Biophysical properties of various ages oil palm plantation in Ultisols of Bengkulu

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Abstract. Oil palm plantation (OPP) expands to soil with less suitable including Ultisol. The purposes of this study were (1) to compare some selected soil properties among various OPP ages and (2) to determine the correlation among the selected soil properties. A Completely Randomized Block Design with single factor treatments of oil palm age consisting of 2-yr, 3-yr, 4-yr, 8-yr, and 32-yr of OPP, and all treatments was repeated three times. Blocking was based on the OPP floor positions: circle weeding (CW), frond stack (FS), and between palm (BP). All data were statistically analyzed using ANOVA with 5% α, and DMRT at 5% α was used to compare treatments. The result showed that using Ultisol in OPP with good management especially keeping or improving soil organic C through maintaining understory vegetation, may reach soil sustainability. Increasing oil palm ages followed by increasing organic C, water holding capacity (WHC), and decreasing bulk density (BD). The highest oil palm root density (OPRD), oil palm dry root density (OPDRD), and CO₂ emissions were found at the 8-yr OPP, while the highest value of understory vegetation biomass weight (UVBMW) and understory vegetation biomass dry weight (UVBMDW) were reached at 4-yr OPP. Organic C was weakly correlated with actual soil moisture (ASM) (r=0.485) and aggregate stability (AS) (r=0.465)

Keywords: biophysical properties, oil palm age, plantation floor, understory vegetation.

1. Introduction
The area of oil palm plantation (OPP) in Indonesia continuously developed. In 1986 area of OPP in Indonesia was 593.800 ha (0.59 mil. ha), in 2002 was 4.11 mil. Ha, in 2014 was 10.75 mil. ha, while by the end of 2019 was reported to be 14.6 mils. ha [1]. Besides its area, crude palm oil (CPO) production was also reported to continuously increase, making Indonesia the biggest CPO production globally, followed by Malaysia. It was predicted that OPP in Indonesia would continuously develop in line with the increasing demand of CPO to fulfill it for biodiesel. Oil palm can grow well in various soil orders such as Andisols, Histosols, Entisols, Inceptisols, and Ultisols. However, more detailed land suitability for oil palm cultivation may result in unsuitable or less suitable in each soil order. Since the demand for land for OPP development increases, while the available suitable soil is limited, soil with less suitable was exploited. A couple of risks of forcing less or unsuitable land were soil degradation, higher cost per unit product, and unsustainable plantation. Oil palm cultivation is the most controversial issue regarding
environmental concerns such as global warming and biodiversity due to forest conversion to OPP [2], [3].

Ultisols were soils with advanced development characterized by relatively low CEC, low base saturation (BS), and low P, K, Ca, and Mg, with high Al and acidity generally because of their intensive leaching processes. As a result, the most suitable Ultisols have been developed. At the same time, the available land for OPP development was dominated by less suitable land, with various restrictions such as soil depth and soil topography. In Indonesia, the coverage area of Ultisols is about 46.27 mil. ha, distributed in Kalimantan is 21.94 mil. Ha, Sumatera is 9.47 mil. ha, Maluku and Papua are about 8.86 mil. Ha, Sulawesi 4.30 mil. Ha, Java is about 1.17 mil. ha, and Nusa Tenggara is less than 0.53 mil. Ha. In Bengkulu, Ultisol is the second largest area (0.71 mil. ha) after Inceptisols which cover more than 0.99 mils. Ha. Most Inceptisols, however, are in steep slope areas and are generally assigned as conservation forests [4].

Most plants can be cultivated in Ultisol. However, more management attention, such as fertilizer, must be given due to its limited nutrient availability. Although Ultisol can be used to cultivate most plants, OPP is believed to cause decreasing soil biophysical properties. Deterioration of soil properties may happen due to preparation activities before planting, such as land clearing, burning organic matter waste, and utilizing heavy machinery [5]. It has also happened during the growing processes of OPP, such as decreasing organic matter, clay content, aggregate stability, and increasing soil BD [6]. Therefore, besides the natural characters of Ultisols, OPP management could also affect the deterioration of soil biophysical properties. Plantation management varies greatly among plantations, moreover when smallholders of OPP are considered.

