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Soil diversity influences on oil palm productivity in ultramafic ecosystems, Southeast Sulawesi, Indonesia

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Abstract. *Alam S, Purwanto BH, Hanudin E, Putra ETS. 2020. Soil diversity influences oil palm productivity in ultramafic ecosystems, Southeast Sulawesi, Indonesia. Biodiversitas 21: 5521-5530.* Ultramafic is a unique ecosystem with an environmental gradient due to its high soil diversity. Understanding soil diversity in ultramafic ecosystems is fundamentally required to support sustainable agriculture management, particularly in oil palm plantation. This study investigated the relationship between soil diversity and productivity of oil palm in ultramafic ecosystems, Southeast Sulawesi. The soil survey has taken in Oheo, Langgikima, and Routa districts. Soil sample was collected from various toposequence, including upper, middle, and lower slope to describe soil properties, including soil texture, pH, CEC, SOC, TN, Av-P, Exc-K, Exc-Ca, and Exc-Mg. Whilst observation of oil palm productivity was done by recording the fresh-weight of fruit yield in hectare unit during a month. The results showed that the soil characteristics from the three sites were significantly different in soil texture, pH, CEC, Av-P, Exc-Ca, and Exc-Mg. A similar trend was also recorded in oil palm productivity wherein the highest oil palm productivity was discovered in Oheo (556.41±96.26 kg ha^{-1}), followed by Langgikima (501.11±54.84 kg ha^{-1}) and Routa (163.19±17.55 kg ha^{-1}). Our study founded: pH, CEC, Av-P, Exc-K, Exc-Ca, and Exc-Mg significantly affected the productivity of oil palm. Based on these results, the soil diversity highly affected oil palm productivity in ultramafic ecosystems.

Keywords: *Elaeis guineensis,* pedodiversity, sustainable agriculture, toposequence, ultramafic ecosystems

Abbreviations: Av-P: available phosphorus, C: clay content, CEC: cation exchange capacity, Exc-Ca: exchangeable calcium, Exc-K: exchangeable potassium, Exc-Mg: exchangeable magnesium, pH: pH H_2O, R: rainfall, Sa: sand content, Si: silt content, SOC: soil organic carbon, T: toposequence, TN: total nitrogen, Y: oil palm yield

INTRODUCTION

Soil is the main component of ecosystems that play dominant functions in supporting plant growth and development (Amundson et al. 2003; Khatun et al. 2017). It has an essential contribution to fulfilling water and nutrients which highly required by plant for optimizing their physiological process (Behera et al. 2016; Kurniawan et al. 2018). Soil properties vary in every type of ecosystem due to the impact factors related to its pedogenesis, such as climate, parent materials, relief, organism, and time (Ibáñez and Feoli 2013; Nguyen-Thanh et al. 2017). Soil quality is also diverse, particularly in an ecosystem affected by human activities, including oil palm plantation (Rendana et al. 2016; Sadono et al. 2019; Purwanto and Alam 2020). The diversity of soil characteristics also directly effect the variation of oil palm productivity (Woittiez et al. 2017; Tao et al. 2018). Therefore, the availability of information about soil diversity is necessary for estate managers to determine the best strategy for improving oil palm productivity.

The information of soil diversity in the context of sustainable agriculture management, especially in an oil palm plantation, is fundamentally required to formulate the best alternative prescriptions for maintaining soil fertility and minimizing the risk of land degradation (Webb et al. 2011; Tiemann et al. 2018). For example, the application of fertilization using dolomite is necessary to increase oil palm productivity in Ultisols (Cristancho et al. 2011). The use of cover crops with Leguminoceae species is helpful to minimize run-off and erosion in oil palm plantation in Oxisols (Samedani et al. 2015) and these nitrogen-fixing crops also potentially improve the availability of soil nitrogen (Abdalla et al. 2019). Many studies also report that soil diversity can be used as an indicator to evaluate the environmental preservation in oil palm plantation (Pauli et al. 2014; Rendana et al. 2016; Behera et al. 2018). Good management in oil palm plantation should be capable of preventing soil degradation along with the increment of oil palm yield (Guillaume et al. 2016).

