**BIODIVERSITAS**
Volume 26, Number 5, May 2025
Pages: 2148-2156

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d260513

# Residual stand damage caused by logging operations in secondary forest in Berau District, East Kalimantan, Indonesia

**YOSEP RUSLIM♥, DIAH RAKHMAH SARI, ROCHADI KRISTININGRUM, EMI PURWANTI, WIDIA SRI UTAMI, SLAMET ASHARI, FENTY LEONIKA**

Faculty of Forestry and Tropical Environment, Universitas Mulawarman. Jl. Penajam, Kampus Gunung Kelua, Samarinda 75123, East Kalimantan, Indonesia. Tel.: +62-541-735089, Fax.: +62-541-735379, ♥email: yruslim@gmail.com; yruslim@fahutan.unmul.ac.id

Manuscript received: 7 February 2025 2025. Revision accepted: 1 May 2025.

**Abstract.** *Ruslim Y, Sari DR, Kristiningrum R, Purwanti E, Utami WS, Ashari S, Leonika F. 2025. Residual stand damage caused by logging operations in secondary forest in Berau District, East Kalimantan, Indonesia. Biodiversitas 26: 2148-2156.* In Indonesia, selective logging now mainly occurs on logged-over forests following the second rotation. Yet, information is lacking on the impacts of logging operation in these secondary forests. This study aims to determine the impacts of logging operations, particularly tree felling and log skidding, on residual stands in secondary forest and to see the relationship between felling intensity and stand damage and forest opening. This study was conducted in a logging concession in Berau District, East Kalimantan Province, Indonesia. To determine changes in stand structure before and after harvesting, 6 plots of 100x100 m were established. After felling and skidding, an inventory was conducted to record the number of damaged trees and the type of damage. The result revealed that with harvesting intensity averaged 11 trees per hectare, it caused residual stand damage due to felling and skidding of 17.85% and 16.62%, respectively. The most common type of damage after tree felling was broken trees, with an average of 19 trees ha$^{-1}$, and the main damage during the skidding process was collapsed/tilted trees, with an average of 28 trees ha$^{-1}$. In addition, it was found that the average opening of skid roads after the harvesting process was 13.26%. We suggest mitigation strategies including planning the skid road before harvesting, opening the skid road before felling, limiting the number of trees felled per hectare, implementing directional felling, and extending the maximum winching.

**Keywords:** Felling intensity, forest opening, logged-over forest, skid road, stand damage

## INTRODUCTION

Tropical rainforests represent a significant ecological system on the Earth. After Brazil, Indonesia possesses the second-largest area of tropical forest in the world. The country's landscape is characterized by a variety of biomes, including rich mangrove forests along the shorelines, lowland tropical rainforests, mountain forests in inland Sumatra, Sulawesi, and Borneo, and subalpine and alpine vegetation in Papua (Tsujino et al. 2016). However, since the 1970s Indonesian tropical forests have been continuously pressured as there has been a significant decrease in forest coverage, with the area of forest decreasing from 87% to 50% of the total land area (Dwiyahreni et al. 2021). To slow down deforestation and forest degradation, there has been substantial advancement in Indonesia's forest policies and governance to oversee and manage the land designated for forestry and conservation purposes, often called *Kawasan Hutan* or State Forest Areas which encompass 120 million hectares. One of the strategies is through the establishment of *Kesatuan Pengelolaan Hutan (KPH)* or Forest Management Units (FMUs) which implement sustainable forest management using the principles of landscape approach. They are expected to engender a reduction in deforestation and forest degradation through improved forest planning and oversight, the establishment of open access avoidance strategies, and the enhancement of fire mitigation and response measures (Chervier et al. 2025).

The dynamics of forest succession are initiated by a disturbance event, which can be categorized as either natural or human caused. Examples of natural disturbances include tree falls and landslides, whereas human-caused disturbances may involve anthropogenic activities, such as selective logging and swidden agriculture. After the disturbance, plants typically colonize the gap in the forest (Mottl et al. 2019). In the context of selective logging, the disruptions caused by timber harvesting operations in tropical rainforest have been demonstrated to have a detrimental effect on the structure of residual vegetation and its floral diversity. In Indonesia, a study by Purwoko et al. (2018) investigated the effects of logging which reduced vegetation diversity and caused residual stand damage. Research conducted in Brazil has shown a change in the natural regeneration of flora due to the impact of logging operations (Bezerra et al. 2021). In addition, the consequences of these activities extend beyond the impact on vegetation, encompassing the detrimental effects on fauna and soil (Wirnoyo et al. 2022; Gunawan et al. 2024). The use of heavy machinery in timber harvesting, as well as its subsequent transportation, contributes to soil compaction (Ruslim et al. 2016; Matangaran et al. 2019a). Furthermore, the decrease in number of trees, resulting from the harvesting of timber in conjunction with the damage to residual vegetation, leads to alterations in forest carbon storage (Saimun et al. 2021; Condè et al. 2022; Dangwal et al. 2022).

Selective logging, also known in Indonesia as *Tebang Pilih Tanam Indonesia (TPTI)*, has been observed to have a considerable detrimental impact on vegetation. Selective logging in natural forests typically comprises several stages, including forest inventory and planning, road construction, timber felling and skidding, and transportation of logs. The execution of these practices invariably entails a certain degree of disturbances (Matangaran et al. 2022). Logging practices have been shown to have a significant impact on forest canopy, including removal of canopy, creation of open space, and destruction of vegetation around the harvested trees or residual stands (Winstanley et al. 2024). Residual stand damage is primarily caused by timber cutting, log skidding, and the tools used during skidding (Ruslim et al. 2016), although this is highly dependent to the density of logging operations (Matangaran et al. 2019b). Furthermore, there is additional damage to soil as a result of the use of heavy machinery during log extraction.

Reduced Impact Logging (RIL) is a series of improved timber harvesting techniques of selective logging in natural forests. It is of particular interest given its relatively low cost and numerous potential environmental benefits (Ellis et al. 2019). For example, in conventional logging practice, bulldozer is commonly used when moving logs from cutting site which might open up the forest, disturb natural vegetation, degraded the quality of remaining stands and soil (Ruslim et al. 2016; Matangaran et al. 2019a, b). On the other hand, RIL might use mono-cable method to minimize the impact of moving logs. For example, in a timber concession in natural forest in East Kalimantan mono-cable winches with 20 hp and 26 hp engines equipped with 100 m sling cables resulted in very little damage to the standing residue and soil compared to bulldozers (Ruslim 2011, et al. 2016).

