Asian Journal of Agriculture and Biology
https://doi.org/10.35495/ajab.2026.072

Original Article

Implications of selective logging on carbon stocks and CO_2 emission potential for supporting sustainable natural forest management

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Received: 17 February 2026 / Revised: 21 June 2026 / Accepted: 28 June 2026 / Published Online: 25 July 2026

Abstract

Tropical natural forests are vital ecosystems that provide a wide range of ecosystem functions, biodiversity conservation, and most critically, carbon stock and sequestration. Selective logging with the reduced impact logging (RIL) technique still generates logging residues and residual stand damage, which reduces the forest's ability to recover and function as a long-term carbon stock. This study presents an integrative assessment of carbon loss resulting from RIL operations in tropical forests by simultaneously quantifying emissions from logging residues and residual stand damage. The study was conducted in a log over area of natural mountain forest at PT. Kayu Tribuana Rama, which is geographically located at 01°13'01"–01°29'49" South latitude and 112°12'12"–112°36'43" East longitude. The results show that the total potential carbon stock and CO_2 emission after logging reached 4.804-ton C. ha^{-1}, equivalent to 17.612 ton $CO_2eq.ha^{-1}$, comprising 15.4% from logging residues and 18.2% from residual stand damage. Logging efficiency ranged from 74.8% to 78.7%, with an average of 75.9%, while the degree of residual stand damage ranged from 27.5% to 37.1%, with an average of 33.6%, classified as moderate damage. The calculation of forest carbon and potential CO_2 emissions after logging in natural production forests must integrate calculations from logging residues and residual stand damage to improve the methodology within the carbon Measurement, Reporting, and Verification (MRV) system. The development of this methodological approach is essential for improving the accuracy of logging-related emission estimates and supporting performance-based incentive schemes, including payments for environmental services, carbon credit mechanisms, and sustainable biodiversity credits.

Keywords: Selective logging, Logging residues, Residual stand damage, Post-logging carbon emissions, Carbon stock and stock, Sustainable tropical natural forests

How to cite this article:
Soenarno, Yuniawati, Abdulah L, Heriansyah I, Wardani M, Darwo, Dewi R, Kalima T, Suhartana S, Mindawati N, Oryzanti P, Susila IWW, Utomo PM, Effendi R, Andini S, Waluyo TK, Siswadi and Rochmayanto Y. Implications of selective logging on carbon stocks and CO_2 emission potential for supporting sustainable natural forest management. Asian J. Agric. Biol. 2026: e2026072. DOI: https://doi.org/10.35495/ajab.2026.072

Introduction

Until recently, the destruction of tropical natural forests due to logging practices was feared to affect forest carbon sinks and increase potential carbon emissions. Forest carbon sinks are an important way to achieve carbon sequestration, and therefore require strengthened forest protection and sustainable management (Zhou et al., 2022). Indonesia has a strong commitment Forest carbon sinks are an important way to achieve carbon sequestration, and therefore require strengthening forest protection and sustainable management. As an implementation, the government issued a strategic policy that requires logging activities to apply logging impact reduction techniques (Ministry of Environment and Forestry, 2021). However, in practice, there is still a lot of logging waste in the form of stem cleavage residues, such as base and tip pieces above branches and stand damage. The presence of logging waste causes a direct loss of carbon stocks in the forest ecosystem (Seidl et al., 2014; Harris et al., 2021; Nolan et al., 2021) and increases the potential for CO_2 emissions (Shearman et al., 2012; Irland, 2011; Pearson et al., 2014; Irawan and Purwanto, 2020). In addition, forest disturbance will adversely affect the important role of forests in absorbing and storing carbon as long-term biomass (Irundu and Bedduand, 2020).

Tropical forests serve as major carbon stocks, absorbing and storing carbon in the form of above-ground biomass, below-ground biomass, dead wood, litter, and soil organic carbon (Baccini et al., 2012; Reyna-Bowen et al., 2019). Natural forest ecosystem disturbances, particularly those induced by logging activities, contribute to a reduction in the capacity of forests to absorb and sequester carbon. Logging is one of the principal drivers of forest degradation and significantly contributes to global carbon emissions (Pearson et al., 2014; Sasaki et al., 2016). Selective logging, which involves the harvesting of commercially valuable tree species above a specified diameter threshold, results in direct impacts on forest structure, composition, and carbon stocks (Griscom et al., 2019). The extraction of trees generates logging residues, including stumps, buttress remnants, stem bases, and crown segments, which constitute a source of direct CO_2 emissions through decomposition (Numazawa et al., 2017). Furthermore, residual stand damage, including broken, uprooted, leaning, and bark-wounded trees, represents an additional and significant source of carbon emissions that is frequently underestimated (Matangaran et al., 2019). The cumulative effect of these emission sources underscores the need for comprehensive carbon accounting that encompasses both logging residues and residual stand damage (Pearson et al., 2014; Herold et al., 2011). Logging waste from felled trees ranges from 15-20% (Soenarno et al., 2021) and even reaches 45% (Budiaman and Audia, 2022). Research shows that damage during conventional harvesting is greater, ranging from 48% to 65%, compared to RIL, which ranges from 28% to 38% (Pinard et al., 1996; Sist et al., 2003b). In fact, the level of standing tree damage with RIL has decreased, ranging from 21.9% to 27.8% (Yuniawati and Dulsalam, 2020; Matangaran et al., 2019). The high levels of logging waste and residual stand damage are due to the suboptimal accuracy of forest carbon calculations for better forest management using the correct logging methods (Budiaman and Audia, 2022; Soenarno et al., 2023).

Indonesia's commitment to achieving the 2030 Net Zero Carbon Emissions target for the Forestry and Other Land Use (FOLU) sector, as outlined in Government Regulation No. 23/2021 (Ministry of Environment and Forestry, 2021). In this regulation, Indonesia emphasizes the sustainable use of forest resources, the conservation of forest ecosystem functions, and long-term forest productivity as the core principles guiding improved management of forest concessions to minimize emissions from forest degradation while maintaining the productive functions of natural forests. Under this framework, the forestry sector is expected to become a net carbon sink by 2030, contributing significantly to the Nationally Determined Contribution (NDC) under the Paris Agreement.