Oil palm plantation in Indonesia has extensively developed in many provinces, including Southeast Sulawesi. The management of oil palm plantation in this location is enticing since it is developed on ultramafic rock which is rich in magnesium (Mg) and iron (Fe). It was also supported by previous study reporting that oil palm plantations established in the ultramafic ecosystem were faced with high content of Fe and Mg (Tufaila et al. 2011). Other studies have also found that soil developed from ultramafic rock is frequently rich in Mg and also Fe released from mineral weathering (Lesovaya et al. 2012; Bani et al. 2014; Vithanage et al. 2019). This circumstance is exceptionally contradictory because both elements have different effects on oil palm productivity. The productivity of oil palm will decrease along with the higher percentage of Fe (Woittiez et al. 2017). In contrast, higher content of Mg will increase oil palm productivity (Cristancho et al. 2011; Behera et al. 2018). Interestingly, the soil diversity of ultramafic ecosystems immensely varies since it is located in a region with a wide environmental gradient in topography and rainfall (Minasny et al. 2010; Siebecker et al. 2017; Marescotti et al. 2019). The high soil diversity also correlates with various growth performance of its vegetation since there is an interaction between soil characteristics and vegetation performance (Ibáñez et al. 2014; van der Ent et al. 2015; Echevarria et al. 2018).

This study has designed to identify soil diversity in ultramafic ecosystems and its relationship to oil palm productivity. It was principally different from the previous research that only focused on soil genesis and its potential use. The specific objectives of this study were: (i) to identify soil diversity under oil palm plantation established in ultramafic ecosystems; (ii) to assess the influence of soil diversity on oil palm productivity in ultramafic ecosystems.

MATERIALS AND METHODS

Study area

This study has conducted in a commercial oil palm plantation, located in Southeast Sulawesi. It had a geographic position in 03°00' to 03°35' S and 121°45' to 122°20' E (Figure 1). Topography was gradient with slope level ranging from 0-25%. Elevation ranges from 33 to 241 m above sea level. The average daily temperature was 24.9 °C with a minimum of 22.7 °C and a maximum of 28.3 °C. The mean air humidity approaches 97.3%. Annual rainfall varied from 2,146 to 3,307 mm year^{-1} during the last ten years from 2007 to 2016. The highest rainfall is recorded in March. Dry periods occurred for 2-4 months from August to November. The parent materials of soil originated from ultramafic rocks. The age of oil palm plants in the surveyed area was 9 years.