Regardless of its risk in developing OPP, oil palm is one of the most productive vegetable oil crops per unit area, and it is one of the most important agricultural industries in Indonesia [7] [8]. Besides its important role in agricultural industries, OPP is also noted as the most controversial environmental issue, such as biodiversity and global warming due to forest conversion to OPP. Because of its controversial issues, oil palm industries attract more attention to broad stakeholders. As a result, there is considerable market demand for palm oil to be certified as sustainable by the Round Table on Sustainable Palm Oil (RSPO) [9]. With a life cycle of more than 20 yr, oil palm can operate long-term sustainable management practices. One of the most crucial aspects for plantation to be certified by RSPO was to improve soil sustainability [10].

In line with the issues of plantation sustainability, this study was conducted to determine the soil biophysical properties of 2-yr to 32-yr OPP in PT Bio Nusantara Technology Bengkulu. The general purposes of this study were to understand the effect of OPP in less suitable land for soil sustainability, while the specific objectives were : (1) to compare some selected soil biophysical properties among 2-yr, 3-yr, 4-yr, 8-yr, and 32-yr OPP; and (2) to determine the correlation among the selected soil biophysical properties.

2. Methods
The research consisted of field activities and laboratory analysis. Field activities included soil sampling, measuring in situ CO\textsubscript{2} emissions, taking sample understory vegetation, and observing earthworm populations density (EWPD) in PT Bio Nusantara Technology, Pondok Kelapa, Central Bengkulu, Bengkulu (Figure 1). Geographically, PT Bio Nusantara Technology is located at around 3°40’ South and 102°14’ East. The research area was selected based on the different OPP ages, similar soil properties, or the same soil order. The OPP ages varied from 2 yr to 32 yr old, while the soil order was described as the Ultisol. The laboratory analysis activities included all soil sample analyses for selected soil biophysical properties and were carried out in the Soil Science Laboratory, Faculty of Agriculture, University of Bengkulu. All field activities were carried out during the rainy season, and by the time of soil sampling, the lower part of the OPP area was flooded, ranging from 0.1 to 3 m water depth for more than a week.

The study used a Randomized Completely Block Design (RCBD). The treatments consisted of oil palm ages, namely 2-yr, 3-yr, 4-yr, 8-yr, and 32-yr of OPP. All treatments were repeated three times
(the repetition was nested in oil palm age), resulting in 15 experimental units containing five oil palm plants with a plot size of 10 m x 20 m. Blocking was carried out based on three different plantation floor positions, including circle weeding (CW), between palm (BP), and frond stack (FS). Soil sampling was carried out using a ring sampler for undisturbed soils, while disturbed samples were collected by digging it from 0-20 cm depth. All selected variables, including earthworm population density (EWPD), understory vegetation biomass weight (UVBW), understory vegetation density (UVD), in situ CO$_2$ emission, and oil palm root density (OPRD) were determined in each treatment.

Undisturbed soil samples were used to determine the soil bulk density (BD), water holding capacity (WHC), field capacity soil moisture (FCSM), and actual soil moisture (ASM) using the gravimetric method [12]. At the same time, the disturbed soil samples were used to determine the organic C and aggregate stability (AS). A part of disturbed samples was kept in a refrigerator for aggregate stability (AS) analysis. At the same time, the rest was air-dried, ground, and sieved to pass a 0.5 mm sieve for organic C analysis [13]. Soil AS was determined according to the drip method [14]. In situ CO$_2$ emission determination following modified-method of Anderson's [15]. EWPD, OPRD, and oil palm dray root density (OPDRD) were determined based on the same soil monolith (20 cm x 20 cm x 20 cm) taken from each plot. EWPD and OPRD were determined by hand sorting method from the collected soil monolith [16]. Earthworms were counted, including the cocoon, and it was presented in (indiv. m$^{-2}$). Oil palm roots were also taken from the same collected soil monolith, washed, air-dried, and weight for OPRD (g m$^{-2}$). The roots were oven-dried for 24 hours at 60 °C and weighed to obtain root dry weight, and the OPDRD was presented in (g m$^{-2}$). Determination of UVD was performed by making a subplot of 0.5 m x 0.5 m, and all individual vegetation were counted, and the UVD was presented in (veg. m$^{-2}$). The understory vegetation biomass weight (UVBMW) was determined by cutting and collecting all vegetations, including litter inside the 0.5 m x 0.5 m subplot, and presented in (g m$^{-2}$). The understory vegetation biomass dry weight (UVBMDW) was determined by taking a sub-sample of UVBMW and oven it for 24 hr, in 60 °C and weight it for the dry weight (g m$^{-2}$) [17].

