SOIL SCIENCE ANNUAL
2022, 73(4), 156574

https://doi.org/10.37501/soilsa/156574

The effects of forest conversion to oil palm plantation on soil quality in the Kaos sub-watershed, Indonesia

Syahru Ramadhan[1*], Hermansah[2], Bujang Rusman[2], Syafrimen Yasin[2]

[1] Andalas University, Faculty of Agriculture, Department of Agricultural Science, Limau Manis, 25163, Padang, Indonesia
[2] Andalas University, Faculty of Agriculture, Department of Soil Science, Limau Manis, 25163, Padang, Indonesia

[*] S. Ramadhan, syahrugis@gmail.com, syahru@student.unand.ac.id, ORCID iD: https://orcid.org/0000–0002–3182–6652

Received: 2021-12-28
Accepted: 2022-11-15
Published online: 2022-11-15
Associated editor: Ł. Mendyk

Keywords:

Land-use change
Oil palm plantations
Principal component analysis
R statistics
Soil quality indicators

Abstract

Several countries have experienced widespread forest conversion, including Indonesia where Jambi Province is the most affected region. The majority of forests in the province have been converted to oil palm plantations. Between 1995–2018, 7,846 hectares of secondary forest in the Kaos sub-watershed were converted to oil palm plantations. Land conversion causes soil degradation that, in turn, impacts soil quality. Therefore, the aim of this study was to determine the potential change in soil quality (and the main factors that affect soil quality) as land undergoes conversion from secondary forest to oil palm plantations. Soil samples were taken from six locations in a secondary forest, a cleared forest area, and oil palm plantations of four different age classes, and a soil quality index (SQI) was calculated for each land use. Principal Component Analysis (PCA) was used to evaluate the soil data. SQI values in the Kaos sub-watershed ranged from 0.45–0.53, which indicates that the soils are of medium quality. The greatest SQI value (0.53) was associated with the secondary forest site, while the lowest SQI value (0.45) was found on oil palm plantation #1 (age class: 0–5 years). Furthermore, the factors that affected SQI in our study were found to be base saturation, organic carbon content, and bulk density. In conclusion, the conversion of secondary forest to oil palm plantations in the Kaos sub-watershed causes a decrease in the SQI values.

1. Introduction

During the period 2011–2019, between 0.44–1.09 million hectares of land were deforested in Indonesia (Ministry of Environment and Forestry, 2020). This was due to land-use change in various regions of the country, including Jambi Province (Clough et al., 2016). Most of the forests in the province have been converted into oil palm plantations, now one of the most cultivated crops in the country. Indonesia has the largest area of oil palm plantations globally (Fauzi et al., 2014), and accounts for approximately 34.18% of the global oil palm area. Moreover, the area under oil palm in the country has increased by approximately 50% over the past ten years (Bou Dib et al., 2018).

The growth of oil palm areas has created problems in the Batanghari watershed, and approximately 7,846 hectares of secondary forest have been converted into oil palm plantations in the Kaos sub-watershed. Conversion of forests to young oil palm plantations will reduce water infiltration and storage (Dislich et al., 2016). In addition, oil palm cultivation employs a monoculture system, which requires early clearing of the land, which results in sedimentation and loss of nutrients in the runoff (Oksana et al., 2012).

Land conversion plays a significant role in the decline in soil quality (Supriyadi et al., 2016), which can be defined as the interaction between the physical, chemical, and biological properties of the soil. According to Amacher et al., (2007), soil quality indicators (SQI) include bulk density (BD), pH, soil organic matter, total nitrogen (N), cation exchange capacity (CEC), and potassium (K), magnesium (Mg), calcium (Ca), and phosphorus (P) concentrations. Furthermore, Abid and Lal (2008) suggest that organic carbon (C) content is also an important indicator of soil quality. These indicators should be considered if evaluating the potential change in soil quality that occurs as a result of land conversion.

Nasrullah (2010) has stated that an increased runoff coefficient and enhanced sedimentation loading will aggravate watershed conditions. This process occurs due to the absence of vegetation cover on the soil surface, which permits the direct impact of rain onto the soil surface, thereby causing erosion and affecting soil quality.

Consequently, soil monitoring is required in oil palm plantations in anticipation of potential land degradation (Rusman et al., 2019). This can be achieved by assessing soil quality related to the ecosystem functions (Safaei et al., 2019). Soil quality is the ability of the soil to function as a medium for the optimal growth of plants or crops (Thoumazeau et al., 2019). In addition, soil quality is related to water quality enhancement, human health compatibility and the environment. Hence, it can be used to describe the properties and condition of the soil (Utomo et al., 2016). Given the number of indicators associated with soil properties and behavior, a SQI is required that can integrate all soil quality indicators (Brady & Weil, 2008).

Quantitative determination of the impact of converting forest land into cleared land and then into oil palm plantations is essential for good management. Clear and measurable indicators, such as pH, water content, total nitrogen (N), exchangeable potassium (K), organic carbon (C) content, base saturation (BS), organic matter content, BD, total pore space, and volumetric moisture content are also needed. These indicators play an essential role in determining soil quality, and they also affect the reactions that occur within the soil and plant productivity. Therefore, it is necessary to have soil indicators that can be measured accurately and are representative of the land use.

According to Comte et al. (2013), the impact of oil palm plantation land management practices on soil properties, such as soil pH, organic C content, and nutrient availability, varies according to soil type and topographic position, age of the oil palm stand, and is also influenced by rainfall and hydrological characteristics. Our study aims to determine the impact on soil quality in a sub-watershed of converting secondary forests into oil palm plantations based on features and indicators of the soil properties. Specifically, this study aims to answer the following questions:

1) what is the SQI for (a) secondary forest, (b) a cleared forest area, and (c) oil palm plantations of four age classes (0–5 years, > 5–10 years, > 10–15 years, > 15 years), in the Kaos sub-watershed?
2) what indicators influence soil quality in the Kaos sub-watershed?

2. Materials and methods

2.1. Study area and soil sampling

The Kaos sub-watershed is located at latitude 1° 18′ 4.278″–1° 30′ 35.573″ S and longitude 103° 12′ 52.905″–103° 26′ 59.725″ E. The sub-watershed covers approximately 38,046 hectares, and is located in Sekernan District, Jambi Province. In 1995, the sub-watershed contained a forest area of 12,968 hectares (34.1%) and oil palm plantations covered 2,437 hectares (6.41%). In 2018, the forest area had decreased to 4,982 hectares (13.1%) and oil palm plantations had increased to 18,822 hectares (49.5%). The Kaos sub-watershed is important as it is part of the Batanghari watershed and is one of 108 priority watersheds whose carrying capacity must be restored as they are too low due to soil degradation.