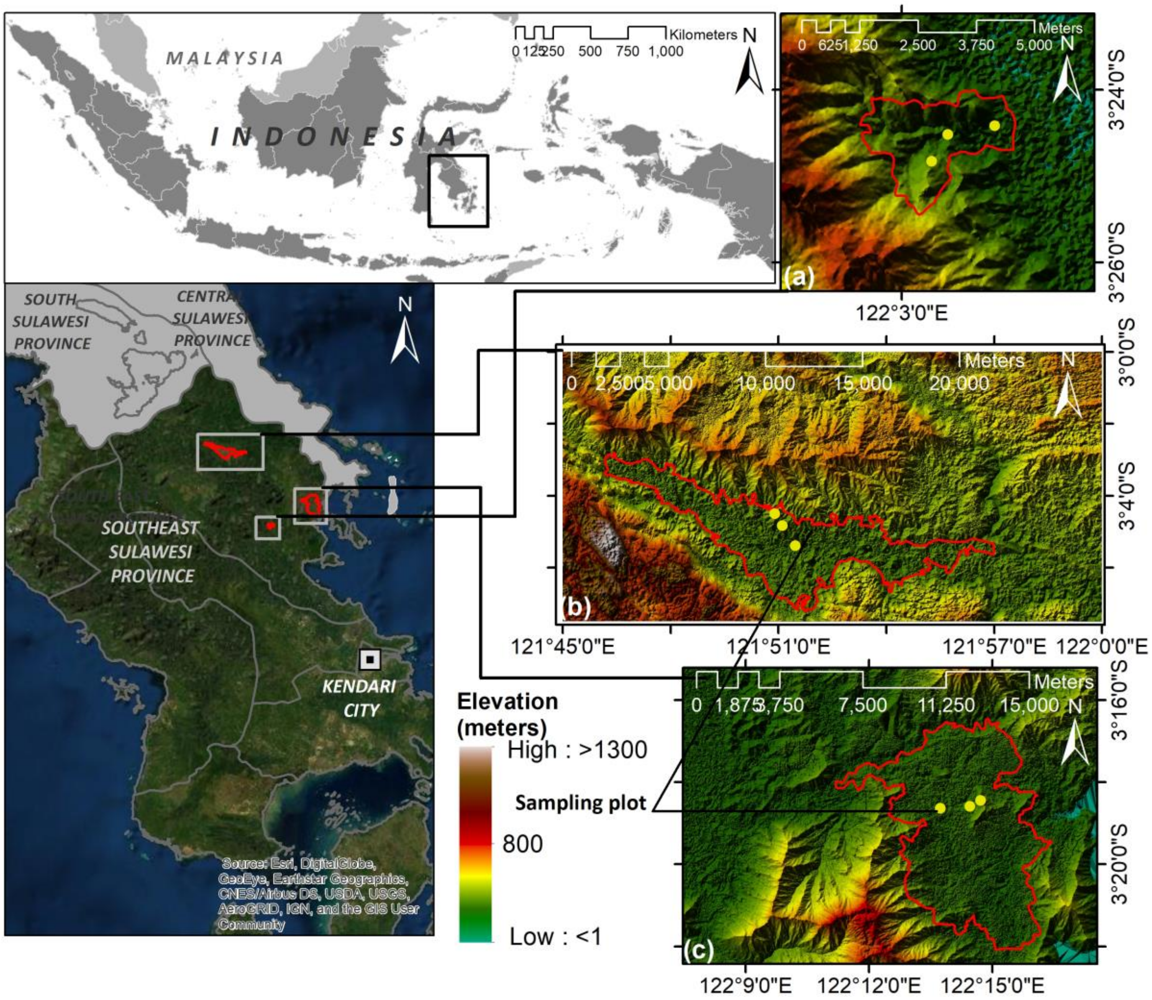

Figure 1. Study area of commercial palm oil plantation located in Southeast Sulawesi, Indonesia: A. Oheo; B. Routa; and C. Langgikima. The yellow dot indicated the sampling location for soil survey.

Table 1. Details location for soil sampling in the study area based on-site, toposequence, elevation, annual rainfall, and coordinates

Site	Toposequence	Symbol	Elevation (m asl)	Slope (%)	Rainfall (mm year $^{-1}$)	Coordinate	
						Latitude	Longitude
Oheo	Upper	OU	136	23	3077.4	S 03°24'49"	E 122°03'21"
Oheo	Middle	OM	60	15	3077.4	S 03°24'31"	E 122°03'32"
Oheo	Lower	OL	33	2	3077.4	S 03°24'25"	E 122°04'04"
Langgikima	Upper	LU	142	22	3306.8	S 03°18'26"	E 122°14'43"
Langgikima	Middle	LM	80	9	3306.8	S 03°18'35"	E 122°14'27"
Langgikima	Lower	LL	44	1	3306.8	S 03°18'38"	E 122°13'44"
Routa	Upper	RU	241	18	2145.7	S 03°04'50"	E 121°51'06"
Routa	Middle	RM	166	9	2145.7	S 03°04'30"	E 121°50'53"
Routa	Lower	RL	139	2	2145.7	S 03°05'23"	E 121°51'27"

Table 2. Soil analysis protocol for quantifying the selected soil physical and chemical properties

Soil parameters	Symbol	Units	Protocol	Reference
Soil particle-size distribution	Sa, Si, C	%	Pipette	Haluschak (2006)
Soil acidity	pH	-	pH meter	van Reeuwijk (2002)
Cation exchange capacity	CEC	cmol(+) kg $^{-1}$	Ammonium acetate	Estefan et al. (2013)
Soil organic carbon	SOC	%	Walkley-Black	Pansu and Gautheyrou (2006)
Total nitrogen	TN	%	Kjeldahl	Pansu and Gautheyrou (2006)
Available phosphorus	Av-P	ppm	Olsen/Bray*, spectrophotometer	van Reeuwijk (2002)
Exchangeable potassium	Exc-K	cmol(+) kg $^{-1}$	Ammonium acetate	Estefan et al. (2013)
Exchangeable calcium	Exc-Ca	cmol(+) kg $^{-1}$	Ammonium acetate	Estefan et al. (2013)
Exchangeable magnesium	Exc-Mg	cmol(+) kg $^{-1}$	Ammonium acetate	Estefan et al. (2013)

Note: * Olsen method was used in soil pH > 5.5, while Bray method was used in soil pH < 5.5

