Soil Disturbance by Logging Operation of Industrial Plantation Forest in Indonesia

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Abstract. Logging concessions in natural forest and industrial plantation forest are the main producers of logs in Indonesia. Several companies of industrial plantation forest have been successfully planted with fast-growing species such as Acacia mangium for pulpwood. These plantation forests have entered their annual harvesting period. Some options of timber harvesting machines such as forwarder, harvester, feller buncher, and excavator are chosen to remove timber from stump to the log landing site. The negative impact of such machines includes the loss of topsoil and soil compaction. The objectives of the research were to analysis soil compaction by excavator with log carrier in forwarding log from stump to landing site. Bulk density, cone index and deep of rut were measured after logging operation at the harvesting site at one of industrial plantation forest of South Kalimantan. The result showed that soil bulk density increase with the increase in the number of excavator with log carrier passes. The rut was formed on several places on the soil surface, particularly near landings and under the log carrier. The ground pressure of the excavator and log carrier caused the formation of the rut on the soil surface. Weight of excavator plus loads had caused pressure on the track of the contact with the ground. Rut formed and high soil bulk density indicated the soil compaction occurred by the harvesting operation.

1. Introduction

Skidding or forwarding the logs is part of timber harvesting activity. Skidding generally uses heavy machines. Skidding machine operations generally damage forest soils in the form of opening of soil surface layers or soil compaction. Using forwarder in skidding log in industrial forest plantations causes soil compaction. High ground pressure of the forwarder tire and the surface contact affect very intensive of soil compaction. More the soil compacted the more decrease soil porosity. Forwarder maneuvers cause the formation of deep rut on the traces of the tire which shows soil damage due to heavy equipment operations [1, 2, 3, 4].

Logging operation using harvesting machines such as forwarder causes an increase soil bulk density, reduce total porosity, reduce infiltration rate dan soil permeability, reduced water capacity and
change in soil structure [5]. Each pass of harvesting machines tends to cause soil compaction, more traffic machines passes the more soil compacted [6].

There is a relationship between skidding intensity (machine traffic or machine passage) or number of timber extracted with the increase in soil density of forest soil. The higher skidding intensity the more soil bulk density increases. At the beginning of skidding of forwarding the log up to 4 to 5 passes there is a drastic increase in soil bulk density but subsequently it is relatively constant [7, 5].

In some harvesting areas of industrial plantation forest use forwarders in timber harvesting but there are several timber companies using modified excavator called pontoon excavators. The objectives of this study are to measure the level of soil bulk density after skidding operation and analyze the comparation between two skidding machines of it impact to soil bulk density and rut formation.

2. Method

2.1. Materials
An excavator machines with a carrier log were observed for this soil compaction study. The excavator machine specification included in the Figure 1 and Table 1. The soil compaction tools used for this research were cylinder soil sampler, mainly for the soil mass measurement. Cone penetrometer were used to measure cone index value, which collected the soil resistance information underneath the carrier log. The study location is one of industrial plantation area in South Kalimantan, in which the Acacia mangium planted. This study location selected based on the intensity of log skidding activities used in the timber harvesting activity in the forest and also the availability of excavator with log carrier (local name: ponton darat) used for this skidding process.

![Excavator ZX 200](image1)

![Log carrier](image2)

**Figure 1.** Excavator ZX 200 skidding the log using log carrier

| Machine          | Specification                  |
|------------------|--------------------------------|
| **Excavator**    |                                |
| Model            | Excavator Hitachi ZX200         |
| Engine rate power| 110 kW (147 HP)                |
| Operation weight | 19 800 kg                      |
| **Log carrier**  |                                |
| Dimension (lxwxh)| (4x2x0.7) m                    |
| Material         | Steel                          |
| Wire rope (length)| 2 m                           |
| Capacity (load of wood) | 12-14 m³                |

Source: Hitachi Construction Machinery, www.hitachi.com
2.2. Procedure

The soil compaction measurement started with tracking and following a line of production in the skidding process. The excavator mobility was tracked from each harvesting block from the stump to the landing site for collecting the log. The trajectory of every heavy machine in the forest were tracked, followed by marking on each traverse movement (passage) on the same pathway. The marking of this passage activity was performed up to 8 times on the same machine pathway. The soil compaction measurement conducted 10 times, soil ring and cone penetrometer sampling protocol were performed every 3 meters of pathway length. Bulk density measurements were performed on the soil laboratory by weighting each of the soil sample collected from the pathway followed by water content measurement and soil physical properties. Soil resistance was measured using cone penetrometer to obtain the cone index on the top soil to the 40cm depth of soil. The result of this cone index was used as quantitative parameter for the soil compaction parameter using surface resistance indicator on the cone penetrometer. The more positive the cone index value means the density of the soil is increasing.