Soil sampling was carried out in Bukit Baling Village, Jambi Province (Kaos sub–watershed, Batanghari Watershed) (Fig. 1). The climate in the area is classed as very wet based on the climate classification of Schmidt and Fergusson (1950), and the re-

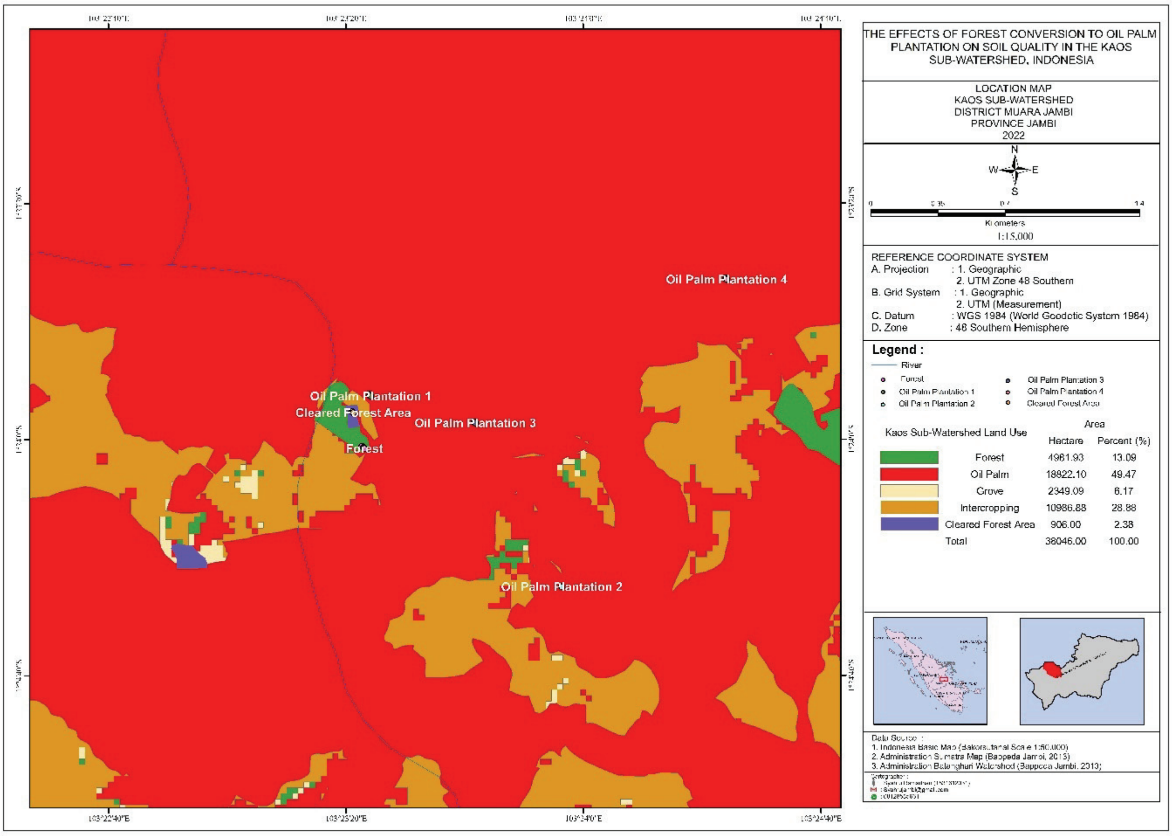

Fig. 1. Map of the Kaos sub-watershed, Indonesia with location of sampling sites in this study.

search area has a Q value = 0.09. Distribution of rain throughout the year is uneven. The research site is composed of interspersed sandstone tuffaceous sandstone and claystone, with the parent material acid tuff and Ultisol soil type (Table 1). The slope of the study site is 8–15%.

A purposive sampling method was used to determine soil quality in (a) a secondary forest, (b) a cleared forest area, and (c) oil palm plantations of four age classes (0–5 years, >5–10 years, >10–15 years, >15 years) (Table 1).

Plots were established in the forest, cleared forest area, and oil palm plantations (protecting three oil palm trees). Each plot was 22 × 4 m in area, which cuts the slope. Soil samples were taken with a soil ring (diameter 5 cm) and a soil hand borer and were collected at the following depths: 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm. For each plot area, sampling was carried out at six locations at four depths and three replications, to produce a total of 72 samples.

The soil sampling process was carried out with two methods: disturbed and undisturbed soil sampling. For the former, a sample ring and a drill were used. All the collected samples were used for BD analysis, and only the disturbed samples were used for soil chemical analysis (pH H_2O, N, K and organic C con-

Table 1
Soil sampling location details.

Land Use	Vegetation age (years)	Geology	Parent material	Soil Taxonomy		Sampling location
				Humidity	Soil type	
Forest	48	Tmpm	Sour tuff	Udic	Ultisols -Typic Kandiudults	1° 24' 1.177" S 103° 23' 22.744" E
						1° 24' 1.380" S 103° 23' 23.010" E
						1° 24' 1.551" S 103° 23' 23.157" E
Oil palm plantation #1 (age class: 0–5 years)	3	Tmpm	Sour tuff	Udic	Ultisols -Typic Kandiudults	1° 23' 52.310" S 103° 23' 24.018" E
						1° 23' 52.555" S 103° 23' 24.113" E
						1° 23' 52.679" S 103° 23' 24.252" E
Oil palm plantation #2 (age class: > 5–10 years	9	Tmpm	Sour tuff	Udic	Ultisols -Typic Kandiudults	1° 24' 24.869" S 103° 23' 56.378" E
						1° 24' 24.903" S 103° 23' 56.411" E
						1° 24' 24.989" S 103° 23' 56.430" E
Oil palm plantation #3 (age class >10–15 years)	12	Tmpm	Sour tuff	Udic	Ultisols -Typic Kandiudults	1° 23' 57.044" S 103° 23' 41.651" E
						1° 23' 57.121" S 103° 23' 41.783" E
						1° 23' 57.223" S 103° 23' 41.864" E
Oil palm plantation #4 (age class: >15 years)	22	Tmpm	Sour tuff	Udic	Ultisols -Typic Kandiudults	1° 23' 32.719" S 103° 24' 24.055" E
						1° 23' 32.890" S 103° 24' 24.146" E
						1° 23' 32.955" S 103° 24' 24.233" E
Cleared forest area	–	Tmpm	Sour tuff	Udic	Ultisols -Typic Kandiudults	1° 23' 55.291" S 103° 23' 21.026" E
						1° 23' 55.336" S 103° 23' 21.156" E
						1° 23' 55.478" S 103° 23' 21.299" E

tent). The soil samples were then brought for physical analysis to the Agriculture Faculty, Jambi University. Chemical and biological analyses were conducted at the Environmental Department of Jambi Province.

Before the soil chemical and biological analyses, all the samples were air-dried in the laboratory. Following the recommendations outlined in Balai Penelitian Tanah (2012), determination of soil pH for each soil sample used an H_2O solution with a ratio of 1:5 between the key and the soil, which was then measured with a pH meter. Total nitrogen (N) content was determined by the Kjeldahl method with concentrated sulfuric acid as a reagent and measured by a spectrophotometer at a wavelength of 636 nm. Exchangeable potassium (K) was treated with ammonium acetate reagent (NH_4Ac 1 M, pH 7.0) and then measured with an atomic absorption spectrophotometer (AAS). The organic C content was determined by the Walkley and Black method with concentrated sulfuric acid and potassium dichromate as reagents, and then measured with a spectrophotometer at a wavelength of 561 nm (Balai Penelitian Tanah, 2012).