As primary forests in Indonesia depleted, many selective logging concessions now occur on secondary forests which were previously logged following the extension of company's license. In this context, research is needed to understand the impacts of timber harvesting on residual stands on logged-over forests after the second rotation. Despite the numerous studies on the impacts of logging and skidding on forest stand damage, there is limited knowledge of such practices on secondary which harvesting trees with diameter greater than 40 cm and above. This is particularly evident in the context of tropical forests in Kalimantan where most of logging concessions are now occupying secondary forests. Therefore, this study aims to analyze vegetation diversity, and stand damage after timber harvesting in secondary forest in Berau District, East Kalimantan Province. Specifically, this study focused on stand damage at the tree level and the relationship between harvest intensity, forest openings, and stand damage. It is expected that the present study will provide a valuable guideline for forest operations to reduce stand damage due to harvesting activities in logged forests.

## MATERIALS AND METHODS

### Study area

This study was conducted in the area of Forest Utilization Business Permit in natural forest (PBPH-HA) of PT Sumalindo Lestari Jaya IV (SLJ IV). PT SLJ IV is administratively located in Segah Subdistrict, Berau District, East Kalimantan, Indonesia. Geographically, the concession area of PT SLJ IV is located between 02°04'00"-02°21'00" N and 116°30'00"-117°00'00" E. The forest area is included in the Segah River and Uwau River forest groups. Based on the map of Forest Areas and Waters of East Kalimantan Province scale 1:250,000 (Decree of the Minister of Forestry and Plantations No.79/Kpts-II/2001), the PBPH-HA area of PT SLJ IV is entirely located in the Limited Production Forest (HPT). In general, the topographic conditions in the PT SLJ IV working area are dominated by a rather steep slope class (15-25%) which covers ±54.72% of its area. The altitude ranges from 50-500 meters above sea level, where the lowest area is in the area adjacent to the Segah River, while the highest area is in the west or adjacent to a protected forest.

Data collection was conducted from July to October 2024 at the RKTPH 2024 XII-04, XII-14, and XII-18 cutting blocks. The site lies between 02°04' 00"-02°21'00" N and 116°30'00"-117°00'00" E (Figure 1). The concession area covered 63,550 hectares and was secondary natural forest. The topography is medium to steep with the soil types primarily podzolic and latosol. The minimum monthly precipitation was 197.4 mm in January and maximum was 329.8 mm in December. The forest stand composition was characterized by an uneven-aged forest, predominantly comprising species from the family Dipterocarpaceae.

The company implements Reduced Impact Logging (RIL). Timber harvesting was conducted through selective cutting to trees with diameter exceeding 40 centimeters, classifying them as commercially viable. In our study, trees were felled using a STIHL MS 382 chainsaw and skidded using a Komatsu D85SS-2 bulldozer. PT SLJ IV is committed to sustainable natural forest management by considering the production, social, cultural, and environmental aspects. Therefore, the Management Unit prefers voluntary forest management certification following the Forest Stewardship Council (FSC) scheme.

### Research procedures

*Experimental design*

This study investigated the changes in stand structure before and after harvest. Research plots were established in the form of a square with size of 100×100 m and a total of six plots were created. In the plot, all trees with size of 10 cm and above were inventoried by identifying their species and measuring their diameter at breast height. All tree species with a diameter at breast height (dbh) ≥10 cm were then inventoried before felling. After the timber felling, an inventory was conducted of the remaining stands to record the number of damaged trees and the type of the damage. Similar procedures were also conducted to record the damage caused by skidding.

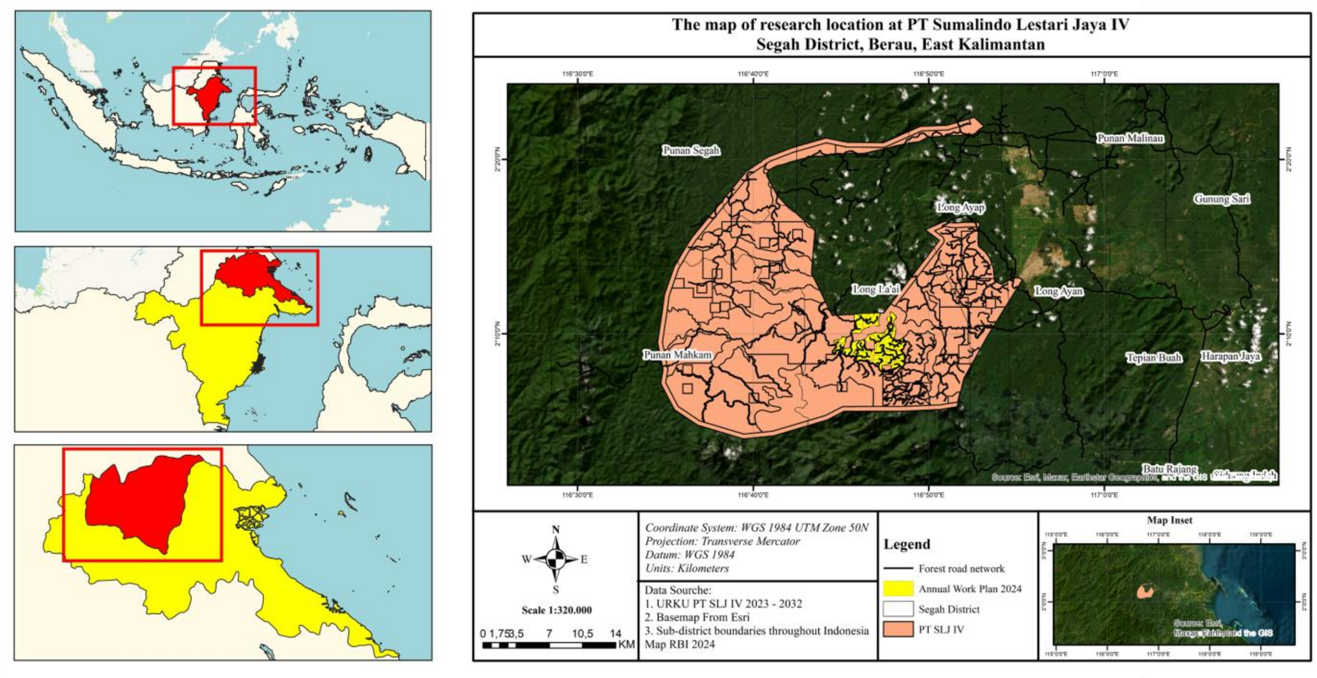


**Figure 1.** Map of the study site located in a logging concession in Segah Subdistrict, Berau District, East Kalimantan Province, Indonesia

*Stand damages*

Residual stand damage was observed by systematically counting the number of remaining stands with various forms of damage, including crown damage, broken stems, collapsed stems or tilted stems, stem wounds, and buttress wounds. Damage type was determined by direct observation on residual stand damage in the affected area after felling or skidding the tree according to the Director General of Forestry Decree No. 564/KPTS/IV-BPHH/1989 on the Guidelines for Selected Logging and Indonesian Planting (TPTI) where a stand was classified as damaged if it had one or more of the following conditions: (i) The tree crown is damaged if more than 30% of the tree's branches or main stem are broken; (ii) A stem wound is observed, extending to a point which is more than a quarter of the circumference from the trunk, with an estimated length in excess of 1.5 meters; (iii) Roots are cut and uprooted, or one-third of the buttress is damaged.

