Soil macroporosity, physical properties and nutrient leaching after forest conversion to rubber and oil palm plantation in an Acrisol of Jambi, Indonesia

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Abstract

Soil degradation is expected to continue as forest conversion into other land uses increases significantly. In Indonesia, Jambi is one of the main areas for the development of oil palm and rubber, which are mainly converted from the forest. As a base for better management, we attempted to study macro-porosity in rubber and oil palm plantation in comparison to secondary forests. Four land use systems (secondary forest, jungle rubber, rubber plantation and oil palm plantations) in Bukit Duabelas, Sarolangun District, Jambi Province, Sumatera, were selected for this study. The number of macropores in vertical or horizontal planes and their related factors (root mass, litter thickness, % organic C, bulk density, water content at pF 0 and pF 2.54, aggregate stability) were measured within the soil profiles. Forest conversion to jungle rubber, rubber and oil palm plantation led to a decrease of macro-porosity in the soil profile, especially in the upper 50 cm. Macropores, both at vertical and horizontal planes in the secondary forest was significantly higher than other land uses. Horizontal macropores in jungle rubber were higher than rubber and oil palm plantation, but not the vertical macropores. Among the soil properties measured, litter thickness, coarse root dry mass (Ø >2 mm), mesopores and aggregate stability were closely associated with soil macro-porosity. However, macro-porosity in the soil profile was insignificantly correlated to soil bulk density and % organic C. Increasing the number of horizontal macropores resulted in higher nutrient leaching, especially K and Na.

Introduction

Tropical forests, which typically play an important role in maintaining environmental quality, continues to decline in three decades, as forest conversion into other land uses increased significantly. Tropical forest with an area of 1,760 million hectares (Watson et al., 2000), has undergone conversion rapidly since the year 1970. In Indonesia itself, in the past 1985-1997 forest conversion was approximately 20 million ha (FWI/GFW, 2002), and it was recognized as the country with the largest increase of forest cover loss from 2000 to 2012 (Hansen et al., 2013).

Forest conversion into agricultural land use in Indonesia has significantly increased since 1980, approximately at the same time when the transmigration program began to reduce population density in Java and hence expanding agricultural land in Sumatra, Kalimantan, and Sulawesi. However, the forest loss was not always related to the expansion of agricultural land but also due to the increasing need for wood industry, forestry, logging, and fires. Outside
Java, FWI/GFW (2002) estimated that 9 to 16 million hectares of forests were converted into oil palm and rubber plantations. About 30% of total forest loss in Indonesia occurred in Sumatera; and 70% of it occurred in Riau, Jambi and South Sumatera (Margono et al., 2012). Jambi is one of the main areas for the development of oil palm and rubber in Sumatra, with an area of 1,284,000 ha and 936,500 ha respectively for oil palm and rubber, from the total coverage area of 5.3 million ha (BPS, 2004).

The forest cover was originally supposed to have relatively high trees density, canopy cover (Martius et al., 2004), understorey vegetation (Hannerz et al., 1997), and litter input (Hairiah et al., 2006), and a deep rooting system. Previous studies showed that forest conversion caused higher bulk density and lower soil porosity in tea plantation (Bahrami et al., 2010); coffee-based agroforestry systems (Suprayogo et al., 2004); cultivated lands (Celik, 2005); in accordance with land use intensity (Yükseke et al., 2010). The effect of land-use transformation on soils have also been discussed to alter soil properties, i.e. soil carbon (Guillaune et al., 2015); soil fertility and soil physical properties in the newly established land use systems (Dechert et al., 2004; Klinge et al., 2004). These also lead to different pedogenesis processes (Agustina et al., 2016); higher leaching sensitivity (Kurniawan et al., 2018); higher runoff and erosion (Dariah et al., 2004; Mohammad and Adam, 2010), in tea plantation (Li et al., 2012), coffee-based agroforestry systems (Widianto et al., 2004), cacao (Dawoe et al., 2014), and oil palm plantation (Sunarti et al., 2008).

Soil properties and soil processes in relation to land use change were mostly connected to the soil porosity. Total soil porosity was commonly predicted based on bulk density and particle density, or pF 0, whereas macropores which play an important role in water flow, were determined between pF 0 and pF 4.2. These methods use undisturbed soil sampling using ring samples, which unfortunately exclude large pores and root channels during the sampling. Only a few researchers studied these pores, which are normally larger than 2 mm in size (macropores). However, these macropores are closely related to infiltration, controlling erosion and nutrient leaching, which in turn leading to soil impoverishment. Evaluating the impact of forest conversion on soil macroporosity, its relation to physical properties and nutrient leaching was still interesting; therefore, we attempted to study these aspects in rubber and oil palm plantation in Jambi.