Some of the results of logging waste research have not been explicitly evaluated in terms of carbon estimates and potential CO_2 emissions (Sist et al., 2003b). Most studies still focus on emissions from felled tree waste (Pearson et al., 2014; Sasaki et al., 2016). Meanwhile, waste from stand damage is rarely included in carbon calculations (Pinard and Putz, 1996; Sist et al., 2003a). As a result, there is a gap in the assessment of actual carbon loss estimates, which combine felled tree waste and residual stand damage waste simultaneously. This results in carbon emissions from logging activities being reported lower than they actually are (Griscom et al., 2020). Logging waste and damaged trees increase carbon storage loss, which is then oxidized into CO_2 emissions (Shearman et al., 2012; Irland, 2011; Pearson et al., 2014; Damptey et al., 2021).

Logging waste releases emissions during the decomposition process, and in the short term functions as soil carbon formation through humification (Frolking et al., 2009). During decomposition, logging waste releases carbon in the form of carbon dioxide (CO_2) into the atmosphere as part of microbial respiration and the decomposition of dead wood tissue (Harmon et al., 1990; Keller, 2007). Thus, the presence of logging waste affects the balance between carbon sink sources and net carbon emission contributors (Baccini et al., 2012; Alice-Guier et al., 2020). Increased emissions contribute to an increase in global surface temperatures (Kabir et al., 2023). Conversely, RIL practices can reduce waste volume by up to 50% compared to conventional methods, while also reducing CO_2 emissions from damaged tree biomass (Putz et al., 2008). The volume and distribution of waste are largely determined by the harvesting system used.

This study investigates how logging residues and stand damage contribute to emissions and reduce carbon sink capacity, and how these processes ultimately affect the long-term sustainability of tropical natural forests. The findings are critical for improving reduced-impact logging (RIL) practices and for integrating carbon-conscious strategies in supporting the sustainability of tropical forest ecosystems.

Material and Methods

Study site

From a silvicultural and ecological perspective, Indonesia's natural forest stands can be classified into: primaty forests, logged-over area (LOA), and secondary forests, with a national average growth rate of approximately 2–3 m³/ha/year (Paul et al., 2015). Indonesia's forest cover area is 51.1%, or 95.5 million hectares, of the country's total land area of 187 million hectares (Indonesia Ministry of Forestry, 2024).

Data for this study were collected from a logged over area (LOA) in concession holder PT Kayu Tribuana Rama (PT KTR), located in Central Kalimantan Province, Indonesia. The study site is characterized by commercially high-value natural forests dominated by meranti tree species groups, including such as meranti merah (*Shorea leprosula* Miq.), nyatoh (*Palaquium* spp.), keruing (*Dipterocarpus elongatus* Korth.), kapur (*Dryobalanops oblongifolia* Dyer), resak (*Vatica* spp.), bangkirai (*Shorea laevis* Ridl.), and mersawa (*Anisoptera* spp.).

The PT KTR concession area is geographically situated at 01°13'01"–01°29'49" South latitude and 112°12'12"–112°36'43" East longitude (Figure 1). Based on the Köppen classification system (Köppen, 1884), the forest type within the KTR concession is classified as a fully humid equatorial rainforest. The topography of the research area ranges from gently sloping to moderately steep terrain. The study was conducted over a four-month period from September to December 2017. The methods used involved direct measurements and observations during and after logging operations.

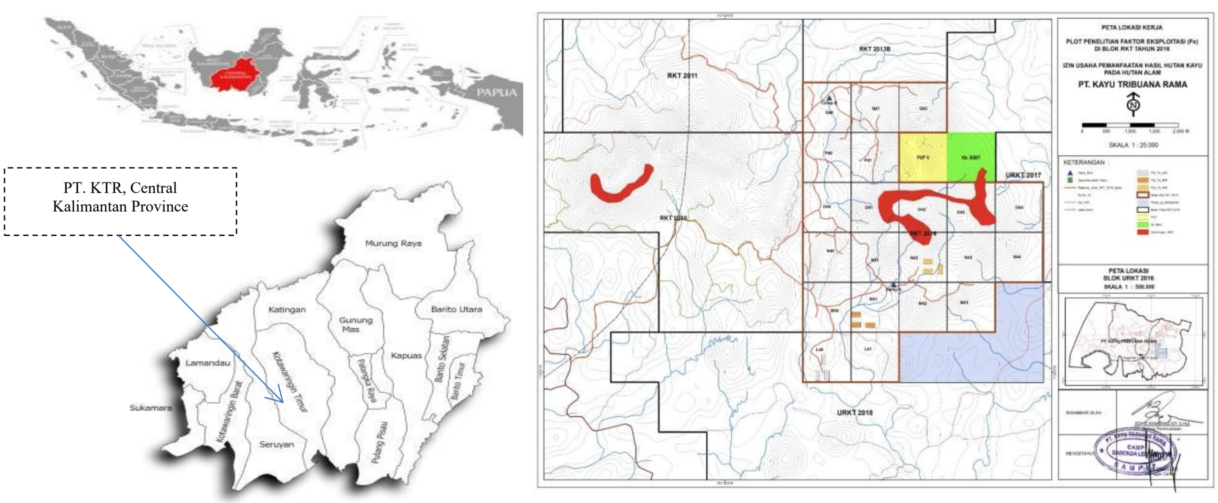

Figure-1. Location of the research site at PT Kayu Tribuana Rama, Central Kalimantan Province

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Forest management at this concession employs reduced-impact logging (RIL) techniques, which represent a potentially sustainable harvesting approach (Elias et al., 2001; Ruslandi et al., 2017). Over the past several decades, KTR has implemented a selective logging system based on Comprehensive Periodic Forest Inventory (IHMB), with a current cutting cycle of 10 years (Ministry of Environment and Forestry, 2019). Under this system, trees designated for felling are selected based on specific criteria, including size, quality, and commercial value, while allowing sufficient growing space for residual trees. The minimum annual production allowance is 76,342 m^3 $year^{-1}$.

The research on carbon implications of logging residues and stand damage under selective logging aimed to improve the accuracy of carbon accounting and support the sustainability of tropical forest ecosystems. The conceptual framework of this research is presented in Figure 2.