**Data analysis**

The measurement of stand damages causing by tree felling was carried out at the sample plot by calculating the mean number of damages per harvested tree. Similarly, this observation was also applied during log skidding. The damages were divided into injuries to living trees and damages to regeneration, depending on where they occurred. The injuries on the remaining trees were categorized into four distinct groups: crown damage, broken trees, stem wounds, and collapse.

The following formula was used to calculate the damage to the residual stand caused by felling and skidding (Elias 1998):

$$K = \frac{R}{P - Q} \times 100\%$$

Where, K: Percentage of damage of the remaining stand; R: Number of damaged trees with a diameter of ≥10 cm by type of damage; P: Number of trees with a diameter of ≥10 cm before felling; and Q: Number of harvested trees. Residual stand damage was classified into: 1) minor if it occurred <25%; 2) moderate if it occurred between 25-50%; and 3) major if it reached >50% (Elias 1998).

## RESULTS AND DISCUSSION

**Tree species diversity**

All sample plots contained 50 tree species (Table 1). The concession only harvested commercial tree species with diameter over 40 cm. The PBPH-HA area of PT SLJ IV is dominated by Dipterocarpaceae species such as *meranti merah* (*Shorea leprosula*), *meranti putih* (*Shorea* sp.), *meranti kuning* (*Shorea* sp.), and *nyatoh* (*Palaquium beccarianum*) and non-Dipterocarpaceae species including *medang* (*Actinodaphne glabra*), *jambu-jambu* (*Syzygium tawahense*), *mendarahan* (*Myristica affinis*) and others.

**Felling intensity, stand damage and forest opening**

Tree density at each plot was different where the plot with the highest density was plot 3 which had trees with a diameter ≥10 cm as many as 427 trees $ha^{-1}$ while the lowest density was at plot 5 with 192 trees $ha^{-1}$ (Table 2). Felling intensity was measured as the number of trees felled per hectare. As demonstrated in Table 2, felling intensity ranged from 8 to 16 trees per hectare. The average of trees with diameter ≥10 cm was 297 trees $ha^{-1}$ with average felling intensity of 11 trees $ha^{-1}$. The average damage to trees with diameter ≥10 cm was 49 trees $ha^{-1}$ or 17.85% damage.

The type of damage was primarily broken trunk with average damage of 19 trees $ha^{-1}$ (38.78%), followed by wounds on the trunk and trees that tilt/fall both with average of 11 trees $ha^{-1}$ (22.45%), and crown damage with average damage of 8 trees/ha (16.33%). In the felling site 14 A-B, the prevalence of damage was by broken trunks (13 trees), collapsed or tilted trees (10 trees) and crown damage (9 trees). In the felling site 4 B, the damage was predominantly broken trunks (25 trees), stem wounds (16 trees), and collapsed or tilted trees (14 trees). In the felling site 18 A-B, it was dominated by broken trunks (19 trees), stem wounds (9 trees), and collapsed/tilted trees (9 trees). The type of damage to standing trees after logging can be seen in Figure 2.

The result of this study is similar with research by Soenarno et al. (2017) who discovered that broken stems were the most prevalent type of damage (56.37%) caused by felling activities in a rainforest in Central Kalimantan. Moreover, Matangaran et al. (2019a) documented that broken stems and crowns were the most common types of damage caused by logging in the rainforests of Central Kalimantan and West Sumatra. In addition, Matangaran et al. (2022) documented that the most prevalent form of tree damage was a leaning tree, which was observed in 63% of the total cases. This was accompanied by damage to the crown (23%), buttress (10%), stem (2%), and bark (2%).

Damage to residual stands due to logging can be minimized to save young stands to maintain production in the next logging rotation. Nonetheless, recent research has unequivocally demonstrated that RIL techniques in isolation, founded upon the principles of the Minimum Cutting Diameter Limit (MCDL) regulation, are inadequate to ensure the implementation of sustainable forest management strategies. The application of the MCDL regulation in mixed dipterocarp forests within the Southeast Asian region has resulted in the felling of a high number of trees with felling intensities ranging from 10-15 trees per hectare (Sist and Ferreira 2007).

The process of forest opening following timber harvesting has been characterized by the creation of an aperture in the forest canopy. The extent of felling gap is directly proportional to the number of trees felled with a smaller number of trees resulting in a reduced forest opening. The regression analysis demonstrated a strong positive correlation between felling intensity and forest opening area as demonstrated in Figure 3.

**Skidding, stand damage and forest opening**

Stand damage is subsequently continued as the harvested tree is skidded which resulted in trails due to the use of heavy machinery such as bulldozers. The results analysis on stand damage due to skidding is presented in Table 3. The mean damage to trees with a diameter of ≥10 cm was 46 trees per hectare, equivalent to 16.60% of the total. Based on damage type, collapsed/tilted occurred on 28 trees (60.87%), followed by stem wounds with 15 trees (32.61%) and damage to buttress with three trees (6.52%). The percentage of skid road opening ranged from 7.8% to 18.4% per hectare with average of 13.26%. The process of forest opening in the context of timber harvesting was invariably initiated by the felling space created by felled trees and the path created by the bulldozer. It was observed that the extent of the opening was directly proportional to the reduction in the number of trees felled, with a decrease in the felling gap and skid trail.