Rut is a deformation surface of soil in a form of concave depression. This surface feature was formed by both machine overburden and carrier log. The rut measurement was calculated using the following equation (Figure 2).

\[ \text{Rut (cm)} = \frac{(R+L)}{2} \]

![Figure 2. Rut measurement after skidding ke log with Excavator ZX200 and log carrier](image)

2.3. Soil Compaction Calculation

Soil density measurement was carried out using a cylindrical tube and calculation of bulk density value was done using the following formula [8]. Soil bulk density were calculated based on the following equation:

\[ \gamma_s = \frac{W_2 - W_1}{V} \]

where:
- \( \gamma_s \) = wet soil mass density (g cm\(^{-3}\))
- \( W_2 \) = weight of wet soil and cylindrical tube (g).
- \( W_1 \) = weight of cylindrical tube (g).
- \( V \) = volume of wet soil sample (cm\(^3\))

\[ \gamma_d = \frac{\gamma_s \times 100}{100 + W} \]

where :
- \( \gamma_d \) = bulk density (g cm\(^{-3}\))
- \( \gamma_s \) = wet soil mass density (g cm\(^{-3}\))
- \( W \) = moisture content of soil sample (%)

Cone penetrometer was pushed into the soil from the soil surface to a depth of 40 cm. Readings of received soil resistance on the cone surface were usually taken at each interval depth of 10 cm, where the value was inputted on the formula for calculating the value of cone index or penetration resistance as follows [9]:
Tp = (0.384Fp + W) / Ak
where: Tp = penetration resistance/cone index (kgf cm$^{-2}$)
Fp = measured penetration force on the penetrometer (kgf)
W = weight of equipment (kg)
Ak = cone base area 3.23 cm$^2$

3. Result and discussion

Timber harvesting performed by clear cutting using a chainsaw. The timber extraction from stump to landing site which a location of piling the log or stacking. This skidding log activity were performed using the excavator with specification of Hitachi Excavator ZX200. An additional tools of log carrier were attached to the back of this excavator (local name: ponton darat). The relative slope of the study area was between 0 to 15%. The type of soil in the study area was the ultisol and texture of this soil was clay.

The control measurement of the soil compaction on the undisturbed soil zone with no excavator and carrier log activity (non-pathway) showed the bulk density of 0.88 ± 0.08 g.cm$^{-3}$. The initial value of undisturbed condition was increased by 10% to the value of 0.97 ± 0.14 g.cm$^{-3}$ after the first excavator passage movement, followed by significant compaction during the second to the fourth passage of the excavator. This significant compaction increased the soil compaction by 30% to the value of 1.31 ± 0.07 g.cm$^{-3}$. The maximum bulk density compacted during the fifth passage of excavator with 1.32 ± 0.06 g.cm$^{-3}$ (Table 2).

| Table 2. Soil compaction by log carrier of Excavator ZX 200 in logging operation |
|----------------------------------|-----------------|-----------------|
| Total number of passages of log carrier | Bulk density (g.cm$^{-3}$) | Porosity (%) |
|----------------------------------|-----------------|-----------------|
| 0*                              | 0.88 ± 0.08     | 66.95 ± 3.03    |
| 1                                | 0.97 ± 0.14     | 63.34 ± 5.13    |
| 2                                | 1.13 ± 0.08     | 57.25 ± 2.95    |
| 3                                | 1.18 ± 0.06     | 55.43 ± 2.45    |
| 4                                | 1.31 ± 0.07     | 50.75 ± 2.76    |
| 5                                | 1.32 ± 0.06     | 50.55 ± 2.36    |
| 6                                | 1.32 ± 0.04     | 50.51 ± 2.13    |
| 7                                | 1.32 ± 0.05     | 50.45 ± 2.54    |
| 8                                | 1.32 ± 0.06     | 50.40 ± 3.12    |

*Undisturbed condition

The critical point of this result was the drastic soil density intensification during the four excavator passages. After this critical point, the constant value of soil density achieved due to the maximum compaction capability up to the 8th excavator passage movement (Figure 3).
In the case of the soil porosity, the natural soil porosity decreases during the soil compaction activity. The rate of porosity reduction yields a positive correlation with the bulk density value. The initial undisturbed value of soil porosity was $66.95 \pm 3.03\%$. This value decreased by 5% to $63.34 \pm 5.13\%$ after the first excavator. The porosity reduced significantly by 24% to $50.75 \pm 2.76\%$. After the fourth excavator passage movement, the porosity of the soil was not reduced further and maintain the value of $\pm 50\%$. The porosity trend showed in the following Figure 4.