Data collection

The soil survey was carried out in three sites, namely Oheo, Langgikima, and Routa. In each site, the soil samples were collected from various toposequence, including upper, middle, and lower slope (Baskan et al. 2016). In this context, we created a soil profile in every surveyed area. Soil profiles were set up between two oil palm trees with a radius of 400 cm from each trunk (Figure 2). The excavation process was designed with size of 200 cm in length and 100 cm in width, respectively, until a depth of 150 cm. The number of soil profiles used in this research was nine units which evenly distributed in each site and toposequence (Table 1). In every soil profile, soil sample was taken from different horizon that has been identifying (Figure 3) (Nurudin et al. 2013). Then, the samples were brought to the laboratory for quality analysis. Several soil attributes were selected to assess the parameters of soil diversity (Thwaites 2000), namely soil particle-size distribution (Sa, Si, C), soil acidity (pH), cation exchange capacity (CEC), soil organic carbon (SOC), total nitrogen (TN), available phosphorus (Av-P), exchangeable potassium (Exc-K), exchangeable calcium (Exc-Ca), and exchangeable magnesium (Exc-Mg). Soil types were classified based on Keys to Soil Taxonomy (Soil Survey Staff 2014) at the sub-group soil category. The detailed protocol for soil analysis was presented in Table 2. In this study, the productivity of oil palm plantation was derived from secondary data which signified by the fresh weight of fruit yield in hectare unit each month from every site and toposequence.

Data analysis

Statistical analysis was executed using software R version 3.6.1 with a significant level of 5%. The package agricolae was used to facilitate data analysis. Normality of data was examined by the Shapiro-Wilk test (Wirabuana et al. 2020). Homogeneity of variance among site and toposequence was evaluated by Fligner-Killen test (Beyene 2016). Comparison mean of soil diversity among surveyed area was analyzed separately for every parameter using Kruskal-Wallis test and followed by Kruskal-Nemenyi (Tenzin and Hasenauer 2016). Relationship between soil diversity and oil palm productivity was identifying using Spearman-Correlation test (Savilaakso et al. 2014). The similar method was also applied to assess the correlation between soil attributes. A hierarchical clustering using heat map was implemented to identify the similarity of soil characteristics among sites (Li et al. 2019). Afterward, the influence of soil diversity on oil palm productivity was tested for each parameter separately by generalized least square regressions (GLS) with maximum likelihood method (Cai et al. 2016). Finally, a stepwise regression was doing to develop an equation that capable of estimating oil palm productivity using soil parameters as predictor variables (Balasundram et al. 2006; Suryanto et al. 2020).

Figure 3. Soil survey activities: (A) Determining horizon in every profile for identifying the diversity of soil layer; (B) Collecting soil sample for laboratory analysis.