**Table 1.** Trees in all sample plots by species, family, and vernacular name

| Species | Family | Local name |
|---|---|---|
| *Actinodaphne glabra* | Lauraceae | *Medang* |
| *Alstonia scholaris* | Apocynaceae | *Pulai* |
| *Anisoptera costata* | Dipterocarpaceae | *Mersawa* |
| *Artocarpus elasticus* | Moraceae | *Terap* |
| *Artocarpus integer* | Moraceae | *Cempedak* |
| *Artocarpus lanceifolius* | Moraceae | *Keledang* |
| *Baccaurea macrocarpa* | Phyllanthaceae | *Kapul* |
| *Calophyllum soulattri* | Calophyllaceae | *Bintangur* |
| *Campnosperma auriculata* | Anacardiaceae | *Terentang* |
| *Castanopsis acuminaatissima* | Fagaceae | *Pasang* |
| *Celtis sinensis* | Cannabaceae | *Penjalin* |
| *Cratoxylum formosum* | Hypericaceae | *Gerunggang* |
| *Dialium indum* | Fabaceae | *Keranji* |
| *Dillenia indica* | Dilleniaceae | *Simpur* |
| *Dimocarpus longan* | Sapindaceae | *Kelengkeng hutan* |
| *Diospyros celebica* | Ebenaceae | *Eboni* |
| *Discaria pubescens* | Rhamnaceae | *Jangkar* |
| *Dipterocarpus confertus* | Dipterocarpaceae | *Keruing* |
| *Dryobalanops aromatica* | Dipterocarpaceae | *Kapur* |
| *Duabanga moluccana* | Lythraceae | *Banuang* |
| *Durio zibethinus* | Malvaceae | *Durian* |
| *Dyera costulata* | Apocynaceae | *Jelutung* |
| *Eusideroxylon zwageri* | Lauraceae | *Ulin* |
| *Fagraea fragrans* | Loganiaceae | *Tembesu* |
| *Garcinia mangostana* | Clusiaceae | *Manggis* |
| *Gluta renghas* | Anacardiaceae | *Rengas tembaga* |
| *Goniothalamus wynaadensis* | Annonaceae | *Mempisang* |
| *Heritiera javanica* | Malvaceae | *Palapi* |
| *Koompassia excelsa* | Fabaceae | *Banggeris* |
| *Koompassia malaccensis* | Fabaceae | *Kempas* |
| *Lansium domesticum* | Meliaceae | *Langsat hutan* |
| *Macaranga gigantea* | Euphorbiaceae | *Mahang/Makar* |
| *Michelia champaca* | Magnoliaceae | *Cempaka* |
| *Myristica affinis* | Myristicaceae | *Mendarahan* |
| *Palaquium beccarianum* | Sapotaceae | *Nyatoh* |
| *Parkia speciosa* | Fabaceae | *Petai Hutan* |
| *Polyalthia longifolia* | Annonaceae | *Banitan* |
| *Pterospermum javanicum* | Malvaceae | *Bayur* |
| *Samanea saman* | Fabaceae | *Trembesi* |
| *Santiria tomentosa* | Burseraceae | *Kenari* |
| *Scorodocarpus borneensis* | Olacaceae | *Kulim* |
| *Shorea laevis* | Dipterocarpaceae | *Bangkirai* |
| *Shorea leprosula* | Dipterocarpaceae | *Meranti merah* |
| *Shorea* sp1. | Dipterocarpaceae | *Meranti kuning* |
| *Shorea* sp2. | Dipterocarpaceae | *Meranti putih* |
| *Shorea stenoptera* | Dipterocarpaceae | *Tengkawang* |
| *Sindora wallichii* | Fabaceae | *Sindur* |
| *Sterculia foetida* | Malvaceae | *Kelumpang* |
| *Syzygium tawahense* | Myrtaceae | *Jambu-jambu* |
| *Vatica rassak* | Dipterocarpaceae | *Resak* |

**Table 2.** Residual stand damage due to timber felling

| Felling site | Plot | Number of trees with diameter of ≥ 10 cm (trees/ha) | Felling intensity (trees/ha) | Residual stand damage | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Crown damage (trees) | Broken trunk (trees) | Stem wounds (trees) | Collapsed/ tilted (trees) | Total (trees) | Percentage (%) |
| 14 A-B | 1 | 250 | 10 | 8 | 6 | 7 | 8 | 29 | 12.08 |
| | 2 | 331 | 10 | 10 | 20 | 9 | 12 | 51 | 15.89 |
| | Average | 291 | 10 | 9 | 13 | 8 | 10 | 40 | 13.99 |
| 4 B | 3 | 427 | 8 | 9 | 23 | 15 | 12 | 59 | 14.08 |
| | 4 | 270 | 16 | 10 | 26 | 16 | 16 | 68 | 26.77 |
| | Average | 349 | 12 | 10 | 25 | 16 | 14 | 64 | 20.42 |
| 18 A-B | 5 | 192 | 16 | 5 | 18 | 8 | 13 | 44 | 25.00 |
| | 6 | 309 | 8 | 6 | 20 | 9 | 5 | 40 | 13.29 |
| | Average | 251 | 12 | 6 | 19 | 9 | 9 | 42 | 19.14 |
| Grand average | | 297 | 11 | 8 | 19 | 11 | 11 | 49 | 17.85 |

**Table 3.** Residual stand damage caused by log skidding

| Felling site | Plot | Number of trees with diameter of ≥10 cm (trees/ha) | Skidded trees | Residual stand damage | | | | | Percentage of skid road opening (%) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Buttress damage (trees) | Stem wounds (trees) | Collapsed/ tilted (trees) | Total (trees) | Percentage (%) | |
| 14 A-B | 1 | 250 | 10 | 5 | 11 | 18 | 34 | 14.17 | 7.81 |
| | 2 | 331 | 10 | 8 | 10 | 23 | 41 | 12.77 | 12.58 |
| 4 B | 3 | 427 | 8 | 3 | 23 | 36 | 62 | 14.80 | 12.92 |
| | 4 | 270 | 14 | 2 | 22 | 45 | 69 | 26.95 | 15.73 |
| 18 A-B | 5 | 192 | 16 | 1 | 7 | 23 | 31 | 17.61 | 18.4 |
| | 6 | 309 | 8 | 2 | 18 | 20 | 40 | 13.29 | 12.1 |
| Average | | 297 | 11 | 3 | 15 | 28 | 46 | 16.60 | 13.26 |


**Figure 2.** Type of stand damages due to tree felling: A. Crown damage; B. Broken tree; C. Stem wounds; D. Collapsed/tilted

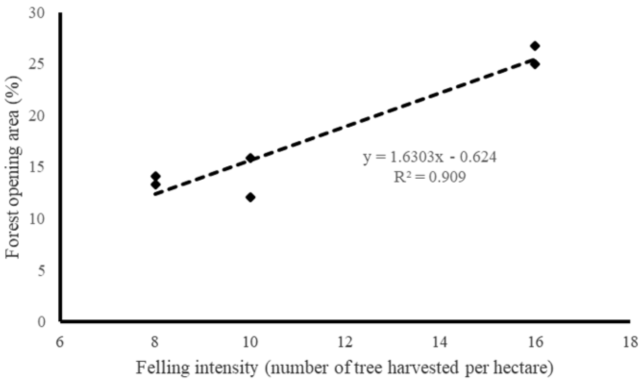


**Figure 3.** The correlation between felling intensity and forest opening

**Discussion**

The study site was characterized by the presence of three species of the Dipterocarpaceae family, with a diameter greater than 40 cm, which is harvestable trees, and a significant number of remaining trees with diameter below this size. The result of this study is consistent with the research by Imai et al. (2019) which found that logging does not exert a substantial influence on tree diversity measurements in Borneo. The current study examined the impacts of logging on stand damage caused by tree felling. The results demonstrated that tree felling caused damage to 17.85% residual stands (Table 3).