All data were statistically analyzed using analysis of variance (ANOVA) with a 5% $\alpha$, and DMRT (Duncan’s Multiple Range Test) at 5% $\alpha$ was used to compare treatments.

3. Results and discussions

3.1. Results

This study has been conducted in PT Bio Nusantara Technology, Pondok Kelapa, Central Bengkulu, Bengkulu. The total area of this plantation is about 6.000 ha, located in the district of Central
Bengkulu, Bengkulu Province, with the elevation ranging from 200 to 300 m above sea level (asl). The soil in this area was described as a Ultisol and dominated by undulating topography. The most planted area has been terraced, and in general, the plantation is well managed, including fertilizer, cover crop, and pest management. In addition, this plantation is integrated with cattle farms, suggesting an improvement in soil fertility.

All collected data were analyzed with analysis of variance (ANOVA), and the analysis result was presented in Table 1.

Table 1. Results of the variance analysis of biophysical soil properties in PT Bio Nusantara Technology OPP Bengkulu.

| Selected Variables | Calc. F  | Probability | CV (%) |
|--------------------|----------|-------------|--------|
| UVBMW (g m\(^{-2}\)) | 17.27** | 0.0005 | 19.15 |
| UVBMDW (g m\(^{-2}\)) | 86.72** | 0.000001 | 15.52 |
| OPRD (g m\(^{-2}\)) | 13.96** | 0.0011 | 21.97 |
| OPDRD (g m\(^{-2}\)) | 11.53** | 0.0021 | 17.07 |
| CO\(_2\) emission (mg m\(^{-2}\) day\(^{-1}\)) | 5.56* | 0.0019 | 21.04 |
| EWPD (indiv. m\(^{-2}\)) | 1.43 ns | 0.3096 | 16.67 |
| Organic C (%) | 10.81** | 0.0026 | 5.86 |
| UVD (veg. m\(^{-2}\)) | 2.17 ns | 0.4380 | 39.72 |
| FCSM (%) | 0.99 ns | 0.4639 | 10.62 |
| BD (g cm\(^{-3}\)) | 6.39* | 0.3030 | 10.06 |

Note: **= significant at 1% \(\alpha\), *=significant at 5% \(\alpha\), ns=not significant at 5% \(\alpha\), \(\#\)= data were transformed by \((X + 0.5)\).

Table 1 shows that plant ages significantly affected UVBMW, UVBMDW, OPRD, OPDRD, CO\(_2\) emission, organic C, WHC, and soil BD but not significantly affected the EWPD, UVD, AS, ASM, and FCSM. All variables are not significantly affected by plantation floor position (block). It indicated that the plantation floor properties are uniform regardless of their position in a CW, BP, or FS. The study on OPP of different ages in peatland reported that the OPP floor's soil properties were significantly different among the CW, FS, and BP. The soil properties of the OPP floor were FS > WC > FS [18].

The 4-yr OPP showing the best UVW and UVDW, and decrease with increasing OPP age reaching the lowest UVW and UVDW at the 32-yr OPP, while the OPRD, OPDRD, and CO\(_2\) emission consistently show no difference among the 2-yr, 3-yr, 4-yr, and 32-yr OPP, but the 8-yr OPP showing the highest OPRD, OPDRD, and CO\(_2\) emission. It was due to the optimum growth of oil palm at the age of 6 to 11 yr. A previous study stated that oil palm reached optimum growth development and productivity from 4 to 11 years old [19]. At the same time, Organic C increase with increasing OPP age, getting the highest value at the 32-yr OPP. Therefore, it is promising that OPP with good management can maintain organic C content in good condition even in relatively less suitable land. Although EWPD and UVD were not significantly affected by OPP age, they followed the UVBMW or UVBMDW and organic C, reaching the highest value at 4-yr OPP. A previous study reported that increasing organic matter content in oil palm plantations could improve soil physical properties such as BD, soil porosity, soil moisture, and soil chemical properties, including CEC, BS, total N, and available P [20].
Table 2. Average of selected biological soil properties including UVBMW, UVBMDW, OPRD, OPDRD, CO₂ emission, EWD, organic C, and UVD of Ultisol in PT Bio Nusantara Technology OPP Bengkulu.