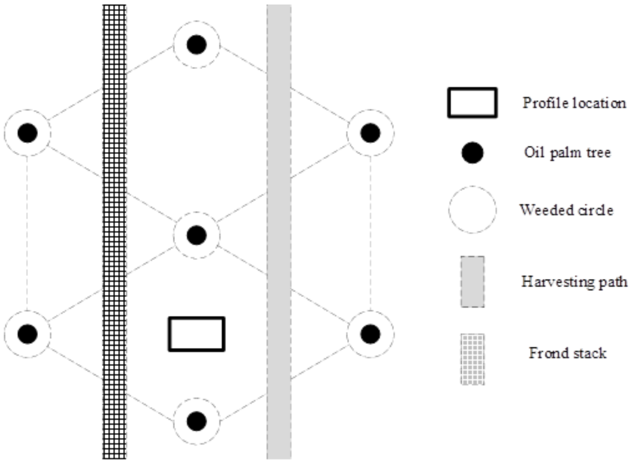

Figure 2. Soil profile location in each selected site

RESULTS AND DISCUSSION

Soil diversity in surveyed area

Summarized results of the observation showed soil diversity of ultramafic ecosystems in the study area highly varied in which there was a significant difference in Sa, C, pH, CEC, Av-P, Exc-K, Exc-Ca, and Exc-Mg from three sites (Table 3). However, this study discovered that the concentration of Si, SOC, TN, and Exc-K from three sites were statistically equal. Interestingly, most soil chemical properties in Oheo substantially had a higher value than Langgikima and Routa. It was possibly caused by different mineral composition and the stage of soil genesis. In general, the source of mineral composition in soil was influenced by the mineral component in rock, the climate condition, and topography in surveyed area. For evidence, a study reported by Alam et al. (2012) found there was different number of mineral components in ultramafic rock from two distinct locations in Konawe and North Kolaka, Southeast Sulawesi. The mineral content of ultramafic rock in North Kolaka was olivine (51%), antigorite (23%), anthophyllite (14%), enstatite (11%), and chromite (1%), In contrast, even though it was also classified as ultramafic rock, the mineral component of rock in Konawe was antigorite (60%), olivine (35%), and chromite (5%). It signified that different sites would result in various mineral components for soil. Other previous studies also recorded similar outcomes (Tufaila et al. 2011; Maulana et al. 2015; Irzon and Abdullah 2018; Khaidir et al. 2019).

Soil fertility in Oheo was also better since it had a balanced distribution of soil texture in Sa, Si, and C. The condition was considerably different from other locations wherein the clay fraction was deeply dominance in soil texture. Turgut and Ates (2017) reported that the content of clay in soil had the potential to become an indicator for identifying the stage of soil genesis. Higher clay fraction in soil indicated the old stage of soil genesis if it had similar parent materials. These findings were also relatively similar to the previous studies which investigated the relationship between pedogenesis and soil physicochemical properties (Lesovaya et al. 2012; Nguyen-Thanh et al. 2017; Aini et al. 2018; van der Ent et al. 2018; Zgangurov et al. 2018).

The different soil diversity in every site also followed by the gradient of oil palm productivity. Our study recorded the productivity of palm oil plantation from the locations was highly different (Table 3). The highest oil palm productivity was observed in Oheo (556.41±96.26 kg ha^{-1}), followed by Langgikima (501.11±54.84 kg ha^{-1}) and Routa (163.19±17.55 kg ha^{-1}). It has occurred since soil properties in Oheo had higher concentration of exchangeable bases than other sites, primarily for Exc-Mg. Several studies explained that the availability of Mg in soil was essentially required to improve the number of fresh fruit bunch in oil palm (Behera et al. 2018; Rhebergen et al. 2018; Tao et al. 2018; Woittiez et al. 2019). Higher content of Mg increased the productivity of oil palm plantation (Cristancho et al. 2011).

Table 3. Comparison mean of soil diversity and oil palm productivity from three different sites

Parameter	Site			*P*
	Oheo	Langgikima	Routa	
Sa	30.70 ± 20.31a	11.97 ± 7.36b	12.53 ± 4.03b	$<0.001^{**}$
Si	33.51 ± 14.92a	29.66 ± 10.70a	31.69 ± 11.85a	0.700^{ns}
C	35.79 ± 16.65b	58.37 ± 12.21a	55.78 ± 10.12a	$<0.001^{**}$
pH	6.10 ± 1.00a	5.99 ± 0.37a	5.42 ± 0.55b	0.009^{**}
CEC	22.66 ± 8.88a	18.28 ±5.43a	12.46 ± 3.61b	$<0.001^{**}$
SOC	1.40 ± 2.04a	2.67 ± 2.95a	1.34 ± 1.72a	0.185^{ns}
TN	0.16 ± 0.09a	0.16 ± 0.09a	0.14 ± 0.08a	0.779^{ns}
Av-P	1.56 ± 0.94ab	1.22 ± 1.03b	1.99 ± 0.40a	0.025^{**}
Exc-K	0.04 ± 0.03a	0.06 ± 0.04a	0.07 ± 0.05a	0.090^{ns}
Exc-Ca	3.09 ± 1.66a	2.29 ± 1.43a	0.81 ± 0.13b	$<0.001^{**}$
Exc-Mg	5.83 ± 5.07a	2.51 ± 2.39b	0.16 ± 0.14b	$<0.001^{**}$
Y	556.41 ± 96.26a	501.11 ± 54.84b	163.19 ± 17.55c	$<0.001^{**}$

Note: Y indicated oil palm productivity; ** signified a significant difference according to Kruskal-Wallis test; ^{ns} showed not significantly different based on Kruskal-Wallis test; the similar letter in row demonstrated not significantly different according to Kruskal-Nemenyi test

Table 4. Comparison mean of soil diversity and oil palm productivity from three different toposequence