This finding is in line with a study in Tana Tidung District, North Kalimantan Province, as determined by post-harvesting assessments (Matangaran et al. 2022). The damage in this study was found to be lower than those in Central Kalimantan and West Sumatra, which registered 27.8% and 22.4%, respectively (Matangaran et al. 2019a). Furthermore, an increase in stand damage has been shown to correspond with an increase in felling intensity (Britto et al. 2019). It has been demonstrated that the level of stand damage has a direct impact on the rate of recovery of the forest following disturbance (Florence et al. 2017; Piponiot et al. 2018; Bodaghi et al. 2020; Han et al. 2021; Hayward et al. 2021; Knoke et al. 2022; Mokake et al. 2024). Despite the meticulous manner when tree felling was executed, the process invariably caused stand damage. The extent to which this occurs is subject to variation due to factors such as stem density, the presence and prevalence of lianas, the dimensions of the tree crown, and the topographical characteristics of the terrain (Medjibe et al. 2011).

The results of this study indicate a lower level of damaged stand compared to a study by Mawazin (2013), which showed that felling 39 stems/ha with a base area of 6.45 $m^2$ and a volume of 76.84 $m^3$ resulting in tree-level stand damage of 27.79%. Suwarna et al. (2014) stated that broken trunks and collapsed trees were the most common forms of damage caused by logging, with proportions of 44% and 20%, respectively. However, damage to residual stands, which are the trees left standing after logging, can be minimized through the application of environmentally friendly logging techniques. Several factors cause damage to standing trees due to logging, such as the wrong direction of tree fall, wind blowing, dense stands, very large and tall tree diameters, steep topography, and the skill of the chainsaw operator. The results of Hwang et al. (2018) showed that in dense stands, the occurrence of residential stand damage was greater than that in sparse stands. Britto et al. (2019) suggested that high stand density should be considered to reduce damage to residual stands. Amoah et al. (2019) stated that the skill of chainsaw operators affects the damage to residual stands due to logging.

The logging operation in this study used RIL (Reduced Impact Logging), which is largely considered as environmentally friendly. Still, several factors caused damage to residual stands after logging, such as the direction of tree fall, vegetation density, large diameter of felled trees, topographic conditions, and the ability of chainsaw operators. Tables 2 and 3 shows that the dominant damages that occurred at each plot were broken branches and collapsed trees caused since the trees that were cut down had an average diameter of ≥40 cm and a tree height that was greater than the remaining stands.

In the skidding process, the distance traversed by winches is a pivotal factor in determining the extent of ground-based skidding to residual stands. Directional felling emerges as a pivotal technique to mitigate the adverse effects of skidding on residual stands. The findings indicated that in skidding operations, minor damage was observed in plots 1, 2, 3, 5, and 6, with damage percentages ranging below 25%, except for plot 4 which exhibited a moderate level of damage, with a percentage of 26.95%. However, on average, the damage to residual stands caused by skidding is still classified as light because it only reached 16.6% in average (Table 3). Skidding is defined as the process of dragging logs from the felling site to designated landing area. The frequency of skidding must be taken into consideration, as the more timber felled, the more frequently the skidding process occurs. This has the potential to cause damage to both residual stands and forest openings. The occurrence of collapsed trees during the process of skidding may be in part attributed to the absence of adequate skidding trail preparation. This suggests that the operator need to undertake a significant degree of bulldozer maneuvering during the process of locating felled trees. In a study undertaken by Soenarno et al. (2017), it was reported that tilted and collapsed trees were the most prevalent damage identified (67.8%) because of skidding in a tropical forest located in Central Kalimantan.

Before tree felling, it is necessary to open forest to create skid road so that the feller can aim the direction the felled tree to the skid road. During skidding, the bulldozer has to widen the skid road and peel the soil so that many dead trees are pushed by the bulldozer which causing wound to the trees on the left and right of the skid road (Figures 4.A and B). The bulldozer is equipped with a cable of a limited length that can be extended when winching a maximum distance of 30 meters.


**Figure 4.** A. The process of creating skid road before tree felling; B. Stem wounds during skidding

Coupled with the bulldozer's maneuverability, this results in a significant number of ground openings and residual stand damage. Due to the substantial quantity of trees per hectare, it was sometimes necessary to change the skidding route as defined during the felling stage to minimize any damage incurred. The most unfavorable scenario arises when the assortments are positioned parallel to the skid trail or at an acute angle to the trail on which they are being skid (Danilović et al. 2015). Although skid trails had been meticulously planned, the process of skidding nevertheless resulted in the occurrence of residual stand damage. A significant proportion of the trees affected by the skidding were uprooted; however, a considerable number exhibited severe bale damage (Medjibe et al. 2011). Consequently, it is imperative that the skid trail path can be traced on the felled tree map to prevent substantial damage. This underscores the importance of each professional's role in preventing damage. Bulldozer operators are required to carry a tree map to facilitate tracking of felled trees. The tree map delineates the identity and location of trees designated to be cut (Yuniawati et al. 2023).