**Materials and Methods**

The research was conducted in Bukit Duabelas landscape of Sarolangun District, Jambi Province (Figure 1). We selected four land use systems (SF = secondary forest, JR = jungle rubber, RP = rubber monoculture, and OP = oil palm plantations), and each repeated three times. In each land use, we measured soil macro-porosity and took soil samples from 5 depths (0-20, 20-40, 40-60, 60-80, and 80-100 cm) for soil physical analysis (bulk density, particle density, pF 0, pF 2.54, aggregate stability and organic C content (Klute, 1986)).

**Figure 1. Research sites in Jambi.**
They were taken in the middle of the adjacent trees (in forest, jungle rubber and rubber plantation) and in 3 different zones in oil palm plantation (fertilized zone, inter-row, and frond piles). For comparison between 4 land uses, we used a weighted average of 3 zones in oil palm plantation based on the coverage area of each zone (Banabas et al., 2008). Macroporosity measurement followed the method described in Suprayogo et al. (2004). The number of macropores was measured using methylene blue, which in principle is calculating the area of the methylene blue dye infiltrate in the soil profile. Methylene blue solution (0.04 g L⁻¹ of water) was applied to a frame over a soil surface of 100 cm x 50 cm x 30 cm (Figure 2), and allowed to infiltrate overnight. The methylene blue which passes the micropores will be absorbed by the soil matrix but will stain the macropores. The distribution of blue stain was drawn on transparent sheets for both vertical and a sequence of horizontal planes (10, 30, 50, 70, and 90 cm depth). These figures were then digitized and the stained area was calculated using Image J program to predict % macropores.

![Figure 2. Measurement of macropores with methylene blue.](image)

In addition, the study collected root samples from each of the 12 plots by digging a pit (1 m x 1.5 m x 1 m depth) in an area outside each plot delineated for destructive sampling. Pits were dug at 2.5-3.5 m distance from a tree with a diameter at breast height (dbh) ≥10 cm. Root mass was sampled using a metal block (20 cm x 20 cm x 10 cm) at a 10-cm depth interval from the top down to 1-m depth. Roots were carefully separated from the soil by washing over a 2-mm mesh screen, and in a basin placed underneath the mesh screen, the fine roots were collected. The roots were categorized into fine roots (≤ 2 mm diameter) and coarse roots (> 2 mm diameter), dried in an oven at 70 °C for 5 days and weighed. A Shapiro-Wilk’s test was first conducted to test the normality of data of total coarse root mass within 1-m depth. For the parameter that showed non-normal distribution, we used logarithm or square root transformation. Differences among land uses for each landscape were assessed using linear mixed-effects models, with land uses as a fixed effect and spatial replication (plot) as random effect followed by the least significant difference test at P ≤ 0.05.

**Results and Discussion**

**Impact of land use on soil porosity**

*Pores in soil matrix*

We defined the content of soil pores predicted by water content (v/v) in the pF curve as pores in the matrix since these pores exclude macropores contribution of root channels and biologic turbation. To differentiate between pores in the matrix and macropores measured by methylene blue, we assumed water content at pF 0 as total pores in the soil matrix, water content at pF 2.5 assumed to be micropores, and mesopores were calculated between the two pF values. Generally, total pores, as well as meso and macropores decreased with increasing soil depth, but not micropores (Figure 3). This might be due to the decreasing organic matter content and increasing clay content with depth.

*Macropores*

The results showed that macropores both on vertical or horizontal planes in the secondary forest were higher than jungle rubber, rubber plantation and oil palm plantation. For vertical macropores, there were no significant differences between jungle rubber, rubber and oil palm plantation. Horizontal macropores, in jungle rubber, however, was similar to secondary forest and higher than rubber and oil palm plantation (Figure 4). The results indicated that forest conversion to other land uses decreased macroporosity, especially the upper soil layer. This also occurred in coffee-based agroforestry in Lampung (Suprayogo et al., 2004; Simanjuntak, 2005) or other cultivated agriculture (Shougarkpam et al., 2010). The results showed that the transformation of forest land to other land uses decreased soil macroporosity, especially at the top layer (0-50 cm). This indicated the occurrence of the destruction process of the aggregates and soil compaction on the soil surface. This could be related to the more open surface in rubber and oil palm plantation due to the lower litter layer, which protecting soil structure from raindrop disruption.
Soil secondary particles will be disaggregated (Ma et al., 2014), and these particles will be easily transported to the deeper layer and filled the pores inside. Furthermore, Suprayogo et al. (2004) found that the decreasing soil vertical and horizontal macroporosity after forest conversion to the coffee plantation was correlated to the decreasing of organic matter, cover crops density, lower and shallower root distribution in the soil profile.

