AGRIVITA Journal of Agricultural Science. 2018. 40(2): 257-266

AGRIVITA
Journal of Agricultural Science

Soil Biochemical Properties and Nutrient Leaching from Smallholder Oil Palm Plantations, Sumatra-Indonesia

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ARTICLE INFO

Keywords:
Fertilization
Frond Stacked
Nutrient Leaching
Oil Palm
Soil Properties

Article History:
Received: November 2, 2017
Accepted: March 28, 2018

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ABSTRACT

The study aimed to assess soil biochemical properties and nutrient leaching in oil palm plantation. The research was conducted in smallholder oil palm plantations which were located in Jambi Province - Indonesia. Nutrient leaching was determined by measuring nutrient concentration in soil solution bi-weekly and monthly in the frond stacked and fertilized areas; soil water samples were collected by using suction cup lysimeter. The result showed that the application of mineral fertilizer (e.g. NPK) and dolomite resulted higher base saturation, exchangeable Ca, and available P in the fertilized than frond stacked and inter row areas ($p \leq 0.05$). Stacking oil palm frond increased the soil macro-porosity, hence decreased leaching of K, Mg, Na, P, and total Al in the frond stacked than in the fertilized areas. The lower leaching losses and the higher soil macroporosity in the frond stacked than in the fertilized areas indicated that either the water did not dilute nutrient in the soil due to bypass flow, or the nutrient release from mineralization did not surpass nutrient demand which is quickly uptaken by palm root. Proper soil management through synchronizing rate of fertilizer application with nutrient output or frequency of fertilizer application may potentially minimize leaching losses.

INTRODUCTION

An efficient nutrient use and soil degradation are the two concerns in maintaining sustainability of oil palm plantation. Oil palm plantation is primarily established in a high weathered soil (e.g. Ultisol, Oxysol) which is characterized as low in soil fertility and high in soil acidity, therefore fertilizer is mainly applied in a high rate to maintain nutrient availability in the soil, as well as to support vegetative growth and fruit production (Comte, Colin, Whalen, Grünberger, & Caliman, 2012). In addition, 40-65 % of total field cost in oil palm plantation is allocated for fertilizer (Comte et al., 2013).

Based on the ownership, in Indonesia, the area of oil palm plantation is managed by three groups, government (6.5 %), private (52.7), and smallholder (40.8 %) (Directorate General of Estate Crop, 2015). The state and private enterprises managed from 3000 to 40000 ha depending on the area of province and usually include a processing mill (Casson, 1999; Dislich et al., 2017). While the smallholder of oil palm plantations is defined as small sized oil palm plantation (average of 2 ha, but can be up to 50 ha) which is managed by farmers or in association with a oil palm company where the company gives technical assistance and agricultural input for the farmers (Lee et al., 2014; Vermeulen & Goad, 2006). Oil palm plantation in the Province of Jambi is dominated by smallholders (61 %), while the large-scale enterprises (both state and private) cover 39 % of oil palm plantation (Statistics of Jambi Province, 2012). The different ownership implicates different soil management practices, including land clearing, fertilization, pests and diseases management.

Soil management practices in most oil palm plantations are conducted by applying mineral

ISSN: 0126-0537 Accredited by DIKTI Decree No: 60/E/KPT/2016

Cite this as: Kurniawan, S., Corre, M. D., Utami, S. R., & Veldkamp, E. (2018). Soil biochemical properties and nutrient leaching from smallholder palm oil plantations, Sumatra-Indonesia. *AGRIVITA Journal of Agricultural Science, 40*(2), 257–266. http://doi.org/10.17503/agrivita.v40i2.1723

fertilizer around the palm tree or cutting the frond and stacking in the palm inter-rows. These practices may increase or replenish nutrient levels in the soils. On the other hand, the application of oil palm empty fruit bunches or oil palm mill effluent (around the oil palm tree) is rarely practiced in smallholder oil palm plantations (Comte, Colin, Whalen, Grünberger, & Caliman, 2012). These management practices lead to spatial variation in nutrient input and consequently affect soil nutrient leaching losses, as the fluxes of nutrient leaching are influenced by nutrients availability in the soil (Dechert, Veldkamp, & Brumme, 2005). The mineral fertilizer application in the area around oil palm tree gives also an impact on the higher soil nutrient stock at local spots (around the oil palm stem) as compared to the unfertilized area such as inter-row (Anuar, Goh, Heoh, & Ahmed, 2008). The variation in nutrient input increases nutrient concentrations of drainage water in the fertilized area than unfertilized area during 75 days of fertilizer application (Tung, Yusoff, Majid, Joo, & Huang, 2009).