Reduced Impact Logging (RIL) is a technique that has been demonstrated to minimize the ecological damage incurred by the harvesting of timber (Ruslim et al. 2016; Dulsalam et al. 2021). To reduce damage from felling and skidding, RIL imposes procedures by determining the felling direction to minimize the harvested trees falling into others, felling parallel to the contour line, felling parallel to the skid road, or forming a fish bone. Elias et al. (2001), Van der Hout (2014) and Dulsalam et al. (2021) sought to ascertain the most effective method for determining the felling direction. The researchers proposed that this should be achieved by either approaching or avoiding the skid mark, with the angle of approach or avoidance set at 30-45 degrees, or by establishing a parallel position of the skidder on the skid trail in the opposite direction to the skid trail. This approach was found to facilitate the direction of felling to a clear area and the crown of the previously felled tree. In the context of steep terrain, the felling direction was found to be oblique to the slope, following the contour of the terrain. Furthermore, skidding and skid road building should normally be stopped during the rain, especially when logging on fine-textured soils such as loams and clays or wet soils or slopes (Van der Hout 2014). A skidding scheme must be formulated in order to mitigate the environmental impact of skidding by implementing a pre-planning strategy for skid roads. Achieving a balanced control over a skidding operation is contingent on the selection of suitable equipment, the determination of the suitable harvest time, individual tree size, location, and spatial distribution. The arrangement of skid trails in a logical manner has been shown to facilitate expedited work and enhance the efficacy of skidding devices (Kooshki et al. 2012; Gumus and Turk 2016). The impact of a conventional harvesting method on the subsequent harvesting was evaluated and compared with an alternative and improved harvesting method. The latter was performed by a well-trained professional chainsaw operator experienced in reduced impact logging techniques and included the use of a snatch block and a skidding cone (Britto et al. 2019).

The process entails the imposition of a maximum tree-felling intensity per hectare, thereby markedly diminishing the incidence of stand damage (Suhartana et al. 2022). The present study revealed that the increase in felling intensity resulted in corresponding increase forest opening as also found by Matangaran et al. (2022). Reduced Impact Logging (RIL) has been applied in the management of natural forests to minimize wood harvesting residues (Parasakoo et al. 2017). Furthermore, the integration of decision support system techniques has been demonstrated at PT SLJ IV to enhance accessibility to marked trees and to reduce the length of skid roads. So, the skid trail pattern must be planned and opened before harvesting takes place so that the length of the skid road can be minimized to reduce stand damage.

To minimize damage to stands after skidding, it is mandatory to use skidding equipment that has a long-line winching cable system, such as a monocable-winch machine with a winch cable length of 100 m and a Rimbaka Harvester (log fisher) with a winch cable length of 150 m. It is recommended that the focus of future research be expanded to encompass the exploration of other long-line winching technologies that have been extensively utilized in Malaysian Borneo. This technology is equipped with a 150-metre-long cable sling, which has been found to cause a lower rate of damage to the stand than a bulldozer (Norizah et al. 2012). Furthermore, the implementation of monocable-winch can reduce carbon emissions through avoided forest degradation and reduction in diesel fuel consumption (Ruslim 2011, et al. 2016; Pearson et al. 2017).

In the context of climate change, harvesting merchantable trees (dbh 10 cm) can emit 21.54 MgC $ha^{-1}$ carbon stock or equivalent to 13.20% of above ground carbon (Romero et al. 2021). In addition, the commercial bale is responsible for 3.26% of the carbon removed directly from the forest in the harvested trunks for wood production (Romero et al. 2021). Implementing long-line cable winching would be instrumental in achieving significant emissions reduction, with the additional benefit of mitigating the construction of bulldozer skid trails. These trails have been identified as a primary contributor to soil erosion in the harsh Indonesian terrain where logging operations are currently underway (Putz et al. 2018). The term RIL-C is used to denote a set of enhanced logging practices that minimize carbon emissions which involves several strategies such as directional felling, the optimization of log extraction methods (for example, skidding or yarding), the planning of skid trails and roads, the enhancement of bucking techniques, and winching with long lines cable (Griscom et al. 2014, et al. 2019; Pearson et al. 2014). There have been various advantages of using a monocable winch since 2010, but until now, this tool has not been applied. This is due to social considerations because it requires many human labor and safety factors and will also become a competitor to heavy equipment that has been used since 1970 in Indonesia.

In conclusion, with intensity of logging and skidding averaged 11 trees per hectare, the percentage of stand damage and tree mortality after felling and skidding was 17.85% and 16.62%, respectively. The average skidding road opening after the harvesting process was 13.26%. The level of damage of residual stand and the opening of skid road was comparatively minor when compared to other case studies. There was a significant relationship between felling intensity and forest opening as increase in logging intensity was directly correlated with an increase in the clearance of skid roads. The findings of this research suggest that planning the skid road prior to harvesting, opening the skid trail before felling, limiting the number of trees felled per hectare, conducting directional felling to the skid trail, and extending the maximum sling cable (winching) can minimize the damage caused by felling, skidding and forest opening, while also ensuring less severe impact on tree species biodiversity and natural regeneration.

## ACKNOWLEDGEMENTS

This work was funded by the Indonesian Ministry of Research, Technology, and Higher Education, Republic of Indonesia, through Fundamental Research Grant-Regular, with main contract number 061/E5/PG.0200.PL/2024, dated June 11, 2024 and derivative contract 602/UN17.L1/HK/2024. The authors also wish to express their deep appreciation and gratitude to the Institute for Research and Community Service (LP2M) of Universitas Mulawarman, Dodi Kurnaedi, and Suryadi from PT Sumalindo Lestari Jaya IV and gratefully acknowledge the anonymous reviewers for their constructive feedback to improve the manuscript. The authors would also like to thank Friska Bunga Mangalik, Intan Pandini, Cakra Handika Hafidz, and Muhammad Ade Nizar for field data collection. Furthermore, we extend our appreciation to all parties who have contributed their support and efforts, facilitating the successful execution of this research.

## REFERENCES

Amoah CM, Issifu H, Tom-Dery D, Husseini R, Baatuuwie BN, Ochire-Boadu K, Asante WJ. 2019. Logging effect of illegal chainsaw milling and conventional logging in Krokosua Hills Forest Reserve, Ghana. Intl J Conserv Sci 10 (1): 177-186.

Bezerra TG, Ruschel AR, Emmert F, Nascimento RGM. 2021. Changes caused by forest logging in structure and floristic diversity of natural regeneration: Relationship between climate variables and forest dynamics in the eastern Amazon. For Ecol Manag 482: 118862. DOI: 10.1016/j.foreco.2020.118862.

Bodaghi AI, Nikooy M, Naghdi R, Tavankar F. 2020. Logging damage to residual trees during sustainable harvesting of uneven age stands in the Hyrcanian forests of Iran. N Z J For Sci 50: 1. DOI: 10.33494/nzjfs502020x15x.

Britto PC, Jaeger D, Hoffmann S. Robert RCG, Vibrans AC, Fantini AC. 2019. Impact assessment of timber harvesting operations for enhancing sustainable management in a secondary Atlantic Forest. Sustainability 11 (22): 6272. DOI: 10.3390/su11226272.