Bulk density was determined with the ring method. A ring (diameter: 5 cm) was inserted into the ground by pressing it to a specific depth, then carefully disassembled so as not to change the soil volume. Soil samples were dried for 24 hours at 105°C, then weighed (Balai Penelitian Tanah, 2006).

Data on the fertilization schedule at each oil palm sampling location was obtained through an interview with the owner of the plantation. Oil palm plantation #1 (age class: 0–5 years) was not fertilized, while plantation #2 (age class: >5–10 years) and plantation #3 (age class: >10–15 years) 360–480 kg/hectare/year received Phonska fertilizer (N: 15 %, P: 15%, K: 15%). Plantation #4 (age >15 years) 240–360 kg/hectare/year received Mahkota fertilizer (N: 13% P: 8%, K: 27%).

2.2. Data Analysis

The SQI was determined using a Dell Inspiron laptop running on Windows 10 operating system, while the data were analyzed using R software v3.4.3 (R Development Core Team, 2017). Correlation analysis of the soil properties parameters was used to determine soil indicators that affected each other and was followed by minimum data set (MDS) determination. Furthermore, principal component analysis (PCA) was used to select the most appropriate indicator that influenced the principal components (PC). Soil quality was then assessed using the SQI and by scoring the selected PCA variables and MDS that had the least influence on the soil properties. The following is a PCA script using the R statistic:

- PCA1.pca<–prcomp(PCA1[,4:13], scale = TRUE)
- summary(PCA1.pca)
- str(PCA1.pca)
- PCA1.pca$rotation
- PCA1.pca$x

The PC that was used as the MDS had a standard deviation value > 1 PC. For each PC, the indicator with the greatest score was used and this score was then used as the Weighting Index (Wi), while the selected indicator score in each PC was multiplied by the score of each chosen indicator to determine the SQI at each sample point. The score interval (Si) ranged from 1–5, and the greater the variable score, the greater the weighting. Therefore, the SQI calculation was established by multiplying the sum of the variable scores by Wi. The SQI can be calculated using equation 1 (Andrews et al., 2004):

$$SQI = \sum_{i=1}^{n} Wi \times Si \quad (1)$$

where:
SQI : Soil Quality Index
Wi : Weighting Factor
Si : Scoring Indicator

The Soil Quality Index (SQI) results obtained from these calculations were then classified according to Cantu et al., (2007), as shown in Table 2.

Table 2
Soil quality index (SQI) classification scheme as presented in Cantu et al. (2007).

Soil quality	Range	Class
Very high	0.80–1.00	1
High	0.60–0.79	2
Moderate	0.40–0.59	3
Low	0.20–0.39	4
Very low	0.00–0.19	5

3. Results

3.1. Soil characteristics

The highest pH value (4.8) was obtained from oil palm plantation #4, while the lowest (4.2) was obtained from the cleared forest area. The highest N content (0.21%) was found in the secondary forest, while the lowest (0.04%) was obtained from oil palm plantation #2 and the cleared forest area. The highest soil organic C content (3.07%) was found in the secondary forest, while the lowest value (0.79%) was obtained in plantation oil palm #2. Oil palm plantation #2 also had the highest K content (0.23%), while the lowest was found in the cleared forest area (0.04%). The greatest BS value (14.15%) was found in the secondary forest, while oil palm plantation #1 had the lowest value (7.54%).

The greatest BD value (1.35 g/cm^3) was obtained in oil palm plantation #1, while the lowest value (1.14 g/cm^3) was found in the secondary forest (Table 8). Greatest total pore space content (54.8%) was obtained in the forest, while oil palm plantation #1 had the lowest value (47.6%). The secondary forest had the greatest organic matter content (5.3%), while oil palm plantation #2 had the lowest (1.36%). The greatest volumetric moisture content (24.1%) was obtained from oil palm plantation #2, while the cleared forest area had the lowest content (18.98%).

3.2. Principal Component Analysis

The SQI was determined with statistical analysis using PCA (Table 3), which can also determine the soil quality indicators that significantly affect soil functions by making a MDS to reduce indicators and avoid redundancy. The MDS value taken is the minimum parameter that most influences soil quality indicators with the provisions of eigenvalue 1. For each PC, only the factor with the greatest weighting was selected, determined PC1–PC3. The indicator set as MDS for each PC is based on the greatest loading factor and is correlated with each other (Vasu D et al., 2016).

The results of the PCA showed that the most important soil properties used in determining the SQI value were BS, organic C content, and BD. In the secondary forest, BS (11.24–14.15%), organic C content (1.10–3.07%) and BD (1.14–1.19 g/cm^3) were the most important, while the lowest values were observed in oil palm plantation #1, i.e., BS (7.54–9.11%), organic C content (0.90–1.85%) and BD (1.33–1.36 g/cm^3).

Table 3
Principal Component Analysis (PCA).

PC: principal component; N: nitrogen; C: carbon; K: potassium; BS: base saturation; BD: bulk density; TPR: total pore space; OM: organic matter; VMC: volumetric water content.

	PC1	PC2	PC3
Standard deviation	2.47	1.28	1.24
Proportion of Variance	0.61	0.16	0.15
Cumulative Proportion	0.61	0.77	0.92
pH H_2O	0.30	–0.12	0.38
N	0.37	0.29	–0.02
C	0.34	0.37	–0.22
C:N Ratio	–0.29	0.08	–0.37
K	0.32	0.22	0.39
BS	0.39	–0.14	–0.01
BD	–0.30	0.30	0.44
TPS	0.26	–0.39	–0.44
OM	0.34	0.36	–0.22
VMC	0.22	–0.55	0.27

4. Discussion

4.1. Soil quality indices in the different land use types

The selected indicators and soil quality calculation results of each utilized land use carried out with the quality index formula are shown in Table 4. The average SQI values for each land use ranged from 0.45–0.53. The differences in the SQI values are caused by the various land use systems, which are influenced by land management actions.

Under the classification scheme presented in Cantu et al., (2007), all the land uses in our study were classed as *moderate* soil quality. Soil depth at 0–10 cm in the secondary forest exhibited the greatest SQI value (0.61), which is classed as *high* quality, while the lowest SQI value at that depth (0.48) was found in oil palm plantation #1 and the cleared forest area. The greatest SQI value at 10–20 cm depth (0.54) was recorded in the forest and in oil palm plantation #4. The lowest SQI value (0.48) at that soil depth was found in oil palm plantation #1, oil palm plantation #2, and the cleared forest area. The greatest SQI value at 20–30 cm depth (0.48) was recorded in the forest, oil palm plantation #2, oil palm plantation #3, oil palm plantation #4, and the cleared forest area, while the lowest SQI value (0.42) at that depth was in oil palm plantation #1. The greatest SQI value at 30–40 cm depth (0.48) was in the forest, and the lowest SQI value (0.42) was recorded in oil palm plantation #2, oil palm plantation #3, oil palm plantation #4, and the cleared forest area.