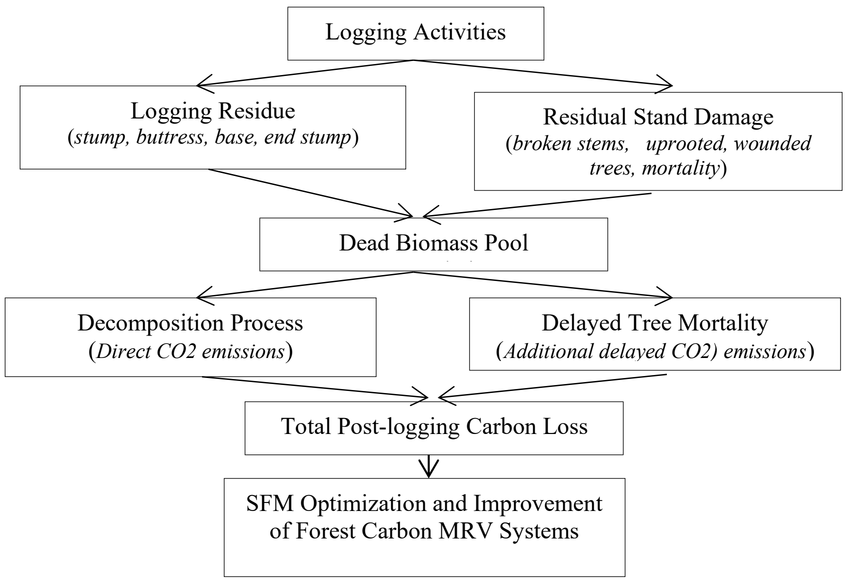

Figure-2. Conceptual research framework diagram.

Material and equipment

The materials used in this study comprised all tree species with a diameter at breast height (DBH) ≥20 cm recorded during the pre-logging inventory, tree labels, and marking paint. Measurement instruments included Global Positioning System (GPS) receivers, measuring tapes for plot delineation and log length measurement, phi bands for diameter measurement of felled trees, tally sheets and writing implements, tree distribution maps, clinometers for slope measurement, compasses, digital cameras for documentation, and machetes. Harvesting equipment consisted of a STIHL 70 chainsaw with a 6.5 HP engine and a Caterpillar G7 crawler tractor with a 175 HP engine.

Sample plot design and research procedure

This study was conducted in three felling compartments that were purposively selected and represented different topographical conditions, namely flat terrain (M41), gentle slopes (L40), and moderately steep slopes (N42). In each selected logging compartment, three observation plots were systematically established, each covering an area of 2 ha with a plot size of 200 m × 100 m. Within each plot, all trees with a DBH ≥20 cm were identified by species and measured for DBH. Plots were established using systematic sampling. The first plot was positioned purposively within the logging compartment, and subsequent plots were placed systematically at 100 m intervals, adjusted according to field conditions (Figure 2). Within each plot, all potential tree species with a DBH ≥20 cm were marked and identified to species level, and trees eligible for harvesting were determined. Individual tree positions were not recorded. The total number of potential trees in logging compartments L40, M41, and N42 are 56, 42, and 70 trees, respectively, of which 9, 10, and 13 trees have a diameter of 40 cm or more and therefore meet the criteria for harvesting as roundwood. The tree sampling method was carried out by chainsaw operators on selected trees, and the measurement and recording of logging residues, utilized wood, and residual stand damage was done by directly measuring the base and tip diameter, length, and assortment condition. Logging residues and residual stand damage measured have a diameter of ≥20 cm (Sist et al., 2003a), including wood damage types.

Data collection

The data collected in this study covers all logging residu consisting of felled tree waste, wood waste along skid trails, wood waste at landing points (TPn), and wood waste from damaged standing trees. Felled tree waste comprised stump residues, buttress remnants, basal segments, and apical segments up to the first branch height (clear bole) remaining after bucking of each felled tree. Logging residu was assessed as a potential source of forest carbon stock and CO_2 emissions. Utilized wood from logging plots is excluded from calculations of forest carbon stocks and CO_2 emission potential because it has been extracted out of the logging area.

Data analysis

Calculation of above-ground biomass of logging waste

Above-ground biomass (AGB) was calculated using the allometric equation developed by Chave et al. (2005):

$$\mathbf{AGB = 0.0509 \times \rho \times D^2 \times H} \qquad (1)$$

Where:
AGB = above-ground biomass (kg), ρ = represents wood specific gravity (g cm^{-3}), D = diameter at breast height (cm), and H = total tree height (m). The wood density value used in this study was 0.61 g cm^{-3} for logged-over forests, following the reference values reported by Hairiah et al. (2011).

Calculation of carbon stock

Carbon stock was calculated using the IPCC (2006) equation:

$$\mathbf{C_s = B \times 0.47} \qquad (2)$$

Where:
C = carbon stock (ton C. ha^{-1}), B represents total biomass (ton. ha^{-1}), and 0.47 = the carbon content conversion factor.

CO_2 equivalent calculation

CO_2 equivalent was calculated using the following equation:

$$\mathbf{CO_2eq = (44/12) \times C_s} \qquad (3)$$

Where:
CO_2eq is the standardized measure of climate effects expressed in t CO_2eq, the factor 44/12 represents the ratio of molecular weight of CO_2 to carbon, and C_s denotes the calculated carbon stock (t C ha^{-1}).

Residual stand damage calculation

Residual stand damage (RSD) was calculated using the following formula (Matangaran et al., 2019):

$$\mathbf{RSD\ (\%) = [c / (a - b)] \times 100\%} \qquad (4)$$

Where:
RSD = the percentage of residual stand damage (%), *a* = stand density (trees ha^{-1}), *b* = felling intensity or the number of felled trees (trees ha^{-1}), and *c* = the number of damaged trees (trees ha^{-1}). The degree of residual stand damage was classified based on the following parameters (Elias, 2008): (1) damage less than 25%: mild damage; (2) damage between 25% and 50%: moderate damage; and (3) damage exceeding 50%: severe damage.

Statistical analysis

Statistical analyses were performed using appropriate procedures for treatment comparisons. Mean differences were evaluated using the Least Significant Difference (LSD) test at $p < 0.05$. Results are presented as mean ± standard deviation (SD).

Abbreviations

CO_2	=	carbon dioxide
RIL	=	reduce impact logging
PT	=	limited liability company
SFM	=	sustainable forest management
DBH	=	diameter at breast height

IHMB	=	comprehensive periodic forest inventory
GPS	=	global positioning system
L40, M41, N42	=	name of felling compartments
HP	=	horse power
TPn	=	landing points
AGB	=	above-ground biomass
ρ	=	wood specific gravity
H	=	total tree height
C	=	carbon stock
B	=	biomass
RSD	=	residual stand damage
LSD	=	least significant difference test
MRV	=	measurement, reporting, and verification.

