should also be prioritized. Organic fertilizers generally have lower associated emissions than synthetic fertilizers, particularly when upstream production processes are considered. Their targeted use in combination with chemical fertilizers can therefore contribute to emission mitigation in teak plantations. In addition, fertilizer management can be further optimized through precision forestry practices that emphasize site-specific, data-driven application based on soil nutrient status and stand requirements. The use of enhanced-efficiency fertilizers, such as controlled-release formulations or nitrogen-enriched products, can further reduce nitrogen losses and associated N_2O emissions by improving synchronization between nutrient availability and tree uptake (Raymond et al. 2016). Collectively, these practices maintain forest productivity while minimizing the carbon footprint of silvicultural operations.

Timber harvesting operations played a pivotal role in the source of emissions, when almost two-thirds of carbon dioxide emissions were sourced from thinning and final felling during the rotation period. The use of a chainsaw for felling, delimbing, and cross cutting work phases totaled 0.48 $kgCO2eq/m^3$ of emissions, which was 28% less than that reported in a study of Eker and Çoban (2021), where 0.67 $kgCO2eq/m^3$ of emissions were produced from pine tree harvesting. Both studies showed that carbon dioxide was particularly emitted into the air during the cross cutting work phase owing to the highly intensive use of the chainsaw. Farm tractor-based skidding emitted 4.24 $kgCO2eq/m^3$ over a distance of 380 m, which is relatively low compared to Eker and Çoban (2021), who reported 4.08 $kgCO2eq/m^3$ at a 100 m extraction distance. Short distance transportation did not have direct relevant references for comparison in the literature, because our study involved a local circumstance-built TL method supply chain using a very old truck equipped with a winch system and practically skidding a small payload, emitting 5.3 kgCO2eq/m^3. Long-distance transportation by a similar but newer truck model was studied, detecting emissions of 3.169 kgCO2eq/m^3 when the average distance was 50 km (Eker and Çoban 2021). This comparison highlights the substantial impact of machinery age and technical efficiency on fuel consumption and emissions. The reliance on older equipment in the studied plantation likely contributed to elevated emission intensities and may limit the direct generalizability of these results to plantations using more modern, fuel-efficient machinery. In general, road gradient and class, driving speed, and payload mass are the main explanatory factors for fuel consumption and emissions (Anttila et al. 2022, 2023). Consequently, the adoption of modern truck fleets, improvements in road conditions and geometry, and optimization of payload capacity represent effective management options for reducing harvesting-related emissions and lowering the overall carbon footprint of teak plantations.

The machines used in this study were old, which caused relatively high emissions during site preparation, fire break construction, extraction, piling by farm tractors, and short distance transportation by winch-equipped trucks. To minimize operational emissions in plantation management, machinery should be modernized by selecting machines that are not too small, while simultaneously increasing harvested stem size volume and reducing emissions (Allman et al. 2025). Harvesting emissions from thinning operations were not directly measured; instead, they were estimated by proportionally scaling emissions from final felling based on area (kg CO_2eq ha^{-1}) and volume of removed timber (kg CO_2eq m^{-3}). This approach was chosen because its main purpose was to assess the area-based carbon footprint during the 30-year rotation period. The data obtained from thinning operations can provide a deeper understanding of the topic, especially because life cycle assessment is dependent on several factors such as silvicultural practices, harvesting methods, harvesting conditions, and machine operator skills (Eker and Çoban 2021; Weyrens et al. 2022; Kärhä et al. 2024). Our study included a cradle-to-gate (log yard of timber auction) life cycle assessment; further analyses are recommended to extend the assessment to a cradle-to-grave overview to estimate the carbon footprint of commonly manufactured teak products, where indirect emissions are also taken into account.

In conclusion, this study presents the foremost direct carbon dioxide emissions in the life-cycle assessment of Thai teak plantations. The total operational emissions were estimated at 4,633.4 kg CO_2eq ha^{-1}, of which silvicultural practices contributed 1,726.5 kg CO_2eq ha^{-1} (37.3%) and harvesting operations accounted for 2,906.9 kg CO_2eq ha^{-1} (62.7%). Among silvicultural activities, firebreak construction represented the largest emission source (1,176.0 kg CO_2eq ha^{-1}), followed by fertilizer application (338.0 kg CO_2eq ha^{-1}). For harvesting operations, emissions averaged 14.2 kg CO_2eq m^{-3}, with short distance transportation (5.3 kg CO_2eq m^{-3}), timber extraction (4.2 kg CO_2eq m^{-3}), and log piling (4.1 kg CO_2eq m^{-3}) as the dominant contributors. The highest annual emissions occurred during the first thinning at year 15, highlighting the strong influence of harvesting logistics on the overall carbon footprint.

Faced with the need for decarbonization of forest management operations to mitigate the impact of climate change, the life-cycle assessment of teak plantations is part of the rising awareness of GHG pollutant estimation to help in decision-making to reduce harmful impacts to the climate. This study demonstrated that all forestry management activities within teak plantations contribute to carbon dioxide emissions, although the magnitude varies depending on the nature of the activity, frequency, type, and size of the machine or petrol-powered tool, and the influence of extraction and transportation distances. However, less focus is needed to prioritize brush cutter use because of its small share of emissions compared to timely weed control. Similarly, during harvesting operations involving chainsaw use, farm tractors and trucks were the main contributors to emissions. The findings indicate that emission reduction efforts in teak plantations should prioritize both nutrient management, firebreak construction, and harvesting logistics. For plantation managers, practical mitigation measures include conducting soil nutrient analyses prior to fertilizer application, adopting integrated nutrient management with greater reliance on organic amendments, optimizing machinery size and engine capacity, and improving forest road networks to reduce skidding and transport distances. Regular maintenance and timely replacement of outdated machinery can further enhance fuel efficiency and reduce emissions. For policymakers, the results underscore the need to support low-carbon plantation management through technical guidelines for fertilizer use, incentives for energy-efficient machinery, and investment in plantation infrastructure. Collectively, these actions provide feasible pathways to reduce the carbon footprint of teak plantation management while supporting sustainable forestry development and national climate change mitigation objectives.

Several limitations should be acknowledged. First, the analysis focused on direct operational emissions and did not include indirect emissions from soil processes, nursery production, or downstream processing of harvested wood products. Second, harvesting emissions during thinning were estimated by scaling final felling data, which may introduce uncertainty because operational conditions can vary across stand ages and harvesting intensities. Finally, the results are based on a single plantation site, which may limit generalization to other teak management systems with different machinery, terrain, or management regimes.

Future research should expand the assessment to multiple plantation sites, incorporate direct measurements of thinning operations, and extend the life-cycle analysis to a cradle-to-grave framework that includes wood processing, product use, and end-of-life stages. Integrating operational emissions with biomass carbon sequestration and harvested wood product storage would also provide a more comprehensive evaluation of the net climate mitigation potential of teak plantation forestry.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the FIO of Thailand for providing access to the study site and their support throughout this study. We also extend our sincere thanks to the FIO staff, whose assistance and cooperation greatly facilitated fieldwork and data collection.

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