There was a decrease in soil quality at each soil depth at all sites. This is because the soil contains less organic matter and nutrients in the deeper layers. In addition, it is more difficult for plant roots to penetrate the soil in the deeper layers where there are more macropores and fewer micropores, so that the soil becomes denser and the organic matter content and nutrients in the soil are much less compared to the topsoil.

Our results show that the forest site had the greatest SQI value (average: 0.53) of all land uses. This is consistent with the findings of Primadani et al. (2010). Work by Utomo et al. (2016) suggested that a forest ecosystem is a sustainable watershed ecosystem. The forest plant canopy can cover the soil surface, and organic materials (leaves or twigs) are added at any time and will undergo weathering and decomposition and increase the organic matter content of the soil. The soil also supports ecosystem services, such as climate regulation, water supply, C sequestration and nutrient cycling (Pereira et. al. 2018). In our study, the lands use areas other than forest exhibited similar SQI values.

Differences in SQI were observed for each land use due to the impact of forest conversion (Safaei et al., 2019). According to Palupi et al. (2022), soil quality can decrease, persist, or increase according to the land management method. In general, soil quality in a natural forest is solely influenced by its environment, while non-forest land is also affected by human activities (e.g., forest managers). Land management actions that can achieve sustainable agricultural goals include the provision of organic matter into the soil, the application of fertilizers at optimal levels, the utilization of the soil according to its capacity, and the employment of environmentally friendly farming materials and techniques (Palupi et al., 2022).

In our study, oil palm plantation #1 had the lowest average SQI value as it did not receive organic fertilizer, which provides an organic C supply to the soil. Organic C content in the soil affects the exchange of cations, soil structure and BD values. Our results show there was an increase in SQI values with each age class of the oil palm plantations: oil palm plantations #1 (SQI: 0.45), #2 (0.48), #3 (0.48) and #4 (0.50). In oil palm plantation #1, the canopy was open, and the ground floor was not covered with litter or leaves. Hence, nutrients were quickly washed away to the lower areas of the site. A planta-

Table 4
Soil quality index (SQI) values for the secondary forest, land cleared area and oil palm plantations in the Kaos sub-watershed, Indonesia. BS: base saturation; C: carbon; BD: bulk density; S_i: scoring indicator; W_i: weighting factor; Sum (∑): Total; SQI: soil quality index.

Land use	Depth (cm)	Indicator			Si × Wi	∑ (Si × 5)	SQI	Average SQI
		BS	C	BD				
		Wi						
		0.39	0.37	0.44				
		Si						
Forest	0–10	1	4	4	3.63	6.00	0.61	0.53
	10–20	1	3	4	3.26	6.00	0.54	
	20–30	1	2	4	2.89	6.00	0.48	
	30–40	1	2	4	2.89	6.00	0.48	
Oil palm plantation #1 (age class: 0–5 years)	0–10	1	2	4	2.89	6.00	0.48	0.45
	10–20	1	2	4	2.89	6.00	0.48	
	20–30	1	1	4	2.52	6.00	0.42	
	30–40	1	1	4	2.52	6.00	0.42	
Oil palm plantation #2 (age class: >5–10 years)	0–10	1	3	4	3.26	6.00	0.54	0.48
	10–20	1	2	4	2.89	6.00	0.48	
	20–30	1	2	4	2.89	6.00	0.48	
	30–40	1	1	4	2.52	6.00	0.42	
Oil palm plantation #3 (age class: >10–15 years)	0–10	1	3	4	3.26	6.00	0.54	0.48
	10–20	1	2	4	2.89	6.00	0.48	
	20–30	1	2	4	2.89	6.00	0.48	
	30–40	1	1	4	2.52	6.00	0.42	
Oil palm plantation #4 (age class: >15 years)	0–10	1	3	4	3.26	6.00	0.54	0.50
	10–20	1	3	4	3.26	6.00	0.54	
	20–30	1	2	4	2.89	6.00	0.48	
	30–40	1	1	4	2.52	6.00	0.42	
Cleared forest area	0–10	1	2	4	2.89	6.00	0.48	0.46
	10–20	1	2	4	2.89	6.00	0.48	
	20–30	1	2	4	2.89	6.00	0.48	
	30–40	1	1	4	2.52	6.00	0.42	

tion requires good soil conditions for growth and for the early development of the oil palm plant before it enters the fertilization phase. Consequently, soil and water conservation efforts are needed to prevent erosion and sedimentation, minimize nutrients losses and ensure that nutrients are available for the growing oil palm plants.

Good soil quality is characterized by high organic matter content, low BS, high soil porosity, and rapid infiltration rates. Increased soil organic matter inputs will trigger the activity of soil organisms; greater movement of soil organisms will result in better porosity and stability of soil aggregates. However, SQI values will differ for each land use depending on the type of plant, the slope of the land, and inputs to the soil (Cardoso et al., 2013). Thus, it is necessary to maintain soil quality to ensure availability of nutrients, and to protect the soil from damage, such as erosion and chemical residues, and most importantly, ensure that the health of the soil and biological activity in the soil remain optimal (Palupi et al., 2022).

Oil palm plantations are often characterized by elevated soil acidification levels (low soil pH) and decreased soil C stocks in tandem with increased oil palm cultivation time. Research by Pauli et al. (2014) showed that decreased soil pH and organic C stocks were unavoidable during oil palm cultivation. According to Smith et al. (2012) and Nelson et al. (2011), the impact of oil palm plantation on soil properties, such as soil pH, organic C content, and nutrient availability, varies according to soil type, topographic position, age of the plantation, and is also influenced by rainfall and hydrological characteristics.

Therefore, good practice for managing oil palm plantations would be to increase soil pH and C content through the most suitable combination of organic and inorganic fertilizers to increase productivity and improve soil health and quality (Pauli et al., 2014).

In our study, the SQI in the cleared forest area was classed as *moderate* (0.46). Cleared forest area in our context is defined as land that was previously secondary forest but that was later cleared for other land uses. The loss of forest area due to land clearing can cause the failure of the natural canopy, which can lead to erosion and loss of nutrients contained in the soil, thereby leading to soil degradation. Thus, it can indirectly reduce the quality of the soil. Due to increasing population growth in the region, there is a limited availability of land, which causes intensification of agricultural land (Palupi et al., 2022). Li et al. (2019) state that human activities have significantly reduced the soil quality in almost 40% of the world's agricultural land through soil erosion, atmospheric pollution, intensive tillage, overgrazing, land clearing, salinization, and desertification. In addition, the continuous conversion of land into plantation areas can also cause forest fires, which can reduce the organic C content in the soil, increase the temperature of the soil, leading to NH^{4+} and NO^{3-} losses to the atmosphere, and decreased P content in the soil.