Chervier C, Atmadja SS, Nofyanza S, Annisa CN, Nurfatriani F, Kristiningrum R, Sahide MAK, Suhardiman A, Umar S. 2025. Impact of Indonesia's Forest Management Units on the reduction of forest loss and forest fires in Sulawesi. Ecol Econ 227: 108418. DOI: 10.1016/j.ecolecon.2024.108418.

Condè TM, Tonini H, Higuchi N, Higuchi FG, Lima AJN, Barbosa RI, Pereira TS, Alexander M. 2022. Effects of sustainable forest management on tree diversity, timber volumes, and carbon stocks in an ecotone forest in the northern Brazilian Amazon. Land Use Policy 119: 106145. DOI: 10.1016/j.landusepol.2022.106145.

Dangwal B, Rana SK, Negi VS, Bhatt ID. 2022. Forest restoration enhances plant diversity and carbon stock in the sub-tropical forests of western Himalaya. Trees For People 7: 100201. DOI: 10.1016/j.tfp.2022.100201.

Danilović M, Kosovski M, Gačić D, Stojnić D, Antonić S. 2015. Damage to residual trees and regeneration during felling and timber extraction in mixed and pure beech stands. Šumarski List 2015 (5-6): 253-262.

Dulsalam, Soenarno, Suhartana S, Sukadaryati, Yuniawati, Herniningrum M, Andini S. 2021. Reduced impact logging in the dried land natural production forests in Indonesia. IOP Conf Ser Earth Environ Sci 914 (1): 012060. DOI: 10.1088/1755-1315/914/1/012060.

Dwiyahreni A, Fuad HAH, Sunaryo, Soesilo TEB, Margules C, Supriatna J. 2021. Forest cover changes in Indonesia's terrestrial national parks between 2012 and 2017. Biodiversitas 22 (3): 1235-1242 DOI: 10.13057/biodiv/d220320.

Elias, Applegate G, Kartawinata K, Machfudh, Klassen A. 2001. Reduced Impact Logging Guidelines for Indonesia. Center for International Forestry Research (CIFOR), Bogor. DOI: 10.17528/cifor/001384.

Elias. 1998. Reduced Impact Timber Harvesting in the Tropical Natural Forest in Indonesia. Food and Agriculture Organization of the United Nations, Rome.

Ellis PW, Gopalakrishnaa T, Goodmanb RC, Putz FE, Roopsind A, Umunaye PM, Zalmanf J, Ellis EA, Mo K, Gregoire TG, Griscom BW. 2019. Reduced impact logging for climate change mitigation (RIL-C) can halve selective logging emissions from tropical forests. For Ecol Manag 438: 255-266. DOI: 10.1016/j.foreco.2019.02.004.

Florence LG, Vanclay JK, Glencross K, Nichols JD. 2017. Understanding 48 years of changes in tree diversity, dynamics, and species responses since logging disturbance in a subtropical rainforest. For Ecol Manag 393: 29-39. DOI: 10.1016/j.foreco.2017.03.012.

Griscom B, Ellis P, Putz FE. 2014. Carbon emissions performance of commercial logging in East Kalimantan, Indonesia. Glob Change Biol 20: 923-937. DOI: 10.1111/gcb.12386.

Griscom BW, Ellisa PW, Burivalovab Z, Halperinc J, Marthinusd D, Runtinge RK, Ruslandi, Shoch D, Putz FE. 2019. Reduced impact logging in Borneo to minimize carbon emissions and impacts on sensitive habitats while maintaining timber yields. For Ecol Manag 438: 176-185. DOI: 10.1016/j.foreco.2019.02.025.

Gumus S, Turk Y. 2016. A new skid trail pattern design for farm tractors using linear programming and geographical information systems. Forests 7 (12): 306. DOI: 10.3390/f7120306.

Gunawan H, Setyawati T, Atmoko T, Subarudi, Kwatrina RT, Yeny I, Yuwati TW, Effendy, Abdullah L, Mukhlisi, Lastini T, Arini IRD, Sari UK, Sitepu BS, Pattiselanno F, Kuswanda W. 2024. A review of forest fragmentation in Indonesia under the DPSIR framework for biodiversity conservation strategies. Glob Ecol Conserv 51: e02918 DOI: 10.1016/j.gecco.2024.e02918.

Han X, Huang J, Yao J, Xu Y, Ding Y, Zang R. 2021. Effects of logging on the ecological strategy spectrum of a tropical montane rain forest. Ecol Indic 128: 107812. DOI: 10.1016/j.ecolind.2021.107812.

Hayward RM, Banin LF, Burslem DFRP, Chapman DS, Philipson CD, Cutler MEJ, Reynolds G, Nilus R, Dent DH. 2021. Three decades of post-logging tree community recovery in naturally regenerating and actively restored dipterocarp forest in Borneo. For Ecol Manag 488: 119036. DOI: 10.1016/j.foreco.2021.119036.

Hwang K, Han HS, Marshall SE, Dumroses DSP. 2018. Amount and location of damage to residual trees from cut to length thinning operations in a young Redwood Forest in Northern California. Forests 9: 352. DOI: 10.3390/f9060352.

Imai N, Sugau JB, Pereira JT, Titin J, Kitayama K. 2019. Impacts of selective logging on spatial structure of tree species composition in Bornean tropical rain forests. J For Res 24 (6): 1-6. DOI: 10.1080/13416979.2019.1666958.

Knoke T, Paul C, Gosling E, Jarisch I, Mohr J, Seidl R. 2022. Assessing the economic resilience of diferent management systems to severe forest disturbance. Environ Resour Econ 84: 343-381 DOI: 10.1007/s10640-022-00719-5.

Kooshki M, Hayati E, Rafatnia N, Ahmadi MT. 2012. Using GIS and design skid trails for the forest products. Taiwan J For Sci 27 (1): 117-124.

Matangaran JR, Anissa IN, Adlan Q, Mujahid. 2022. Changes in floristic diversity and stand damage of tropical forests caused by logging operations in North Kalimantan, Indonesia. Biodiversitas 23 (12): 6358-6365. DOI: 10.13057/biodiv/d231233.

Matangaran JR, Putra EI, Diatin I, Mujahid M, Adlan Q. 2019a. Residual stand damage from selective logging of tropical forests: A comparative case study in central Kalimantan and West Sumatra, Indonesia. Glob Ecol Conserv 19: e00688. DOI: 10.1016/j.gecco. 2019.e006882351-9894.