Results and Discussion

Pre-logging assessment
Forest stand potential

The results of stand potential assessment based on clear bole volume before logging operations is presented in Table 1. The diameter distribution was dominated by the 20–39 cm diameter class, predominantly consisting of the meranti group (*Shorea* spp.), while trees meeting harvest criteria (≥40 cm diameter) are relatively scarce. In felling compartement of M41, L40, and N42, the density of trees with diameters ≥20 cm was 63, 49, and 83 trees ha^{-1}, respectively (Table 1). Among these, trees with diameters ≥40 cm eligible for harvesting averaged 8 trees ha^{-1} with a mean volume of 5.009 $m^3.tree^{-1}$. Specifically, cutting blocks M41, L40, and N42 contained 7, 7, and 10 $trees.ha^{-1}$ with mean volumes of 4.328, 5.907, and 5.062 $m^3.tree^{-1}$, respectively. This potential was considerably lower than that reported in previous studies conducted in five concession areas in Central Kalimantan 5.561 $m^3.tree^{-1}$ (Soenarno et al., 2021) and East Kalimantan 9.923 $m^3.tree^{-1}$ (Soenarno et al., 2016).

Table-1. Potential forest stands before logging operations.

Felling Compartment	Tree Species Group	Ø 20-39 cm		Ø > 40 cm		Total Ø > 20 cm	
		Density ($trees.ha^{-1}$)	Volume ($m^3.tree^{-1}$)	Density ($trees.ha^{-1}$)	Volume ($m^3.tree^{-1}$)	Density ($trees.ha^{-1}$)	Volume ($m^3.tree^{-1}$)
M41	Protected wood groups	4	0.589	1	0.512	5	1.101
	Meranti wood groups	41	0.492	5	6.868	46	7.36
	Mixed dipterocarp wood groups	11	0.677	2	2.083	13	2.76
	Fancy wood groups	1	0.525	1	0.688	2	1.213
	Sub Total	56	0.571	9	2.538	65	3.109
lL40	Protected wood groups	1	0.570	3	2.513	4	3.083
	Meranti wood groups	34	0.615	6	6.695	40	7.31
	Mixed dipterocarp wood groups	8	0.663	2	3.632	10	4.295
	Fancy wood groups	-	-	-	-	-	-
	Sub Total	42	0.616	10	4.280	53	4.896
N42	Protected wood groups	1	1.002	1	2.463	2	3.465
	Meranti wood groups	60	0.65	9	6.092	69	6.742
	Mixed dipterocarp wood groups	7	0.672	2	4.632	9	5.304
	Fancy wood groups	2	0.613	1	1.748	3	2.361
	Sub Total	70	0.734	13	3.734	83	4.468
	Grand Mean	56	0.640	11	3.517	67	4.158

The distribution of tree density and stand volume by diameter class before harvesting is illustrated in Figure 2. The figure demonstrates that trees in the ≥40 cm diameter class exhibited lower stand volume compared to other diameter classes, despite their relatively low density. This pattern is consistent with the well-established inverse relationship between diameter class and tree density (Istomo and Dwisutono, 2016). Larger diameter trees indicate greater age and consequently store more carbon than younger trees (Istomo and Farida, 2017). The potential carbon stock converted from biomass is strongly influenced by tree diameter (Kasianus et al., 2018). In normal forest types, stand density is typically very high; therefore, when large-diameter trees are lost through harvesting, damage, or mortality, the forest structure and composition are naturally replaced by trees from smaller diameter classes, enabling natural regeneration that ensures forest sustainability (Suwardi et al., 2013).

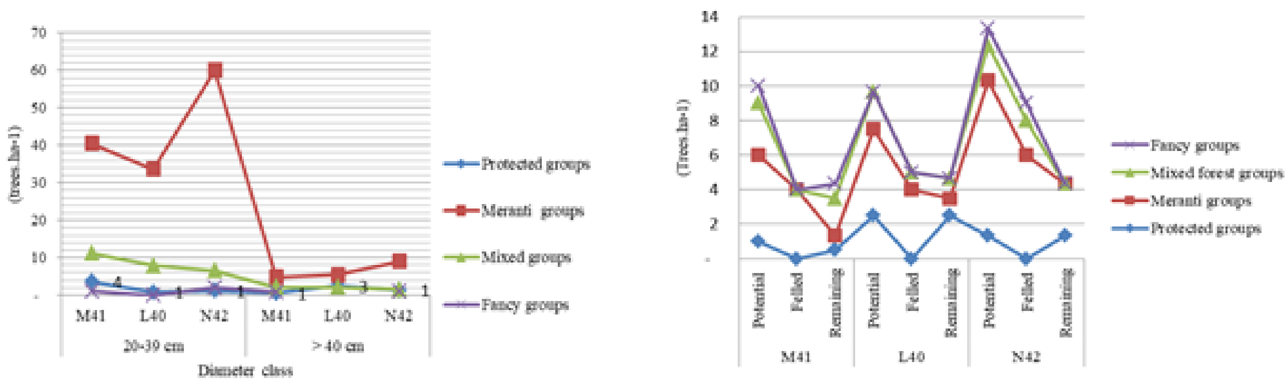

Figure-2. Distribution of potential stands prior to logging by felling compartment.

Carbon stock and CO_2 emission potential before to logging

The calculation of carbon stock and CO_2 emission potential before logging in felling compartments M41, L40, and N42, as presented in Table 2, revealed values ranging from 26.540 to 44.078-ton C. ha^{-1} (97.296–161.590 ton CO_2 eq.ha^{-1}), with an average of 40.897-ton C. ha^{-1} or 149.928 ton CO_2eq. ha^{-1}.

Table-2. Carbon stocks and CO_2 emission potential before logging.