| Plant age (yr) | UVBMW (g m⁻²) | UVBMDW (g m⁻²) | OPRD (gm²) | OPDRD (gm²) | CO₂ emiss. (mg m⁻² day⁻¹) | EWD (indiv. m⁻²) | Organic C (%) | UVD (veg. m⁻²) |
|---------------|----------------|----------------|------------|-------------|-----------------------------|-----------------|--------------|----------------|
| 2             | 644.14 b       | 377.54 b       | 93.80 b    | 90.27 b     | 876.12 b                   | 0.00            | 3.61 c       | 18.81          |
| 3             | 447.09 bc      | 182.40 c       | 108.85 b   | 998.79 b    | 50.00                       | 3.96 bc         | 32.91        |
| 4             | 669.30 b       | 749.46 a       | 397.53 a   | 1784.38 a   | 33.33                       | 4.38 b          | 37.61        |
| 8             | 248.44 c       | 87.26 d        | 152.57 b   | 1334.46 ab  | 16.67                       | 4.86 a          | 30.56        |
| 32            |                |                |            |             |                             |                 |              |

Note: numbers followed by the same letter in the same column indicated DMRT were insignificant at 5% α.

Table 3. Average of selected soil physical properties including AS, ASM, WHC, FCSM, and BD of Ultisol in PT Bio Nusantara Technology OPP Bengkulu.

| Plant age (yr) | AS (ml) | ASM (%) | WHC (%) | FCSM (%) | BD (g cm⁻³) |
|---------------|---------|---------|---------|----------|-------------|
| 2             | 4.40    | 46.87   | 58.33 bc| 49.22    | 0.92 a      |
| 3             | 10.03   | 46.19   | 56.83 c | 49.63    | 0.90 a      |
| 4             | 4.83    | 48.67   | 65.33 ab| 55.79    | 0.69 bc     |
| 8             | 11.60   | 48.07   | 63.08 ab| 50.69    | 0.83 ab     |
| 32            | 9.23    | 53.03   | 67.82 a | 55.36    | 0.67 c      |

Note: numbers followed by the same letter in the same column indicated DMRT were insignificant at 5% α.

Table 3 shows that increasing OPP age followed by increasing WHC indicates that soil of older OPP has better properties relating to its capability to retain soil moisture. It is in line with decreasing soil BD with OPP age. The soil BD drops from 0.92 g cm⁻³ at 3-yr OPP to 0.67 g cm⁻³ at the 32-yr OPP. It may be due to more oil palm and understory vegetation roots that make soil has more pore space. A similar trend with the WHC was found in ASM, which consistently increases with increasing OPP age.

Table 4. Summary of the significant Pearson correlation values among biophysical properties of Ultisol in PT Bio Nusantara Technology OPP Bengkulu.

| Soil properties          | Correlation value (r)¹ | Correlation strength ² |
|--------------------------|------------------------|------------------------|
| Organic C x ASM          | 0.485 *                | Weak                   |
| Organic C x AS           | 0.465*                 | Weak                   |
| FCSM x EWD               | 0.615**                | Moderate               |
| FCSM x WHC               | 0.659**                | Moderate               |
| FCSM x CO₂ emission.     | 0.694***               | Moderate               |
| CO₂ emission. x WHC      | 0.434**                | Weak                   |
| OPRDW x UVBMDW           | -0.481*                | Weak                   |