**Figure 3.** Tendency of increasing soil bulk density related with the increasing number of log carrier.

**Figure 4.** Tendency of decreasing soil porosity related with the increasing number of log carrier passages.

The available method for soil compaction measurement are cylinder soil sampler for bulk density measurement and cone penetrometer for the cone index. The cone penetrometer is the simplest method available and commonly selected for its swiftness with less precision. In this research, the cone penetrometer measurement on the undisturbed (initial) soil showed the increasing cone index with
The cone index measurement after first excavator passage with the carrier log attached showed an increase in the cone index not only on the soil surface but also through the 40cm depth.

The cone index parameter increased at the same rate as the soil compaction occurred and the value showed a significant raise at the top soil level to the 20cm depth. The soil compaction was occurred at a lower intensity for the further depth until it appear to reach the constant during the third passage of excavator and also in the depth of 30cm (Figure 5). The initial cone index value of undisturbed soil condition was 5.4 kgf.cm\(^{-2}\) at the top soil level and 13.0 kgf.cm\(^{-2}\) at 40cm depth. The highest soil compaction occurred at the last (8\(^{th}\)) passage of excavator with cone index value of 12.14 kgf.cm\(^{-2}\) at the top soil level and 14.1 kgf.cm\(^{-2}\) at the 40cm dept.

**Figure 5.** Cone index in each excavator passagaes at surface to 40 cm soil depth.

**Table 3.** Rut depth of soil surface after the number of log carrier passages

| Total number of passages of log carrier | Left (L)  | Right (R) | (L+R)/2 |
|----------------------------------------|-----------|-----------|---------|
| 0                                      | -         | -         | -       |
| 1                                      | 10 ± 2.4  | 14 ± 1.8  | 12 ± 2.1 |
| 2                                      | 14 ± 2.8  | 14 ± 2.0  | 14 ± 2.4 |
| 3                                      | 16 ± 1.8  | 16 ± 1.6  | 16 ± 1.7 |
| 4                                      | 17 ± 2.3  | 17 ± 2.1  | 17 ± 2.2 |
| 5                                      | 18 ± 1.4  | 18 ± 1.6  | 18 ± 1.5 |
| 6                                      | 18 ± 1.2  | 18 ± 1.0  | 18 ± 1.1 |
| 7                                      | 18 ± 1.0  | 18 ± 1.4  | 18 ± 1.2 |
The weight of the machine with timber attached to the carrier lead to rut soil deformation at the top soil level due to the ground pressure overburden. In the study area, the rut easily recognized and it was developed during the skidding process using the same machine. The rut damage in the excavator trajectory was occurred with $12 \pm 2.1\text{cm}$ at the first passage to $18 \pm 6.2\text{cm}$ at the last (8th) passage of the excavator. The rut depth maintained at relatively constant level start at the fifth passage to the eighth passage with $18\text{cm depth}$ (Table 3). Numerous rut formation occurred on the landing site due to the fact that the area was a merging point of the excavator pathway along with high manoeuvre intensity.

The harvesting machine usage on the production forest known to be compacting the soil by increasing the bulk density at the harvesting machine pathway during the logging operation [10, 11, 12]. Lotfalian & Parsakhoo [13] found that a maximum compaction of the soil occurred after 18 cycles of skidding passage with bulk density of $1.6 \text{ g.cm}^{-3}$. We suggested that the difference result of our research exist due to the machine different, which yield to the different overburden and ground pressure at the top of the soil. At the same time, increased soil compaction linked to the deformed soil feature known as rut. The rut occurrence known to have a positive correlation to the passage intensity of the harvesting machine [3, 14, 15].

Previous research showed that the soil compaction lead to the disturbed of seedling growth [6, 16, 17]. Coder [18] suggested that the soil compaction yield negative impact on the root development specifically both the longitudinal and the radial root direction. Matangaran [19] suggested that further soil compaction in the production forest yield a problem of a disturbance of young plants development on the compacted soil and also reduced the root penetration of the vegetation. The implication of this disturbance linked to the nutrient absorption interference of the seedling or tree which yield a slower growth rate compared to the vegetation developed in the natural undisturbed soil. The recovery rate of this soil compaction problem was more than one decade [20]. This problem not only caused a problem of biomass loss [21, 22], but also reducing the rain water infiltration which yield to the run off problem related flood [23].

4. Conclusion
We conclude that the excavator manoeuvre and carrier log during the skidding operation are the source of soil disturbance, which modified the of bulk density of the soil and increases the soil compaction. The increasing skidding activity in the production forest yield an intensification of soil compaction, as this skidding operation intensity have a positive correlation to the soil disturbance intensity. The soil compaction occurred from the top soil to $40\text{ cm depth}$ with rut underneath the carrier log by the log overburden.

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