Felling Compartment	Tree Species Group	Ø 20-39 cm		Ø > 40 cm		Total Ø > 20 cm	
		Carbon Stock (ton C.ha^{-1})	CO_2 Emissions (ton CO_2 eq.ha^{-1})	Carbon Stock (ton C.ha^{-1})	CO_2 Emissions (ton CO_2 eq.ha^{-1})	Carbon Stock (ton C.ha^{-1})	CO_2 Emissions (ton CO_2 eq.ha^{-1})
L40	Protected wood	1.107	4.058	0.241	0.884	1.348	4.942
	Meranti wood	9.484	34.768	9.683	35.498	19.167	70.266
	Mixed wood	3.498	12.824	1.958	7.178	5.456	20.002
	Fancy wood	0.247	0.906	0.323	1.184	0.570	2.090
	Sub Total	14.335	52.552	12.205	44.744	26.540	97.296
M41	Protected wood	0.268	0.982	2.363	8.663	2.631	9.645
	Meranti wood	9.836	36.059	12.588	46.148	22.424	82.206
	Mixed dipterocarp	2.492	9.136	1.707	6.258	4.199	15.394
	Fancy wood	0	0.000	0	0.000	0	0.000
	Sub Total	12.596	46.177	16.657	61.065	29.253	107.241
N42	Protected wood	0.471	1.727	2.315	8.487	2.786	10.213
	Meranti wood	18.325	67.179	17.18	62.982	35.505	130.161
	Mixed dipterocarps	2.212	8.109	2.177	7.981	4.389	16.090
	Fancy wood	0.577	2.115	0.822	3.013	1.399	5.129
	Sub Total	21.585	79.131	22.493	82.459	44.078	161.590
Grand Mean		24.241	41.767	16.656	61.061	40.897	149.928

Post-logging assessment

Carbon biomass stock and CO_2 emission potential from logging residues

Logging activity can impact much larger forest areas through canopy clearing, soil disturbance, logging waste, and residual stand damage. Research in tropical forests shows that for every tree harvested, approximately 10–20 core trees are severely damaged, resulting in significant reductions in carbon stocks and ecosystem disruption (Asner et al., 2005). Furthermore, it reduces the forest's carbon-storing capacity. Consequently, the cumulative impacts of selective logging can persist for decades and impact the long-term sustainability of tropical forest ecosystems (Putz et al., 2008). Based on field observations show that not all trees with a diameter of 40 cm or more were felled. This was based on various considerations, such as defects, trees deemed not to meet the size and quality requirements for roundwood production, the risk of breakage, and the inability to transport them to the landing point. All protected wood species were not felled, but for the Meranti species groups, some still remained in felling compartment M41, L40, and N42, at 20%, 20%, and 33%, respectively. However, for the mixed wood group, the M41 logging plot was still intact and had not been logged (100%), while 50% of the L40 plot had been logged. All groups of fancy wood species in plots L40 and N42 have been felled, except in M41 they have not been cut down. A diagram showing the trees that have been cut down and those that remain is presented in Figures 3a and 3b.

The measurement of potential carbon biomass stock and CO_2 emissions from logging residues is presented in Table 3.

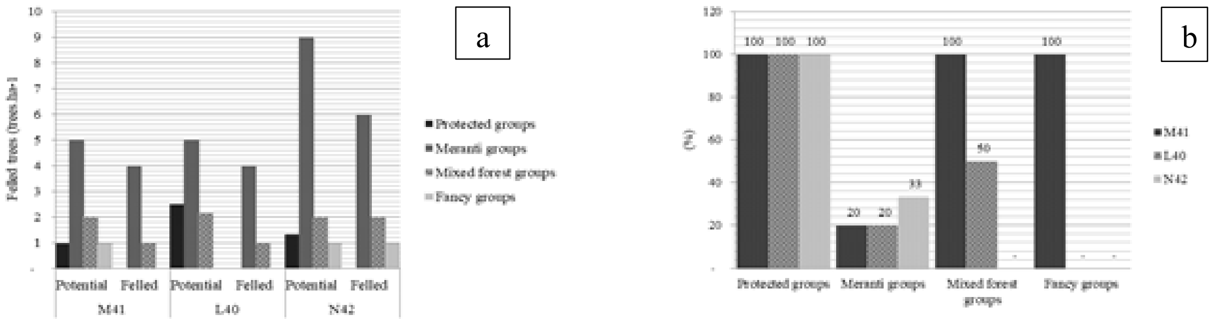

Figure-3. a: Tree felling based on felling location and tree species group; **b:** Percentage of residual stand remaining after logging (%).

Table-3. Carbon stocks and CO_2 emissions from logging residues with a diameter of 20 cm or more.

Felling Compartment	Plots	Logging Intensity (Trees ha^{-1})	Diameter of Felled Trees (cm)	Buttress Heigh (cm)	Felling Heigh (cm)	Carbon Stock of Felled Trees (ton C ha^{-1})	Logging Residue: Carbon Stock (ton C ha^{-1})	Logging Residue: CO_2 Emissions l (tonCO_2 eq. ha^{-1})	Logging efficiency indexes (%)
M41	1	4	65.3	76.6	44.6	7.816	1.524	5.589	80.5
	2	4	56.0	51.8	42.7	5.951	1.575	5.774	73.5
	3	4	56.7	85.3	45.1	6.046	1.891	6.933	68.7
	Mean	4	59.3	71.2	44.1	6.604	1.664	6.099	74.8
L40	1	3	54.2	165.0	90.0	4.545	1.246	4.568	72.6
	2	7	56.6	86.9	72.5	12.703	2.143	7.857	83.1
	3	4	65.8	96.5	91.2	6.382	2.720	9.972	57.4
	Mean	5	58.9	116.1	84.6	7.877	2.036	7.466	74.1
N42	1	7	84.8	131.8	72.6	35.451	2.716	9.956	76.5
	2	10	80.0	138.7	67.9	109.884	3.453	12.659	78.3
	3	9	72.3	144.5	62.5	31.178	1.405	5.151	95.5
	Mean	9	79.0	138.3	67.7	58.838	2.525	9.255	78.7
Grand Mean		0	65.7	108.6	65.5	24.440	2.075	7.607	75.9

The results indicate that the mean carbon stock of logging residues was 2.075 ton C.ha^{-1}, distributed across felling compartments M41, L40, and N42 at mean values of 1.664, 2.036, and 2.525 ton C. ha^{-1}, respectively. The CO_2 emission potential in felling compartments M41, L40, and N42 was 6.099, 7.466, and 9.255 ton CO_2eq.ha^{-1}, respectively, with a grand mean of 7.607 t CO_2eq.ha^{-1}. From a technical perspective, the logging index serves as an indicator of timber harvesting efficiency; a higher logging index corresponds to greater timber utilization efficiency (Soenarno et al., 2021). However, from an ecological standpoint, an elevated logging index implies greater loss of timber population potential, which consequently leads to increased residual stand damage and ecosystem disturbance, thereby undermining forest sustainability. In this context, selective logging represents a priority solution for a harvesting scheme that supports forest conservation efforts.