Matangaran JR, Putra EI, Mashitha MW, Diatin I, Mujahid M, Adlan Q. 2019b. Soil disturbance by logging operation of industrial plantation forest in Indonesia. IOP Conf Ser Earth Environ Sci 394 (1): 012064. DOI: 10.1088/1755-1315/394/1/012064.

Mawazin. 2013. Tingkat kerusakan tegakan tinggal di hutan rawa gambut sungai Kumpeh-Sungai Air Hitam Laut Jambi. Indones For Rehabilit J 1 (1): 39-50. [Indonesian]

Medjibe VP, Putz FE, Starkey MP, Ndouna AA, Memiaghe HR. 2011. Impacts of selective logging on aboveground forest biomass in the Monts de Cristal in Gabon. For Ecol Manag 262 (7): 1799-1806. DOI: 10.1016/j.foreco.2011.07.014.

Mokake SE, Chuyong GB, Egbe EA. 2024. Long-term impacts of selective logging in a tropical rainforest in the East region of Cameroon. Afr J Ecol 62 (4): e13341. DOI: 10.1111/aje.13341.

Mottl O, Plowman NS, Novotny V, Gewa B, Rimandai M, Klimes P. 2019. Secondary succession has surprisingly low impact on arboreal ant communities in tropical montane rain forests. Ecosphere 10 (8): e02848. DOI: 10.1002/ecs2.2848.

Norizah K, Hasmadi IM, Kamaruzaman J, Alias MS. 2012. Operational efficiency of Rimbaka Timber Harvester in hilly tropical forest. J Trop for Sci 24 (3): 368-378.

Parasakoo A, Mustofa M, Shatafe S, Lofalin M. 2017. Decission support system to find a skid trail network for extracing marked trees. J For Sci 63 (2): 62-69. DOI: 10.17221/36/2016-JFS.

Pearson TRH, Brown S, Casarim FM, Murray LT, Sidman G. 2017. Greenhouse gas emissions from tropical forest degradation: An underestimated source. Carbon Balance Manag 12 (3): 1-11. DOI: 10.1186/s13021-017-0072-2.

Pearson TRH, Brown S, Casarim FM. 2014. Carbon emissions from tropical forest degradation caused by logging. Environ Res Lett 9: 034017 DOI: 10.1088/1748-9326/9/3/034017.

Piponiot C, Derroire G, Descroix L, Mazzeie L, Rutishauser E, Sist P, Hérault B. 2018. Assessing timber volume recovery after disturbance in tropical forests - A new modelling framework. Ecol Model 384: 353-369. DOI: 10.1016/j.ecolmodel.2018.05.023.

Purwoko A, Muhdi, Hanafiah AS. 2018. Residual stand damages caused by conventional and reduced impact timber harvesting in the natural forest. Intl J Mech Eng Technol 9 (3): 313-325.

Putz FE, Ruslandi, Ellis P, Griscom BW. 2018. Topographic restrictions on land-use practices: Consequences of different pixel sizes and data sources for natural forest management policies in the tropics. For Ecol Manag 422: 108-113. DOI: 10.1016/j.foreco.2018.04.001.

Romero FMB, Jacovine LAG, Torres CMME, Ribeiro SC, Morais JVTM, Rocha SJSS, Romero RAB, Gaspar RO, Velasquez SIS, Staudhammer CL, Neto JAF, Vidal E, Martin P. 2021. Fearnside forest management with reduced impact logging in Amazonia: Estimated aboveground volume and carbon in commercial tree species in managed forest in Brazil's State of acre. Forests 12: 481. DOI: 10.3390/f12040481.

Ruslim Y, Sihombing R, Liah Y. 2016. Stand damage due to mono-cable winch and bulldozer yarding in a selectively logged tropical forest. Biodiversitas 17 (1): 222-228. DOI: 10.13057/biodiv/d170132.

Ruslim Y. 2011. Implementing reduced impact logging with monocable winch. J Trop For Manag 17 (3): 103-110.

Saimun MSR, Karim MR, Sultana F, Khan MASA. 2021. Multiple drivers of tree and soil carbon stock in the tropical forest ecosystems of Bangladesh. Trees For People 5: 100108. DOI: 10.1016/j.tfp.2021.100108.

Sist P, Ferreira FN. 2007. Sustainability of reduced impact logging in the Eastern Amazon. For Ecol Manag 243: 199-209. DOI: 10.1016/j.foreco.2007.02.014.

Soenarno, Endom W, Bustomi S. 2017. Residual stand damage due to timber harvesting on hilly tropical forest ini Central Kalimantan. Jurnal Penelitian Hasil Hutan 35 (4): 273-288. DOI: 10.20886/jphh.2017.35.3.273-288.

Suhartana, Yuniawati, Gandaseca S, Dulsalam, Soenarno, Ratnasingam J. 2022. Potential of wood harvesting residues and residual stand damage due to timber harvesting: A case study at PT Austral Byna in Central Kalimantan, Indonesia. Intl J For Res 2022: 3251945. DOI: 10.1155/2022/3251945.

Suwarna U, Matangaran JR, Hermawan F. 2014. Residual stand damage caused by timber harvesting in natural peat swamp forest. Jurnal Manusia Lingkungan 21 (1): 83-89. DOI: 10.22146/jml.18515. [Indonesian]

Tsujino R, Yumoto T, Kitamura S, Djamaluddin I, Darnaedi D. 2016. History of forest loss and degradation in Indonesia. Land Use Policy 57: 335-347 DOI: 10.1016/j.landusepol.2016.05.034.

Van der Hout. 2014. Code of Practice for Forest Operations (3rd Edition) for Timber Sales Agreement and Wood Cutting License Holders. Guyana Forestry Commission, Georgetown.

Winstanley P, Dalagnol R, Mendiratta S, Braga D, Galvão LS. 2024. Post-logging canopy gap dynamics and forest regeneration assessed using airborne LiDAR time series in the Brazilian Amazon with attribution to gap types and origins. Remote Sens 16 (13): 2319. DOI: 10.3390/rs16132319.

Wirnoyo, Lukman AH, Nurliana S. 2022. The species diversity and composition of seedlings for degraded land rehabilitation in different phytogeographical regions in Indonesia. Biodiversitas 23 (11): 5771-5781. DOI: 10.13057/biodiv/d231130.

Yuniawati, Andini S, Ningrum MH. 2023. Application of conventional and improved techniques in felling and skidding to residual stand damages. Jurnal Manajemen Hutan Tropika 29 (3): 234-241. DOI: 10.7226/jtfm.29.3.234.