In our study, there was a decrease in the SQI for each land use from the secondary forest to the cleared forest area to the oil palm plantations (Table 5). Moreover, SQI increased in tandem with the age of the oil palm plantations, although the SQI for all land uses was classed as *moderate* quality.

The extreme SQI values observed in this study are related to the Ultisol soil type, which generally exhibits poor soil properties. Hardjowigeno (2003) stated that Ultisol soils are characterized by low soil pH and high aluminum (Al) content, so that they become toxic to plants and causes P fixation. Oil palm plantations are characterized by low nutrient contents, so management actions, such as liming and fertilization, are always required.

Bases leached to the sub-soil will be absorbed by the roots of forest vegetation, which are then returned to the surface through fallen leaves. If the forest is cut down and the vegetation does not have deep roots, annual plants or weeds cannot recycle the bases (nutrients). In our research, the indicator chosen to determine the SQI is relatively poor because of moderate organic C content, very low BS, and high BD (slightly dense soil). In line with Supardi's (1983) statement that Ultisol soils have poor chemical and physical properties due to inherent low organic matter content and high manganese (Mn) and iron (Fe^{+}) concentrations, the P availability for plants is reduced.

Table 5
Average soil quality index (SQI) values for each land use in the study.

Land Use	SQI	Category
Forest	0.53	Medium
Oil palm plantation #1 (age class: 0–5 years)	0.45	Medium
Oil palm plantation #2 (age class: >5–10 years)	0.48	Medium
Oil palm plantation #3 (age class: >10–15 years)	0.48	Medium
Oil palm plantation #4 (age class: >15 years)	0.50	Medium
Cleared forest area	0.46	medium

4.2. Influential indicators in the SQI

Based on the PCA results, three indicators affected the SQI in the Kaos sub-watershed (Table 4) and are related to the soil properties (Velásquez et al., 2007). These indicators were used to determine the SQI for each land use and are addressed below.

4.2.1. Base Saturation (BS)

Our results show that the SQI had a strong relationship with BS with a correlation coefficient r value of 0.8506 (or R^2 = 0.7235) (Fig. 2). In addition, the correlation between SQI and BS was directly proportional and positive.

The land uses in our study exhibited very low BS values (6.07–12.78%) (Table 6). Tan (1991) stated that a soil is considered fertile if it has a BS value of 80%, moderate fertility if BS is 50–80%, and is infertile if BS is 50%, while a soil with a 80% BS

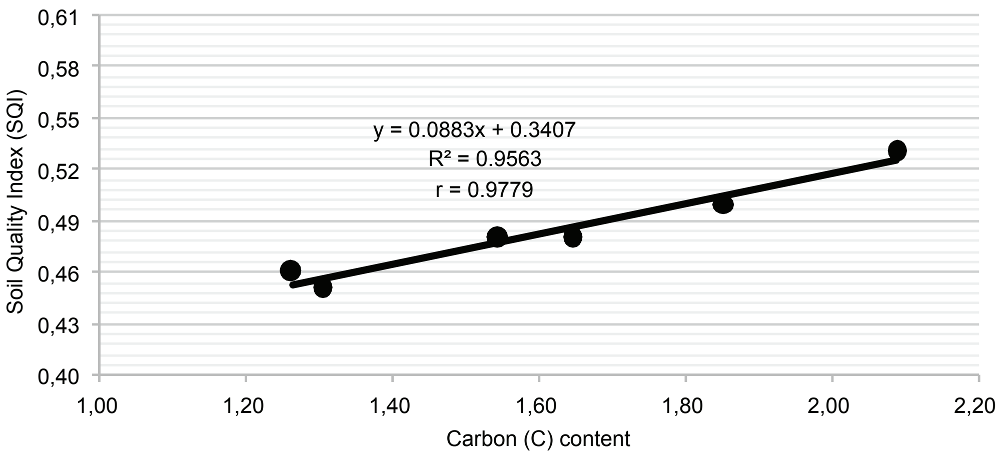

Fig. 2. Soil quality index (SQI) correlation with base saturation (BS).

Table 6
Soil quality index (SQI) and base saturation (BS) values.

Land use	BS (%)	SQI
Forest	12.78	0.53
Oil palm plantation #1 (age class: 0–5 years)	8.44	0.45
Oil palm plantation #2 (age class: >5–10 years)	10.26	0.48
Oil palm plantation #3 (age class: >10–15 years)	10.95	0.48
Oil palm plantation #4 (age class: >15 years)	12.23	0.50
Cleared forest area	6.07	0.46

value can release bases that can be easily exchanged, in contrast to 50% BS soils. Low BS values causes the soil to become acidic, and CEC is also low.

Base saturation is essential for the release of cations and entangled bases. The bases in question include Na, K, Ca, and Mg. For optimal soil productivity, A & L Canada Laboratories (2013) state that a BS value of 80% is required, while soil productivity will be low/decreased if BS is < 40%. Base saturation is closely related to soil pH; a soil with low pH will also exhibit low BS values. Soils with low BS values can be toxic to plants and such a situation exists in acid soils. In addition, BS is often used as an indicator of soil fertility.

Juhos et al., (2019) state that K and sodium (Na) concentrations influence soil quality. Rusman et al., (2019) reported that Na concentration in plants regenerates phosphoenol–phosphatase in C4 and CAM plants, while Pahan (2008) stated that Mg is one of the macronutrients needed by oil palm plants in large quantities. The enzyme phosphatase requires Mg for the transfer of phosphate and for the formation of chlorophyll molecules (Rusman et al., 2019).

4.2.2. Organic Carbon

Our results show that the SQI has a strong relationship with organic C content, with a correlation coefficient r value of 0.9779 (or R^2 = 0.9563) (Fig. 3). In addition, the correlation between SQI and organic C content was directly proportional and positive.

In our study, the organic C content in the land uses ranged from 1.26–2.09% with both low (1.00–2.00 %) and intermediate (2.01–3.00 %) values observed (Table 7). Organic C content is influenced by the quality of litter within each land use, which will also affect the speed of the decomposition process, a finding consistent with Biswas et al., (2017), Juhos et al., (2019), and de Paul Obade (2019). Blanco et al., (2008) stated that a reduction in soil C value also reduces the land biomass and affects root activity. Therefore, changes in the soil C value will affect the soil properties, an essential aspect of ecosystem response to land management.

Soil organic matter is one of the factors that plays a role in plant growth and determines the success of plant cultivation through its influence on the soil properties. According to Nelson et al. (2010), organic matter has a high CEC value, so it plays an essential role in retaining and supplying the main macro and micronutrient cations. Organic matter is a critical component in the soil as it positively affects the physical, chemical, and biological properties (Cayci et al., 2017).

Organic matter also affects the availability of nutrients from other sources and is needed as an energy source by N-fixing bacteria (Anwar and Sudadi, 2013). Organic matter also acts as a soil adhesive agent; organic matter inputs can increase soil microbial activity, which produces organic compounds that can glue the grains of the soil fraction to form more potent and more stable aggregates (Verchot et al. 2011).