The LSD test results presented in Table 4 reveal that the carbon stock and CO_2 emission potential in felling compartment N42 were the highest compared to compartments M41 and L40. A statistically significant difference in carbon stock from felling residues was observed between compartments M41 and N42; however, no significant differences were detected between compartment felling areas M41 and L40, nor between L40 and N42.

Table-4. LSD test results for carbon stock of logging residues.
Dependent Variable: Carbon Stock.

(I) Felling Compartment	(J) Felling Compartment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
L40	M41	.2560	1.71130	.886	-3.9314	4.4434
	N42	-3.9480	1.71130	.061	-8.1354	.2394
M41	L40	-.2560	1.71130	.886	-4.4434	3.9314
	N42	-4.2040*	1.71130	.049	-8.3914	-.0166
N42	L40	3.9480	1.71130	.061	-.2394	8.1354
	M41	4.2040*	1.71130	.049	.0166	8.3914

***.** The mean difference is significant at the 0.05 level.

Field observations indicate that the proportional composition of logging waste types varied among felling compartments, encompassing stump, buttress, base, and ends waste represent at Figure 3. Figure 3 generally illustrates that larger diameter classes tend to produce proportionally greater volumes of ends waste.

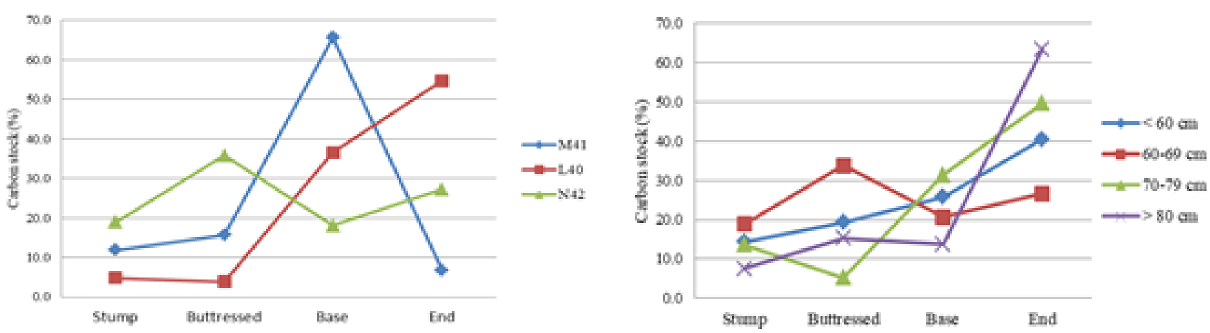

Figure-3. Percentage of logging waste carbon stock after logging.

The observed differences in waste composition among felling compartments are strongly attributed to variations in tree diameter, buttress height, and felling height. The proportional distribution of logging waste types is presented schematically in Figure 3. In compartment M41, basal segment waste accounted the largest proportion (65.6%); in compartment L40, end waste dominated (54.7%); while in compartment N42, buttress waste accounted for the highest proportion (35.8%).

The correlation test results represent carbon stock and tree diameter, buttressed and felling height represent in Table 5.

Table-5. Pearson correlation analysis of carbon stock from felling waste.

Variables	Carbon Stock	Tree Diameter	Buttress Height	Felling Height
Carbon Stock	1	0.826**	0.353	0.141
Sig. (2-tailed)	—	0.006	0.351	0.717
N	9	9	9	9
Tree Diameter	0.826**	1	0.425	0.133
Sig. (2-tailed)	0.006	—	0.254	0.734
N	9	9	9	9
Buttress Height	0.353	0.425	1	0.625
Sig. (2-tailed)	0.351	0.254	—	0.072
N	9	9	9	9
Felling Height	0.141	0.133	0.625	1
Sig. (2-tailed)	0.717	0.734	0.072	—
N	9	9	9	9

** Correlation is significant at the 0.01 level (2-tailed).

The correlation test results in Table 5 show that there is a very strong correlation between carbon stock (sig.=006) and tree diameter. However, there is no significant correlation between height and felling height with carbon stock. In plot M41, chainsaw operators were very careful in dividing the trunk when cutting the ends of felled trees, whereas in plot L40, they were less careful and did not pay attention to the diameter. In the case of plot L40, as a result, during grading measurements at TPn, many cuts were made because the diameter of the stem ends did not meet the requirements. In felling compartment N42, the cutting process at TPn was mainly due to wood defects (slight bending and knots). If assessed solely based on the remaining cutting parameters at TPn, the cutting in plot L40 appears to be better, but the amount of wood waste produced in that cutting plot is certainly greater than in felling compartments N42 and M41. This is reflected in the logging efficiency calculation results, where the lowest logging index was found in plot L-40, followed by plot N-42, and the highest in plot M-41 (see Table 3).

Carbon biomass stock and CO_2 emissions from residual stand damage with a diameter of 20 cm or more

The measured residual stand damage (RSD) resulting from logging operations (felling and skidding) is presented in Table 6. The degree of RSD across felling compartment was relatively uniform, ranging from 30.8% to 31.7%, which is classified as a moderate damage category (Elias, 2008). Table 6 indicates that the felling of one tree resulted in damage to approximately three residual trees. These values are higher than the RSD of 21.1% reported for logging operations in Penobscot County, central Maine, USA (Tavankar and Bodaghi, 2011), and comparable to conventional harvesting damage rates ranging from 33.15% to 38.1% documented in previous studies (Muhdi et al., 2016). Research conducted in the Nav watershed, Hyrcanian forests, Northern Iran, demonstrated that tree-length logging methods resulted in an RSD of 22.7% (Budiaman and Rahayu, 2023). In contrast, a study in the Chafroud forest of Northern Iran on slopes ranging from 20% to 60% found that each felled tree caused damage to approximately 10 residual trees (Behjou and Mollabashi, 2012).

Further research revealed that the rate of forest land damage caused by skidding operations in the N42 logging area was significantly higher than that caused by logging operations (see Figure 4a and 4b).

Table-6. Carbon stocks and CO_2 emissions from RSD with a diameter 20 cm or more.