A lower macroporosity in rubber and oil palm plantation could be associated with the increasing bulk density, which was probably due to the intensive human activities. Activities such as trampling and weeding with herbicide make the soil more compacted and reduce the formation of large pores (Li et al., 2012). Compacted soil surface could induce a reduction in infiltration and percolation, which favour an increase of runoff and erosion. Sunarti et al. (2008) also found higher surface runoff and erosion in the rubber plantations compared to forests.

Factors determining soil macropores

Coarse roots

The study showed that the coarse root mass in the top soil (0-20 cm) were larger in the secondary forest than in the rubber and oil palm plantations (Table 1), in which 89% of the coarse roots were located in the top 40-cm depth. According to Kurniawan et al. (2018), the forest had a higher coarse root mass than oil palm, which could be due to the higher tree densities in forests (471 ± 31 trees ha\(^{-1}\)) than in oil palm plantations (134 ± 6 trees ha\(^{-1}\)). Furthermore, tree size could also influence the differences in coarse roots: in the forest plots, the trees closest to the dug pit were bigger...
(dbh: 24.7 ± 5 cm) than in rubber plantations (dbh: 16.4 ± 2 cm). Another factor that may influence
the higher coarse root mass in the forest than in oil palm and rubber plantations was the understorey
vegetation (e.g., saplings and poles). In the deeper layer (60-80 cm depth of soil), the coarse root mass in
the rubber and oil palm plantation were larger as compared to the forest (Table 1).

Table 1. The mass of coarse root in the 0-100 cm depth within different land uses in Jambi, Sumatra, Indonesia.

| Soil depth (cm) | Forest | Jungle rubber | Rubber | Oil palm |
|----------------|--------|---------------|--------|----------|
| 0 – 20         | 1055.8 ± 280.8 a | 845.9 ± 196.9 ab | 440.2 ± 128.7 b | 374.9 ± 31.9 b |
| 20 – 40        | 232.8 ± 87.9     | 170.3 ± 48.3    | 75.2 ± 30.1    | 129.3 ± 16.6 |
| 40 – 60        | 30.9 ± 12.1      | 113.8 ± 91.9    | 22.9 ± 11.0    | 56.4 ± 13.0 |
| 60 – 80        | 10.5 ± 3.8 b     | 6.7 ± 3.8 b     | 23.1 ± 10.1 a  | 44.4 ± 10.3 a |
| 80 – 100       | 9.0 ± 4.0        | 11.4 ± 7.8      | 12.3 ± 4.7     | 26.2 ± 2.8  |

*Means (± SE n=3) followed by different letters indicate significant differences among land use types (linear mixed-effects model followed by least significant difference test at P<0.05).

Litter thickness

Litter thickness was measured only in the forest, jungle rubber and rubber plantation. Correlation and
regression analysis of the results showed a significant positive correlation between soil macroporosity and
litter thickness which were measured in the forest, jungle rubber and rubber plantation (r = 0.70* and
R² = 0.50). This means that the thicker the litter layer, the higher is the soil macroporosity. Macroporosity is
closely related to rooting depth and soil fauna activities, which largely depend on the quality and
quantity of the litter as a source for organic matter. Macroporosity was found to be higher in the frond
piles compared to fertilized zones and inter row in oil palm plantation. Similar results were also found in
the forest conversion to a coffee plantation in Sumberjaya (Hairiah et al., 2004). However, the results indicated
that litter thickness only contributes 50% of the variation of soil macroporosity, meaning that other
factors play a significant role in determining soil macroporosity.

Soil organic carbon

The results showed that SOC in oil palm plantation was the lowest than other land uses. As explained
earlier, the value was calculated based on the weighted average of the 3 zones measured (fertilizer zone, inter
row, and frond piles). The frond piles area normally has higher SOC content compared to the fertilizer zone
and inter row area. However, the frond piles area is presumed to have only 24% of the whole area,
compared to inter row area (60%) which has the lowest SOC content. This result indicated that the
accumulation of the frond piles could not cope with the decreasing SOC due to the open space between oil
palm trees. Correlation and regression analysis showed that organic carbon is significantly correlated to soil
bulk density (r = -0.64** and R² = 0.41), aggregate stability (r = 0.66** and R² = 0.44), and the total and
mesopores in the soil matrix (r = 0.66** and R² = 0.43). Soil organic matter is well-known as
cementing agent for binding primary particles to form aggregates of secondary particles (Hoorman et al.,
2011). Soil rich in organic matter tend to be well aggregated, hence have higher macroporosity and
lower bulk density. The regression coefficient values range between 41-44%, which means that there are
other factors (56-59%) that affect soil the physical properties. Lado and Ben-Hur (2004) stated that clay
content might also affect the formation of aggregates and their stability. Environmental factors can also
affect the physical properties of the soil, such as farmer’s activities (Li et al., 2012).