Table 7
Soil quality index (SQI) and organic carbon (C) content.

Land use	Organic C (%)	SQI
Forest	2.09	0.53
Oil palm plantation #1 (age class: 0–5 years)	1.30	0.45
Oil palm plantation #2 (age class: >5–10 years)	1.55	0.48
Oil palm plantation #3 (age class: >10–15 years)	1.65	0.48
Oil palm plantation #4 (age class: >15 years)	1.85	0.50
Cleared forest area	1.26	0.46

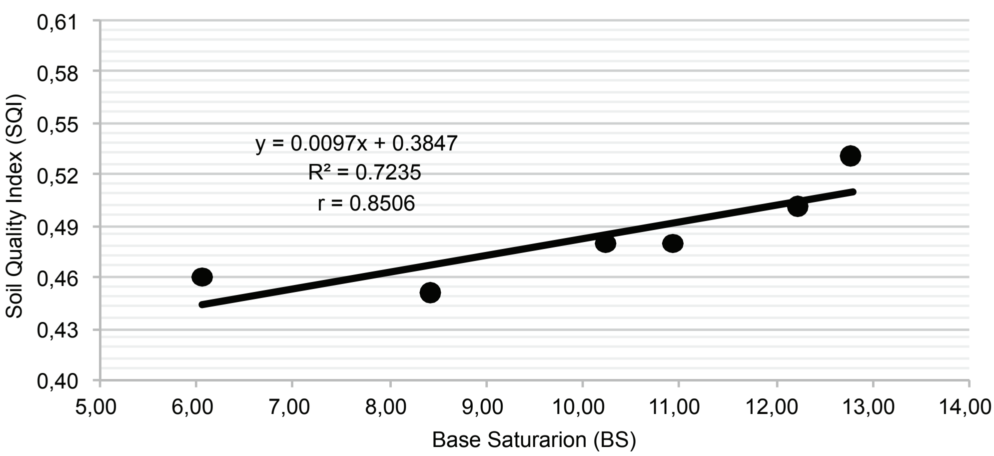

Fig. 3. Soil quality index (SQI) correlation with organic carbon (C) content.

4.2.3. Bulk Density (BD)

Our results show that SQI had a strong relationship with BD with a correlation coefficient r value of -0.9133 (or R^2 = 0.8342) (Fig. 4). In addition, the correlation between SQI and BD was inversely proportional.

In this study, BD values ranged from 1.17–1.35 g/cm³ (Table 8). The average BD value in this study included moderately dense soils (1.2–1.4 g/cm³), and one area had an optimal BD value that was most conducive to plant root growth. Bulk density is one of the main indicators in determining the SQI, as it can describe the process of soil compaction, productivity, and soil erosivity. Intensive land use tends to cause the soil to become compacted, which reduces groundwater availability. As such, intensive tillage will result in lower drainage pores and lower available water capacity.

Pore drainage and available water are correlated with soil water holding capacity (SWHC), which is influenced by soil organic matter, BS, texture, and soil aggregate stability (Rachman et al., 2013). The SWHC metric describes the ability of a soil to retain water, and reflects the influence of soil mineral composition, texture, structure, organic matter, and management (Arya et al., 2008). Soil with good drainage pores and available water capacity must be maintained with good soil management so that the soil can function optimally, especially for plant productivity. In addition, good soil water management is essential for plant growth and production (Hosseini et al., 2016).

The output of this research is expected to serve as a reference for land managers, investors or owners of oil palm plantations. Therefore, future studies should include the monitoring of the SQI in every oil palm plantation age group to ensure that they are appropriately managed to minimize loss of soil quality.

5. Conclusions

1. The SQI value in the Kaos sub-watershed ranged from 0.45–0.53 (classed as *moderate* soil quality). The SQI in the secondary forest, the four oil palm plantation age classes and the cleared forest area were 0.53, 0.45–0.50 and 0.46, respectively.
2. Base Saturation, organic C content, and BD values were the main indicators that can effectively detect the changes in soil quality that may occur during the conversion of forest land to cleared land and then to oil palm plantations. Therefore, management practices need to be optimized to reduce the negative impact of land conversion on soil quality.

Acknowledgments

The authors would like to thank Kemenristekdikti and Andalas University for providing the PMDSU scheme research (contract number: Number 12 /UN.16.17/ PP.PMDSU/ LPPM/ 2018). The authors are also grateful to the Jambi University Soil Laboratory and the State Environment department of Jambi Province, where the soil analysis in this study was carried out.

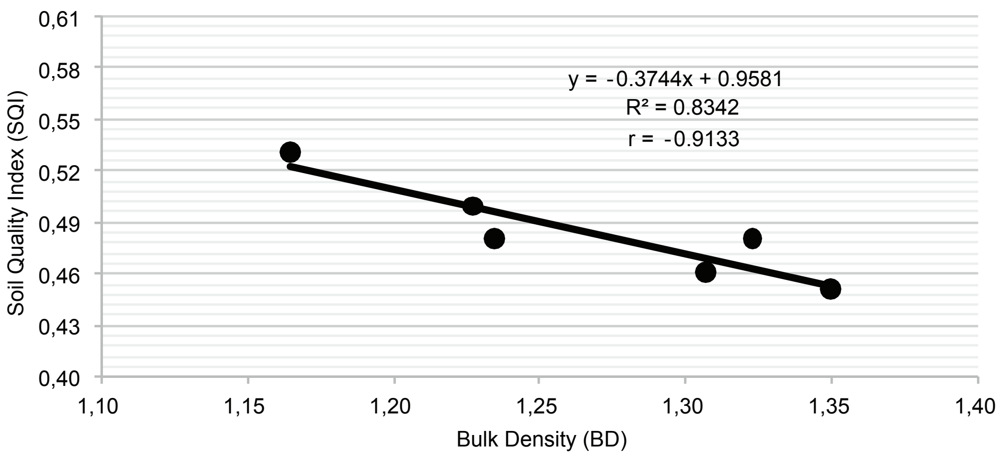

Fig. 4. Soil quality index (SQI) correlation with bulk density (BD).

Table 8
Soil quality index (SQI) and bulk density (BD) values.

Land use	BD (g/cm³)	SQI
Forest	1.17	0.53
Oil palm plantation #1 (age class: 0–5 years)	1.35	0.45
Oil palm plantation #2 (age class: >5–10 years)	1.32	0.48
Oil palm plantation #3 (age class: >10–15 years)	1.24	0.48
Oil palm plantation #4 (age class: >15 years)	1.23	0.50
Cleared forest area	1.31	0.46

References

A & L Canada Laboratories Inc., 2013. Understanding cation exchange capacity and % base saturation. 2136 Jetstream Rd. Fact sheet no. 552, London.