Felling Compartment	Plots	Potential Stands (trees.ha-^{1})	Logging Intensity (trees.ha-^{1})	Residual Stand Damage (RSD) Number of RSD (trees.ha^{-1})	Carbon stock (ton C .ha-1)	Emission (ton CO_2 eq.ha^{-1})	Degree of RSD (%)
M41	1	44	4	8	0.580	2.128	19.8
	2	39	4	14	0.578	2.118	40.0
	3	42	4	14	0.308	1.129	36.8
	Mean	42	4	12	0.489	1.792	30.8
L40	1	44	3	9	0.582	2.135	22.0
	2	61	7	22	0.935	3.428	41.1
	3	54	4	15	1.206	4.420	30.3
	Mean	53	5	15	0.908	3.328	31.7
N42	1	78	7	22	1.798	6.591	30.8
	2	76	10	21	1.697	6.222	32.1
	3	51	9	11	0.815	2.989	26.5
	Mean	68	9	18	1.437	5.267	27.5
Grand Mean		54	6	15	0.944	3.462	33.6

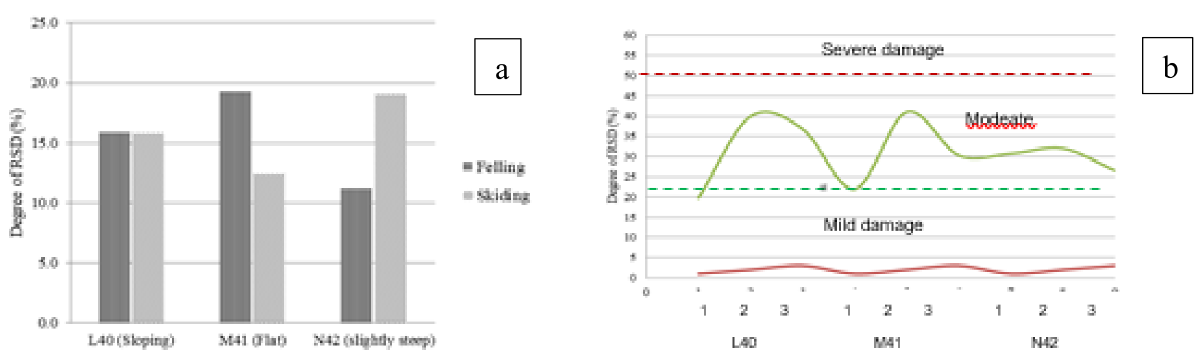

Figure-4. a: Proportion of RSD degrees by felling and skidding; **b:** Level of severity of standing tree damage.

This finding is due to the relatively steep terrain in block N42, which affects the layout of the skidding road network, requiring tractors to make more frequent turns to reach the trees to be skidded. Research conducted in natural forests of South Papua demonstrated that the RSD rate reached 22.9%, of which 13.0% caused by felling operations and 9.9% caused by skidding operations (Yuniawati and Dulsalam, 2020).

Distribution of logging impact on carbon stock and CO_2 emission potential

Based on the data presented in Tables 3 and 6, the total carbon stock and CO_2 emissions were calculated and are presented in Table 7.

https://doi.org/10.35495/ajab.2026.072

Table-7. Total carbon stock and CO_2 emission potential following logging.

Felling Compartment	Plots	Tree Diameter	Logging Intensity	Potential Wood	Total Carbon Stock	Total Emission	Percentage of Total Logging Impact	
							Logging Residue	Logging Stand Damage
		(cm)	(Trees. ha^{-1})	(m^3.ha^{-1})	(ton C.ha^{-1})	(ton CO_2_eq ha^{-1})	(%)	(%)
L40	1	65.3	4	16.630	2.855	10.468	12.3	7.4
	2	56.0	4	12.661	2.979	10.921	17.1	22.9
	3	56.7	5	12.863	2.850	10.448	21.1	15.8
	Mean	59.3	4	14.052	2.894	10.611	15.9	15.0
M41	1	54.2	3	9.671	2.183	8.003	9.8	12.2
	2	56.6	7	27.027	4.544	16.657	20.6	20.6
	3	65.8	4	13.579	3.845	14.095	26.3	4.0
	Mean	58.9	5	16.759	3.524	12.917	19.3	12.4
N42	1	84.8	7	75.428	10.158	37.240	9.8	21.0
	2	80.0	10	233.796	10.962	40.186	13.7	18.3
	3	72.3	9	66.335	2.761	10.121	9.6	16.9
	Mean	79.0	9	125.187	7.960	29.182	11.7	15.8
Grand Mean		65.7	6	51.999	4.804	17.612	15.4	18.2

Table 7 demonstrates that the total post-harvest carbon stock loss and CO_2 emission potential was 4.804 ton CO_2 ha^{-1} and 17.612 ton CO_2 eq. ha^{-1}, respectively, comprising 15.4% from logging residues and 18.2% from residual stand damage. These findings indicate that CO_2 emission estimates based solely on logging residues are inadequate and tend to substantially underestimate the actual total emission potential. Research conducted in Berau Regency, East Kalimantan, Indonesia, similarly reported biomass losses ranging from 2.42 to 5.15 Mg ha^{-1}, with carbon emissions during land clearing of 18.93 Mg CO_2 eq. ha^{-1} (Yuniawati and Tampubolon, 2021). The CO_2 emission potential observed in this study was higher than that reported for natural forests in Boven Digul Regency, South Papua 9.43 Mg CO_2_eq.ha^{-1} (Yuniawati et al., 2022), but lower than CO_2 emissions from logging residue decomposition in the Paragominas region of Pará State, Brazil, which ranged from 20.90 to 41.60 Mg CO_2 eq. ha^{-1} depending on harvesting intensity (Numazawa et al., 2017).

This is because the emission potential in Papua is only calculated from logging residues, while in Brazil it is lower, presumably due to the lower logging intensity at PT KTR, which ranges from 14 to 25 trees per hectare. Furthermore, it is stated that based on simulations of biomass regrowth, it will take approximately 38.3 years if the logging intensity is 30 m^3.ha^{-1} and 18.2 years if the logging intensity is 15 m^3.ha^{-1}. However, stand population growth has a relatively small impact on CO_2 emission levels (Lawal, 2019). The greatest emissions reductions derive from (i) not felling trees that will be left in the forest due to commercial defects, and (ii) use of long-line cable winching to avoid bulldozers (Griscom et al., 2019). In fact, the impact of selective logging causes a significant loss of carbon biomass, reaching 80.94 tons C.ha^{-1}.year^{-1} and CO_2 emissions released into the atmosphere amounting to 297.02 tons CO_2.eq. ha^{-1}. year^{-1} (Junaedi, 2014).