¹: * Pearson two-tail with 10% α; ** Pearson two-tail with 5% α; * Pearson two-tail with 1% α; #: Very weak r < 0.2, weak r = 0.2 – 0.39, moderate r = 0.4 – 0.59, strong r = 0.6 – 0.8, very strong r > 0.8
Besides evaluating the OPP age to biophysical soil properties, this study also aims to find the relationship among soil biophysical properties. The result of the correlation analysis is presented in Table 4. Seven have a significant correlation from 13 selected soil properties at 1%, 5%, and 10% $\alpha$. The correlation range from weak to moderate. Organic C was positively correlated with AS and ASM with $r = 0.485$ and 0.465, respectively. Moderate and positive correlations were showed between the FCSM and EWD, WHC, and CO$_2$ emission with r values of 0.615, 0.659, and 0.694, respectively. A positive correlation also happens between CO$_2$ emission with WHC, with an r-value of 0.434. The only negative correlation was between OPRDW with UVBMDW, with an r-value of -0.481.

3.2. Discussion

The highest UVBMW occurs in 4-yr OPP matched with the highest CO$_2$ emission because optimum oil palm growth occurs between 4 and 11 years [20]. These insitu CO$_2$ emissions were the total emission of roots and microbial respiration. Assuming that the microbial activities were similar, increasing CO$_2$ emission was mainly due to increasing root densities both from oil palm and understory vegetation. A previous study indicated that oil palm root is capable of increasing CO$_2$ emission on the OPP floor to 400% compared to the floor without oil palm root [21]. Organic C increases with OPP age, reaching the highest value at the 32-yr OPP, followed by increasing WHC and decreasing BD. This finding was promising to pursue soil sustainability in OPP, although the plantation was developed in less suitable soil. Soil organic C plays a significant role in determining other soil properties. Soil organic matter is a single entity of soil property capable of influencing other properties, such as WHC, BD, soil structure, and CEC [22]. Organic C was positively correlated with ASM and AS ($r = 0.485$ and $r = 0.465$).

Improving ASM promotes understory vegetation growth and development, biodiversity, microbial activities, and oil palm growth and production. A previous study indicated that understory vegetation did not significantly affect oil palm production due to nutrient competition.

On the contrary, understory vegetation benefits OPP by increasing biodiversity and decomposition rate [23]. Besides the effect of understory vegetation, increasing organic C in this OPP may also be contributed by the integration of cattle farms. A previous study reported that the impact of cattle integration in OPP could increase available soil nutrients, soil physical and biological properties, and fresh fruit bunch production [20].

Organic C was positively correlated with AS, implied that maintaining or improving organic C reduces the risk of soil deterioration through soil erosion. Limiting soil erosion is vital because soil particle/soil mineral is the non-renewable part of soil and land. At the same time, other properties generally are renewable, which can be restored when they deteriorate. Maintaining soil in a good quality (high organic C, strong AS, and low BD) keeps soil in a high resiliency, the soil capability to recover after experiencing pressure or disturbance [24]. Soil with better aggregation has stronger soil erodibility, thus more resistant to erosion, better permeability that facilitates water infiltration, and reduces runoff, resulting in more water stored in the soil profile. The soil in this condition has better resiliency and suggests better sustainability [24, 25]. The finding of this study indicates that using land with less suitable for OPP is possible to get sustainable land management as far as the soil resiliency is maintained by restraining soil erosion and maintaining soil organic C through improving understory vegetation and combining with cattle integration.

4. Conclusions

This study suggests that event in soil with less suitable; it may sustain in OPP with good management especially keeping or improving soil organic C through maintaining understory vegetation. Organic C and WHC increase with increasing OPP age, reaching the highest value of 4.8% and 67.82 % for organic and WHC, respectively, at 32-yr OPP, while BD decreases with time, reaching the lowest value of 0.67 g cm$^{-2}$ at 32-yr OPP. The highest OPRD, OPDRD, and CO$_2$ emissions were 749.46 g m$^{-2}$, 397.53 g m$^{-2}$, and 1784.38 mg m$^{-2}$ day$^{-1}$, respectively was found at the 8-yr OPP. The highest value of UVBMW was 986.43 g m$^{-2}$, and UVBMDW was 533, 99 g m$^{-2}$ reached 8-yr OPP. Correlation among the selected soil
biophysical properties includes weak to moderate correlation strength. Organic C weakly correlated with ASM (r=0.485) and AS (r=0.465).

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