Abid, M., Lal, R., 2008. Tillage and drainage impact on soil quality: I. Aggregate stability, carbon and nitrogen pools. Soil Tillage Research 100, 89–98. https://doi.org/10.1016/j.still.2008.04.012

Amacher, M.C., O'Neill, K.P., & Perry, C.H., 2007. Soil Vital Signs: A New Soil Quality Index (SQI) for Assessing Forest Soil Health. In USDA Forest Research 3. https://doi.org/10.2737/RMRS-RP-65

Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Science Society of America Journal 68, 1945–1962. https://doi.org/10.2136/sssaj2004.1945

Anwar, S., Sudadi, U., 2013. Kimia Tanah. Departemen Ilmu Tanah dan Sumberdaya Lahan. Institut Pertanian Bogor, Bogor. (in Indonesian)

Aprisal, Istijono, B., Juniarti, Harianti, M., 2019. Soil quality index analysis under horticultural farming in Sumani upper watershed. International Journal Geomate 16, 191–196. https://doi.org/10.21660/2019.56.8212

Arya, L.M., Bowman, D.C., Thapa, B.B., Cassel, D.K., 2008. Scaling soil water characteristics of golf course and athletic field sands from particle-size distribution. Soil Science Society of America Journal 72(1), 25–32. https://doi.org/10.2136/sssaj2006.0232

Balai Penelitian Tanah., 2006. Sifat Fisik Tanah Dan Metode Analisisnya. Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian, Bogor. (in Indonesian)

Balai Penelitian Tanah., 2012. Petunjuk Teknis Analisis Kimia Tanah, Tanaman, Air, Dan Pupuk. Badan Penelitian dan Pengembangan Pertanian, Kementerian Pertanian, Bogor. (in Indonesian)

Bin, Z., Xin–Hua, P., 2006. Organic matter enrichment and aggregate stabilization in aseverely degraded Ultisol after Reforestation 11 Project supported by the national. Natural science foundation of China, Pedosphere 16, 699–706. https://doi.org/10.1016/S1002-0160(06)60105-7

Biswas, S., Hazra, G.C., Purakayastha, T.J., Saha, N., Mitran, T., Singha Roy, S., Basak, N., Mandal, B., 2017. Establishment of critical limits of indicators and indices of soil quality in rice–rice cropping systems under different soil orders. Geoderma 292, 34–48. https://doi.org/10.1016/j.geoderma.2017.01.003

Blanco, J.A., Imbert, J.B., Castillo, F.J., 2008. Nutrient return via litterfall in two contrasting *Pinus sylvestris* forests in the Pyrenees under different thinning intensities. Forest Ecology and Management 256, 1840–1852. https://doi.org/10.1016/j.foreco.2008.07.011

Bou Dib, J., Krishna, V.V., Alamsyah, Z., Qaim, M., 2018. Land–use change and livelihoods of non–farm households: The role of income from employment in oil palm and rubber in rural Indonesia. Land Use Policy 76, 828–838. https://doi.org/10.1016/j.landusepol.2018.03.020

Brady, N.C., Weil R.R., 2008. The Nature and Properties of Soils. Pearson Educational International, New Jersey.

Cantu, M.P., Becker, A., Bedano, J.C., Schiavo, H.F., 2007. Evaluacion de la calidad de suelos mediante el uso de indicadores e indices. Ct. Suelo 25(2), 173–178. (in Spanish)

Cardoso, E.J.B.N., Vasconcellos, R.L.F.D., Bini, M.Y.H., Miyauchi, C.A.D., Santos, P.R.L., Alves, A.M.D., Paula, A.S., Nakatani, J.M., Pereira., and Nogueira, M.A., 2013. Soil Health: Looking for Suitable Indicator. What Should Be Considered to Assess the effects of Use and Management on Soil Health. Scientia Agricola 70, 274–298. https://doi.org/10.1590/S0103-90162013000400009

Cayci, G., Temiz, C., & Sözudogru Ok, S., 2017. The Effects of Fresh and Composted Chicken Manures on Some Soil Characteristics. Communications in Soil Science and Plant Analysis 48(13), 1528–1538. https://doi.org/10.1080/00103624.2017.1373794

Clough, Y., Krishna, V.V., Corre, M.D., Darras, K., Denmead, L.H., Meijide, A., Moser, S., Musshoff, O., Steinebach, S., Veldkamp, E., Allen, K., Barnes, A.D., Breidenbach, N., Brose, U., Buchori, D., Daniel, R., Finkeldey, R., Harahap, I., Hertel, D., Holtkamp, A.M., Horandl, E., Irawan, B., Jaya, I.N.S., Jochum, M., Klarner, B., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Kurniawan, S., Leuschner, C., Maraun, M., Melati, D.N., Opfermann, N., Pe´rez–Cruzado, C., Prabowo, W.E., Rembold, K., Rizali, A., Rubiana, R., Schneider, D., Tjitrosoedirdjo, S.S., Tjoa, A., Tscharntke, T & Scheu, S., 2016. Land–use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. Nature Communications 7, 1-12. https://doi.org/10.1038/ncomms13137

Comte, I., Colin, F., Grünberger, O., Follain, S., Whalen, J.K., Caliman, J.P., 2013. Landscape-scale assessment of soil response to long-term organic and mineral fertilizer application in an industrial oil palm plantation, Indonesia. Agriculture, Ecosystems & Environment 169, 58–68. https://doi.org/10.1016/j.agee.2013.02.010

de Paul Obade, V., 2019. Integrating management information with soil quality dynamics to monitor agricultural productivity. Science of the Total Environment 651, 2036–2043. https://doi.org/10.1016/j.scitotenv.2018.10.106

Dislich, C., Keyel, A.C., Salecker, J., Kisel, Y., Meyer, K.M., Auliya, M., Barnes, A.D., Corre, M.D., Darras, K., Faust, H., Hess, B., Klasen, S., Knohl, A., Kreft, H., Meijide, A., Nurdiansyah, F., Otten, F., Pe'er, G., Steinebach, S., Tarigan, S., Tölle, M.H., Tscharntke, T., Wiegand, K., 2016. A review of the ecosystem functions in oil palm plantations, using forests as a reference system. Biological Reviews, 1–31. https://doi.org/10.1111/brv.12295

Fauzi, Y., Widyastuti, Y.E., Satyawibawa, I., Paeru, R.H., 2014. Palm oil. Penebar Swadaya, Jakarta. (in Indonesian)

Grzywna, A., Ciosmak, M., 2021. The Assesment of Physical Variables of the Soil Quality Index in the Coal Mine Spoil. Journal of Ecological Engineering 22(3), 143–150. https://doi.org/10.12911/22998993/132431

Hardjowigeno, S., 2003. Klasifikasi Tanah dan Pedogenesis. Akademika Pressindo, Jakarta. (in Indonesia)

Hosseini, F., Mosaddeghi, M.R., Hajabbasi, M.A., Sabzalian, M.R., 2016. Role of fungalendophyte of tall fescue (Epichloë coenophiala) on water availability, wilting point and integral energy in texturally-different soils. Agricultural Water Management. 163, 197–211. https://doi.org/10.1016/j.agwat.2015.09.024