Parameter	Toposequence			*P*
	Upper	Middle	Lower	
Sa	25.18 ± 19.78a	10.83 ± 4.96b	16.69 ± 10.83ab	0.012^{**}
Si	26.06 ± 6.56b	36.82 ± 9.79a	30.97 ± 15.84ab	0.037^{**}
C	48.76 ± 19.20a	52.35 ± 10.92a	52.34 ± 17.35a	0.774^{ns}
pH	6.34 ± 0.73a	5.29 ± 0.46c	5.83 ± 0.53b	$<0.001^{**}$
CEC	14.77 ± 7.60b	14.79 ± 2.57b	21.92 ± 8.16a	0.003^{**}
SOC	2.49 ± 0.76a	1.08 ± 0.77a	2.47 ± 3.05a	0.223^{ns}
TN	0.14 ± 0.08a	0.14 ± 0.08a	0.18 ± 0.10a	0.401^{ns}
Av-P	1.91 ± 1.09a	1.43 ± 0.68a	1.54 ± 0.74a	0.258^{ns}
Exc-K	0.04 ± 0.03b	0.05 ± 0.03ab	0.07 ± 0.06a	0.041^{**}
Exc-Ca	2.27 ± 1.62a	1.00 ± 0.61b	2.57 ± 1.66a	0.004^{**}
Exc-Mg	3.08 ± 3.43ab	0.23 ± 0.18b	4.31 ± 4.71a	0.003^{**}
Y	353.52 ± 177.05a	399.94 ± 174.48a	391.61 ± 224.01a	0.775^{ns}

Note: Y indicated oil palm productivity; ** signified a significant difference according to Kruskal-Wallis test; ^{ns} showed not significantly different based on Kruskal-Wallis test; the similar letter in row demonstrated not significantly different according to Kruskal-Nemenyi test

Table 5. Results of the best-fit generalized least squares regression for exploring the influence of soil diversity for every parameter on oil palm productivity in ultramafic ecosystems

Response variable	Predictor variable	R-squared	Estimate	Std Error	*P*
Y	Sa	0.112	4.535	1.879	0.020^{ns}
	Si	0.003	0.820	2.322	0.725^{ns}
	C	0.114	-4.069	1.670	0.018^{ns}
	pH	0.249	132.966	34.005	$<0.001^{**}$
	CEC	0.343	15.406	3.141	$<0.001^{**}$
	SOC	0.007	6.963	12.071	0.566^{ns}
	TN	0.006	174.755	318.767	0.586^{ns}
	Av-P	0.137	-82.249	30.413	0.009^{**}
	Exc-K	0.135	-1655.604	618.915	0.011^{**}
	Exc-Ca	0.376	77.154	14.657	$<0.001^{**}$
	Exc-Mg	0.399	32.473	5.872	$<0.001^{**}$

Note: ** signified a significant difference according to GLS test; ^{ns} showed not significantly different based on GLS test

Table 6. Results of stepwise regression for identifying the causality relationship among soil parameters with oil palm productivity in each site, toposequence, and overall area

Location	Intercept	pH	CEC	Av-P	Exc-K	Exc-Ca	Exc-Mg	R-squared
Site								
Oheo	**660.5**	-31.4	-1.17	-16.3	-477.1	19.35	16.6	0.816
Langgikima	**458.6**	37.1	**-8.1**	-4.6	340.9	**-25.5**	5.3	0.891
Routa	**179.6**	-6.8	1.96	2.8	-185.7	24.0	**-102.9**	0.636
Toposequence								
Upper	**-235.8**	79.8	-9.1	-24.5	402.3	**97.8**	9.3	0.923
Middle	**-1039.9**	**269.8**	0.2	-23.9	**-2075.6**	**81.3**	**330.9**	0.932
Lower	-145.8	11.4	18.3	10.4	**-1074.1**	**74.8**	-13.8	0.964
Total	**177.4**	25.6	12.5	**-81.5**	**-1947.9**	**72.4**	-22.7	0.653

Note: the bold number indicated that the coefficient was significantly useful to develop equation model

Table 7. Final equation of stepwise regression for estimating oil palm productivity based on soil attributes in every site, toposequence, and overall area