Bulk density

Generally, all land uses showed decreasing soil bulk density with depth. In the upper 20 cm, jungle rubber
has the lowest bulk density, followed by oil palm, secondary forest and the highest bulk density occurred
in rubber plantation (Figure 5). This data again indicated that secondary forest is actually very much
disturbed, or there is a tendency that a well-managed jungle rubber may maintain low bulk density.
However, when we look at the 60-80 depth, soil bulk density is also higher than other land uses. At this
depth, soil properties are largely affected by the original characteristic of soil parent materials.
Assuming that soils under all land uses experienced similar pedological processes, we would expect that at
all depths, the order of soil bulk density would be oil palm, jungle rubber, rubber plantation, and secondary
forest. However, at the upper 20 cm, soil bulk densities in jungle rubber and secondary forest are lower than oil palm and rubber plantation, respectively.

This indicated that there is an improvement of soil physical condition under jungle rubber and
secondary forest. Increasing bulk density after forest conversion was also indicated in coffee-based
agroforestry systems in Sumberjaya, Lampung, which was due to soil compaction, as indicated by higher
penetration strength (Suprayogo et al., 2004). Similar results were shown in rubber and tea plantation in
China (Li et al., 2012), related to rubber tapping activity intensity. Soil bulk density is apparently insignificantly correlated to macropores in the soil profile. This could be because the measurement of bulk density is based on a small cub (diameter 8 cm, height 8 cm), which excludes larger pore size.

Aggregate stability

The mean weight diameter (MWD) using a wet sieving method was commonly used as an index of soil aggregation. The results showed that all land uses were classified as having very stable aggregate (>2 mm), which decreased with increasing soil depth (Figure 6). There was no significant difference among the land uses; however, secondary forest apparently had rather lower MWD than other land uses. These results were comparable with Banful and Hauser (2011) who studied aggregate stability in secondary forest and bush. Kara and Baykara (2014) also found lower aggregate stability in the forest soil compared to farmland and grassland. The transformation of forests into coffee plantation also showed an insignificant effect on the stability of soil aggregates (Suprayogo et al., 2004).

Mesopores in soil matrix

Macropores in the soil can be formed by the activity of soil fauna, rooting, and the effect of soil physical properties such as cracks (Beven and Germann, 2013). Soil macropores may consist of rooting channels, wormholes and other soil fauna, as well as meso-pores in the soil matrix. Correlation and regression analysis showed that macroporosity in the soil profile was significantly correlated to mesopores in the soil matrix ($r = 0.42^{**}$ and $R^2 = 0.61$). This indicated that measurement macropores in the soil profile was partly coincided with mesopores in the soil matrix which was lower.
predicted from the pF curves. The regression coefficient value which amounted to 61%, indicated the largest part of macro pores in the soil profile was contributed to mesopores in the soil matrix. Whereas the other 39% could be attributed to larger pores affected by earthworm (Hairiah et al., 2004) and root channels (Ghestem et al., 2011).

Consequences of soil macroporosity on nutrient leaching losses

Nutrient leaching losses increased in accordance with horizontal macropores (Figure 7), but not vertical macropores. This was supported by the positive correlation between cumulative horizontal macropores and basic cations leaching fluxes, especially potassium (K⁺) and sodium (Na⁺) (r = 0.54 – 0.57, p = 0.05-0.07, n = 12). A higher soil macro porosity is supposed to have higher water drainage fluxes and as a consequence leading to larger nutrient leaching into deeper layers. The smaller effect of vertical macropores was probably due to the “bypass flow” effect (Suprayogo et al., 2002), in which water infiltrates to the soil, flows through vertical macropores, and directly percolate to the deeper layer. Whereas in the horizontal macropores, the infiltrating water has sufficient time to dilute soil nutrient adsorbed on the solid particle surfaces, and hence increased nutrient leaching process.

Conclusion

Forest conversion to jungle rubber, rubber and oil palm plantation in Jambi tend to decrease macroporosity in the soil profile as well as mesopores in the soil matrix, especially in the upper 50 cm. Macropores, both at vertical and horizontal planes in the secondary forest was significantly higher than other land uses. Macropores at the horizontal plane in jungle rubber was higher than in rubber and oil palm plantation. However, there was no significant difference between the vertical macroporosity in the jungle rubber, rubber and oil palm plantation. This pattern in the profiles was in accordance with soil organic C content, aggregate stability, total and mesopores in the soil matrix, and litter thickness. Among the soil properties measured, litter thickness, coarse root dry mass (Ø > 2 mm), mesopores and aggregate stability were the most determining factors for soil macroporosity. However, macroporosity in the soil profile was apparently insignificantly correlated to % organic carbon and soil bulk density. The increasing number of horizontal macropores resulted in higher nutrient leaching, especially K and Na.

Figure 7. The effect of cumulative horizontal soil macropore on nutrient leaching fluxes (i.e. K and Na).

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