Juhos, K., Czigány, S., Madarász, B., Ladányi, M., 2019. Interpretation of soil quality indicators for land suitability assessment – A multivariate approach for Central European arable soils. Ecological Indicators 99, 261–272. https://doi.org/10.1016/j.ecolind.2018.11.063

Ministry of Environment and Forestry, 2020. Statistik Lingkungan Hidup Indonesia. Jakarta. (in Indonesia)

Machfiroh, N., Supriyadi., Hartati, S., 2014. Determination of Agroforestry Soil Quality Index Based on Soil Chemical Properties in the Upper Bengawan Solo Watershed Wonogiri. Journal of Soil Science and Agroclimatology 11(2), 113–121. http://dx.doi.org/10.15608%2Fstjssa.v11i2.227

Nasrullah., Kartiwa, B., 2010. Analisis Alih Fungsi Lahan dan Keterkaitannya dengan Karakteristik Hidrologi DAS Krueng Aceh. Jurnal Tanah dan Iklim 31, 81–98. (in Indonesian)

Nelson, P.N., Banabas, M., Webb, M., Sheaves, M., Huth, N., McNeill, A., Koczber-ski, G., Berthelsen, S., Orrell, I., 2010. Environmental sustainability indicators for oil palm in Papua New Guinea – conceptual framework for a research and development project. In: 2nd International Conference on Oil Palm and the Environment (ICOPE), Bali, Indonesia, 1–30.

Nelson, P.N., Rhebergen, T., Berthelsen, S., Webb, M.J., Banabas, M., Oberthür, T., Donough, C.R., Indrasuara, K., Lubis, A., 2011. Soil Acidification under Oil Palm : Rates and Effects on Yield. Better Crop. 95(4), 22–25.

Ngaiwi, M.E., Molua, E., Egbe, A.E., 2019. Forest Soil Quality and Potentials for Food Systems Health in the Takamanda National Park in South Western Cameroon. Natural Resources 10, 218–229. https://doi.org/10.4236/nr.2019.106015

Oksana., Irfan, M., & Huda, M.U., 2012. Pengaruh alih fungsi lahan hutan menjadi perkebunan kelapa sawit terhadap sifat kimia tanah. Jurnal Agroteknologi 3(1), 29–34. (in Indonesian)

Pahan, I., 2008. Panduan Lengkap Kelapa Sawit. Penebar Swadaya, Jakarta. (in Indonesian)

Palupi, N.P., Sarjono, A., Hanif, A., 2022. Soil quality index analysis of forest secondary and palm oil plantation. Budapest International Research in Exact Sciences (BirEx) Journal 4(1), 105–115. https://doi.org/10.33258/birex.v4i1.3995

Pauli, N., Donough, C., Oberthür, T., Cock, J., Verdooren, R., Rahmadsyah., Abdurrohim, G., Indrasuara, K., Lubis, A., Dolong, T., & Pasuquin, J.M., 2014. Changes in soil quality indicators under oil palm plantations following application of "best management practices" in a four-year field trial. Agriculture, Ecosystems and Environment 195, 98–111. https://doi.org/10.1016/j.agee.2014.05.005

Pereira, P., Bogunovic, I., Muńoz-Rojas, M., & Brevik, E.C., 2018. Soil ecosystem services, sustainability, valuation and management. Current Opinion in Environmental Science & Health 5, 7–13. https://doi.org/10.1016/j.coesh.2017.12.003

Primadani., Prasti., Utomo, S., Supriyadi., 2010. Mapping of Soil Quality in Several Land Use in Jatipuro District, Karanganyar Regency. Journal of Soil Science and Agroclimatology 7(2), 83–96.

Purakayastha, T.J., Pathak, H., Kumari, S., Biswas, S., Chakrabarty, B., Padaria, R.N., Kamble, K., Pandey, M., Sasmal, S., Singh, A., 2019. Soil health card development for efficient soil management in Haryana, India. Soil & Tillage Research 191, 294–305. https://doi.org/10.1016/j.still.2018.12.024

R Development Core Team., 2017. R: A Language and Environment for Statistical Computing. URL. R Foundation for Statistical Computing, Vienna, Austria. https://www.R–project.org/

Rachman, L.M., Wahjunie, E.D., Brata, K.R., Purwakusuma, W., Murtilaksono, K., 2013. Fisika Tanah Dasar. IPB Press, Bogor. (in Indonesian)

Rusman, B., Agustian., Aprisal., 2019. Changes in Soil Chemical and Physical Properties of Andisols under Oil Palm Smallholder in the West Pasaman District of West Sumatra. IOP Conference Series: Earth and Environmental Science 347. https://doi.org/10.1088/1755–1315/347/1/012040

Safaei, M., Bashari, H., Mosaddeghi, M.R., Jafari, R., 2019. Assessing the impacts of land use and land cover changes on soil functions using landscape function analysis and soil quality indicators in semi–arid natural ecosystems. Catena 177, 260–271. https://doi.org/10.1016/j.catena.2019.02.021

Smith, D.R., Townsend, T.J., Choy, A.W.K., Hardy, I.C.W., Sjögersten, S., 2012. Shortterm soil carbon sink potential of oil palm plantations. GCB Bioenergy 4(5), 588–596. https://doi.org/10.1111/j.1757-1707.2012.01168

Supriyadi., Hartati, S., Machfiroh, N., Ustiatik, R., 2016. Soil quality index in the upstream of Bengawan Solo River Basin According to the soil function in nutrient cycling based on soybean production in agroforestry. Agrivita 38, 55–63. http://doi.org/10.17503/agrivita.v38i1.496

Supriyadi., 2008. Kandungan bahan organik sebagai dasar pengelolaan tanah di lahan kering Madura. Embriyo 5(2), 176–183. (in Indonesian)

Tan, K.H., 1991. Dasar-Dasar Kimia Tanah. Gadjah Mada University Press, Yogyakarta. (in Indonesian)

Thoumazeau, A., Bessou, C., Renevier, M.S., 2019. Biofunctool: A new framework to 152 assess the impact of land management on soil quality. Part A: concept and validation of the set of indicators. Ecological Indicators 97, 100–110. https://doi.org/10.1016/j.ecolind.2018.09.023

Utomo, M., Sudarsono., Rusman, B., Sabrina, T., Lumbanraja, J., Wawan., 2016. Ilmu Tanah : Dasar–Dasar dan Pengelolaan. Prenadamedia Group, Jakarta. (in Indonesian)

Velásquez, E., Lavelle, P., Andrade, M., 2007. GISQ, a multifunctional indicator of soil quality. Soil Biology and Biochemistry 39, 3066–3080. https://doi.org/10.1016/j.soilbio.2007.06.01

Verchot, L.V., Dutaur, L., Shepherd, K.D., Albrecht, A., 2011. Organic matter stabilization in soil aggregates: understanding the biogeochemical mechanisms that determine the fate of carbon inputs in soils. Geoderma 161, 182–193. https://doi.org/10.1016/j.geoderma.2010.12.017