Location	Equation
Site	
Oheo	-
Langgikima	*Y = 458.6 - 8.1CEC - 25.5Exc-Ca*
Routa	*Y = 179.6 - 102.9Exc-Mg*
Toposequence	
Upper	*Y = -235.8 + 97.8Exc-Ca*
Middle	*Y = -1039.9 + 269.8pH - 2075.6Exc-K + 81.3Exc-Ca + 330.9Exc-Mg*
Lower	-
Total	*Y = 177.4 - 81.5Av-P - 1947.9Exc-K + 72.4Exc-Ca*

Note: "-" demonstrated not available equation model due to the no significant coefficient based on stepwise regression

The occurrence of soil diversity in ultramafic ecosystems was influenced by specific factors, particularly in related to toposequence and rainfall (Bani et al. 2014; Baskan et al. 2016; dos Santos et al. 2017; de Almeida et al. 2019). Our study noted there was a significant correlation between the factor and soil attributes in the study area (Figure 4). The relationship between toposequence and rainfall to soil diversity was principally related to leaching and erosion (Smith et al. 2012; Mohammadi et al. 2016; dos Santos et al. 2017; Zgangurov et al. 2018). Higher rainfall linearly increased the risk of leaching and erosion since it became the primary source of run-off (Smith et al. 2012; Thompson et al. 2016; Kandari et al. 2018). Moreover, the slope position in toposequence also determined the intensity of erosion and leaching (de Almeida et al. 2019). The occurrence of erosion and leaching fundamentally affected the gradient of soil fertility and moisture (Romanens et al. 2019). In the middle toposequence, the risk of leaching and erosion was relatively higher than the upper and lower slope since this area had the largest slope among other toposequence positions. Consequently, the run-off process would occur more rapidly which gradually declined soil fertility and increased soil moisture (Gracheva 2011). This fact was also supported by our findings that documented lower soil characteristics in the middle toposequence than other slope positions (Table 4).

This study documented there were similar soil characteristics both in site and toposequence according to the physicochemical attributes (Figure 5). Based on the outcomes of the heat map, there was three specific clusters of soil diversity in the study area. The first cluster has consisted of RL, LM, RU, and LL. The second group has consisted of LU, OM, and RM. The members of the third cluster were OL and OU. In the context of oil plantation management, the stratification of soil diversity was necessary to facilitate the best practice maintenance since it correlated to efficient investment for fertilization cost (Rhebergen et al. 2020). The identical cluster indicated similar soil properties in the site (Moharana et al. 2020). Thus, it could be managed using equal treatment.

Attractively, the heatmap diagram provided a more efficient approach to stratify soil in the study area. According to the outcome of soil classification in every profile, this study found nine different soil sub-groups, i.e. OU (Typic Udorthents), OM (Fragic Hapludults), OL (Lithic Udorthents), LU (Lithic Dystrustepts), LM (Typic Rhodudalfs), LL (Oxyaquic Fraglossudalfs), RU (Plinthic Haplustox), RM (Haplic Plinthustults), and RL (Typic Durustalfs). Referring to the heatmap diagram, the soil classification in sub-groups could be simplified into soil order level. The first cluster consisted of Alfisols and Oxisols. The second cluster was occupied by Inceptisols and Ultisols. The third cluster was possessed by Entisols. Based on these findings, it was clearly demonstrated that oil palm was a species which had high adaptability to the various soil condition.

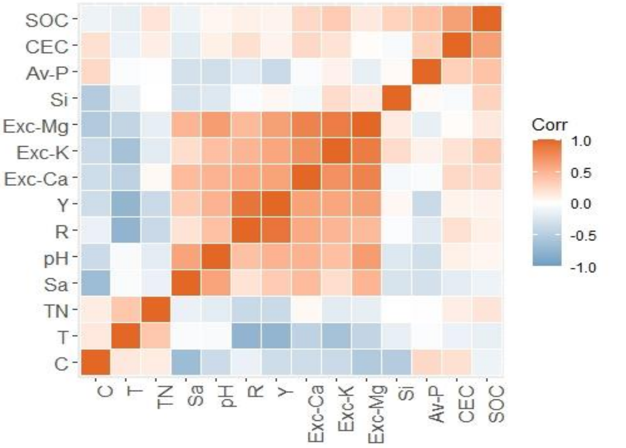

Figure 4. Correlation matrix among observation parameters in the surveyed area. A palette color showed a degree correlation coefficient among observation parameters. T: toposequence; R: rainfall; Y: oil palm productivity