According to several studies, the results of logging efficiency studies are not significantly different from those conducted in the tropical forests of Sumatra, Kalimantan, and Papua, ranging from 15.3% to 25% (Matangaran et al., 2013; Soenarno et al., 2016; Soenarno et al., 2021; Soenarno et al., 2025). Meanwhile, research on logging waste emissions has not been extensively conducted in Indonesia's tropical forests, except for an estimate of the potential carbon stock in industrial plantations at 4.89 tons/ha (Yuniawati and Tampubolon, 2021). The study results indicate emissions in RIL of 30.03 tons of CO_2/ha; however, this emission potential represents the emission factor of standing stock following logging in Central Kalimantan (Dharmawan and Ridwan, 2022). The finding that 15.4% of emissions originated come from logging residues and 18.2% from residual stand damage (RSD) demonstrates that current selective logging practices continue to generate significant sources of carbon emissions. Consequently, the optimization of logging practices should focus on simultaneously reducing both logging residues and RSD, rather than solely improving logging efficiency. From a technical standpoint, this can be done through stricter regulation of felling intensity, enhanced accuracy of directional felling techniques, and more precise planning and arrangement of skid trails to minimize residual stand damage. Furthermore, the logging efficiency index, which currently ranges from 74.8% to 78.7%, indicates opportunities for improvement in operator skills, stricter field supervision, and the implementation of operational standards based on actual after logging damage assessments. These efforts are of essential important to reduce the degree of residual stand damage, which is currently still in the moderate category and has the potential to impede long-term carbon stock recovery. From a policy perspective, the results of this study affirm that carbon accounting and reporting after logging in natural production forests cannot be adequately based solely on logging residues but must integrate the contribution of residual stand damage as an equally important emission source. Therefore, the forestry carbon Measurement, Reporting, and Verification (MRV) framework requires updating to incorporate quantitative RSD indicators as a mandatory component in post-harvesting emission estimation. This integration will enhance the accuracy of carbon reporting, strengthen the credibility of emission reduction claims in the forestry sector, and support the achievement of emission reduction targets while reinforcing the function of natural production forests as long-term carbon stores and stocks. Moreover, performance-based incentive policies, such as the recognition of harvesting efficiency and low RSD levels, can promote the adoption of more responsible and sustainable logging practices.

Therefore, it is strongly recommended to improve the MRV system by integrating logging plot data with high-resolution satellite imagery, as well as utilizing LiDAR, drones, and radar imagery to monitor changes in forest cover. Meanwhile, to support REDD+ and the carbon market as well as sustainable management, measures include: 1) mandating digital recording of RIL activities in all PBPNH concessions, and 2) implementing a combination of RIL-C activities, digital MRV, and periodic satellite monitoring to enhance the credibility of REDD+, attract market investment, and strengthen the implementation of Sustainable Forest Management (SFM).

Conclusions

The natural tropical forests in the concession area of PT Kayu Tribuana Rama (PT KTR) have the most important biodiversity as carbon storage and sequestration, and provide various important ecosystem functions for sustainable timber production. RIL practices in selective logging systems leave logging residues and residual stand damage, which can reduce the forest's ability to recover and function as a carbon sink and sequester. Logging residues and residual stand damage in logging plots with steep topography (N42) are greater than those with flat topography (L40) or level topography (M41). The total potential carbon stock and CO_2 emissions after logging amounted to 4,804 tons $C.ha^{-1}$ or 17,612 tons CO_2_eq, ha^{-1}. The amount of CO2 emissions compared to the total potential carbon stock was 15.4% in the form of logging residues and 18.2% in the form of residual stand damage. There is a highly significant relationship between carbon stock and potential CO_2 emissions with tree diameter. Logging efficiency ranges from 74.8-78.7% with an average of 75.9%, and the level of stand damage ranges from 27.5-37.1% with an average of 33.6%, which is classified as moderate. To optimize RIL practices in selective logging, more accurate technical improvements are needed, along with compliance with the implementation of proper RIL rules and well-controlled monitoring policies. It is considered necessary to improve the Measurement, Reporting, and Verification (MRV) framework for forest carbon by including quantitative indicators of logging residue and residual stand damage as mandatory components in post-logging emission estimates. The research has limitations only from aboveground biomass, and has not included belowground biomass and litter as well as the economic value of carbon, due to data unavailability.

Recommendations

The management of natural production forests in selective logging systems using RIL techniques should focus more on sustainable environmental aspects through stricter control of logging intensity, improved accuracy of directional logging techniques, and more precise planning of logging routes accompanied by appropriate controlled monitoring. For sustainable forest management, it is necessary to include quantitative indicators of logging residue and residual stand damage as mandatory components in carbon stock and carbon emission estimates as performance-based policy indicators, such as environmental service payments and carbon credit mechanisms. Moreover, future research should focus on assessing economic losses and comprehensively evaluating biodiversity and other forest ecosystem services to enhance the competitiveness of forest conservation relative to traditional forest management that relies solely on log production.

Acknowledgement

The author would also like to thank the management of PT Kayu Tribuana Rama for financial support and assistance with field technical personnel through a research collaboration scheme.

Disclaimer: None.

Conflicts of Interest: None.

Source of Funding: This study was carried out with the support of the Research Center for Ecology, National Research and Innovation Agency, Republic of Indonesia. The author would also like to thank the management of PT Kayu Tribuana Rama for financial support and assistance with field technical personnel through a research collaboration scheme.

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Soenarno, Yuniawati & Suhartana S: Investigation and data curation.
Soenarno: Writing—original draft preparation.
Oryzanti P, Susila IWW, Utomo PM, Effendi R, Andini S, Waluyo TK & Rochmayanto Y: Writing-review and editing.
Siswadi, Wardani M, Abdulah L & Heriansyah I: Visualization

All authors have had an equal role as the main contributor who equally discussed the conceptual methodology, validation, formal analysis, draft preparation and provided critical feedback for writing-review and editing the manuscript. All authors have read and approved the final draft of the manuscript.

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