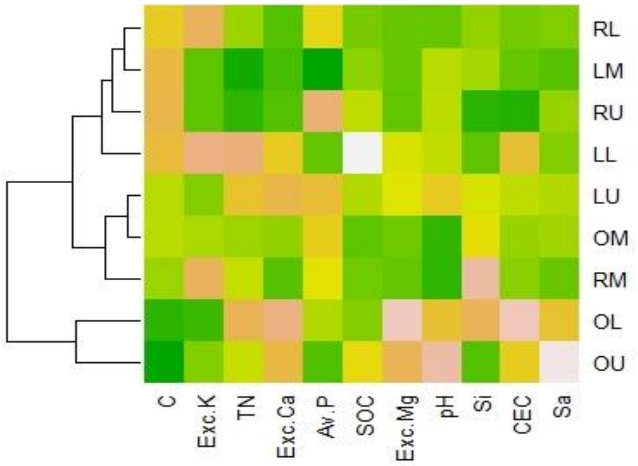

Figure 5. Heatmap between soil profile and soil diversity. Data were presented in OU (Typic Udorthents), OM (Fragic Hapludults), OL (Lithic Udorthents), LU (Lithic Dystrustepts), LM (Typic Rhodudalfs), LL (Oxyaquic Fraglossudalfs), RU (Plinthic Haplustox), RM (Haplic Plinthustults), and RL (Typic Durustalfs). The similar color in the heatmap indicated more similar soil characteristics among locations

Relationship between soil diversity and oil palm productivity

Despite having high adaptability to the wide environmental gradient, particularly related to soil characteristics, the productivity of oil palm substantially depended on the balance and availability of soil nutrients. Therefore, the application of nutrient management was importantly required to improve oil palm productivity. According to the study from Behera et al. (2017), oil palm basically required a high amount of N, P, K, and Mg to substitute the nutrient loss from the harvesting of fresh fruit bunch. It explained why the treatment of fertilization was frequently conducted in oil palm plantation.

In order to formulate the best strategy for nutrient management, mainly in fertilization, the available information about the relationship between soil characteristics and oil palm productivity was necessary. This study found there were several parameters of soil characteristics that statistically influenced oil palm productivity in the surveyed location, i.e. pH, CEC, Av-P, Exc-K, Exc-Ca, and Exc-Mg (Table 5). The higher content of those parameters substantially improved oil palm productivity. It indicated by the positive correlation between oil palm productivity and those parameters (Figure 4). These outcomes were relatively similar to the previous studies on oil palm plantation in different regions (Euler et al. 2016; Silalertruksa et al. 2017; Woittiez et al. 2017; Tao et al. 2018). However, only some parameters were suitable to be used as predictor variables for estimating oil palm productivity (Table 6). Our study realized that the use of equation $Y = 177.4 - 81.5 Av\text{-}P - 1947.9 Exc\text{-}K + 72.4 Exc\text{-}Ca$ was reliable to estimated oil palm productivity in each site and each toposequence (Table 7). This equation provided an accurate estimation approached of 65.3%. Most importantly, even though Av-P, Exc-K, and Exc-Ca could become a significant parameter for predicting oil palm productivity, it did not mean only those variables which became the priority aspects in soil management of oil palm plantation in ultramafic. This study also recorded a significant influence of pH, CEC, and Exc-Mg on oil palm productivity in research site (Table 5). Therefore, a balanced nutrient management was required to improve productivity of oil palm plantation in ultramafic. However, the application of nutrient management treatment must consider the specific soil characteristics in every location.

In conclusion, this study showed soil diversity of ultramafic ecosystems in oil palm plantation exceptionally varied and significantly influenced the gradient of oil palm productivity. The position of toposequence exhibited a significant correlation with soil diversity. Six soil parameters that significantly affected the productivity of oil palm plantation, i.e. pH, CEC, Av-P, Exc-K, Exc-Ca, and Exc-Mg. It indicated those soil parameters should be managed carefully to ensure the sustainable production of oil palm plantation in ultramafic ecosystems. The estimation of oil palm productivity in the study area was counted using equation $Y = 177.4 - 81.5 Av\text{-}P - 1947.9 Exc\text{-}K + 72.4 Exc\text{-}Ca$. Most importantly, a balanced nutrient management was required to improve productivity of oil palm plantation in ultramafic.

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