Oil palm frond stack in the area between oil palm trees can supply large quantities of nutrients into the soil through decomposition and mineralization processes, because oil palm frond contains an esential nutrient for oil palm growth. The previous research reported that nutrient returned the soil from green pruned frond in oil palm plantation per hectare per year approximately 89 kg N, 5.1 kg P, 18 kg K, 45 kg Ca, and 11 kg Mg (Kotowska, Leuschner, Triadiati, & Hertel, 2016). Another study in Sumatra (Dislich et al., 2017; Fairhurst, 1996) reported that 10 t of frond dry matter contained N, P, K, and Mg approximately 125 kg, 10 kg, 147 kg, and 15 kg, respectively. However, the temporal release of N, P, K, and Mg from the pruned fronds is following an exponential equation with higher nutrient release in the beginning, followed by lower release in decomposition phases (Moradi, Teh, Goh, Husni, & Ishak, 2014). In addition, stacking oil palm pruned frond also improves soil physical properties such as soil macro-porosity, which increases soil infiltration rate, and may have high potential leaching of nutrient (Banabas, Turner, Scotter, & Nelson, 2008; Lehmann & Chroth, 2003). Nevertheless, the higher soil macro-porosity under the frond stack will not increase nutrient leaching losses in these areas as long as the nutrient release from oil palm mineralization is low or the water percolation moves rapidly to the deeper layer, called as bypass flow.

Studies on spatial and temporal variability of nutrient leaching in relation to stacking oil palm frond and fertilization is limited. This research aimed to analyze the effect of spreading fertilizer around the palm trees and stacking palm fronds in the palm row on soil biochemical properties and leaching losses in heavily weathered soil. The hypothesizes are: 1) soil nutrient stocks and nutrient leaching losses are higher in the fertilized area than under the frond stack due to the faster release of nutrient through inorganic fertilizer, whereas nutrient release from the decomposing fronds is low and will be absorbed by roots before it is leached, and 2) stacking the pruned fronds will increase soil macro-porosity and bypass flow, resulting in a lower nutrient leaching losses.

MATERIALS AND METHODS

The study was conducted in six smallholder oil palm plantations (01°55'40"-02°0'57" S, 102°45'12'-103°15'33" E) selected in 2 different regencies: Batanghari and Sarolangun regencies, Jambi Province, Indonesia. The mean of annual air temperature and precipitation recorded in Sultan Thaha airport - Jambi Province from 1991 to 2011, were 26.7 ± 0.1°C and 2235 ± 385 mm (data from Jambi- Meteorological, Climatological and Geophysical Agency). The smallholder of oil palm plantations ranged between 9 to 16 years old. Fertilizers were applied at 0.8-1.5 m from palm stem with rates (ha^{-1} $year^{-1}$) of 48 to 138 kg N, from 21 to 38 kg P, and from 40 to 157 kg K; the lower rate was in Sarolangun regency and the upper rate was in the Batanghari regency. Dolomite ($CaMg(CO_3)_2$), kieserite ($MgSO_4.H_2O$) and borate ($Na_2B_4O_2.5H_2O$) fertilizers were applied in some of the plot (200 kg ha^{-1} $year^{-1}$). In oil palm plantation, the frond was regularly cut and stacked at 4 to 5 m from the palm stem with annual input of palm fronds ranged between 5.5 to 7.2 Mg ha^{-1} (Kotowska, Leuschner, Triadiati, Meriem, & Hertel, 2015).

Soil nutrient leaching was measured from nutrient concentration in the soil water, which were collected using suction cup lysimeters at 1.5 m depth in the fertilized (± 1.3 m from the palm tree) and frond stacked areas (4 to 5 m from the palm tree). These samples were taken every two to four weeks period from February to December 2013 by sucking 40 kPa vacuum in the collection bottles. The nutrient concentration in soil water was analyzed for a total of dissolved nitrogen (TDN), NH_4+, NO_3-, total

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P, Na, K, Ca, Mg, and total Al using flow injection colorimetric (for TDN, NH_4+, NO_3-) and inductively coupled plasma-atomic emission spectrometer (for Na, K, Ca, Mg, total Al, total P).

To measure soil biochemical properties, soil samples were taken at 0.1 m depth from the frond-stacked area (3.5 m from the rows of oil palm tree); from the fertilized area (1.4 ± 0.1 m from the palm stem) and from inter row where no fronds were stacked (> 2.0 m from the oil palm tree). Soil samples were air-dried for a week and sieved (2 mm sieve) before measuring the pH, total N, an effective cation exchange capacity (ECEC), soil organic carbon (SOC), exchangeable bases (Ca, Mg, K, Na), extractable P, and total aluminum (Al). Soil sampling and analysis were reported by Allen, Corre, Tjoa, & Veldkamp (2015). To identify whether nutrient leaching was not only caused by the soil nutrient stock but also the water pass flow, they also flow, the study also measured soil macro-porosity using methylen blue dye (Suprayogo et al., 2006) under the frond-stacked and in the fertilized area only in the Sarolangun regency because the soil fraction was dominated by clay content, having high nutrient holding capacity, whereas the soil texture in the Batanghari was loam with lower nutrient retention (Allen, Corre, Tjoa, & Veldkamp, 2015; Kurniawan, 2016). The soil macro-porosity was determined by tracing the distribution of methylene blue dye both vertical and horizontal within the frame of 100 cm x 50 cm x 50 cm (the application of methylene blue was 0.4 g l^{-1} water).

Prior to statistical analysis, the data was tested for normality by using Shapiro-Wilk's test. Logarithmic or square-root was used to transform the non-normal data. Differences in soil nutrient stocks, element concentration in soil solution, and soil macro pore between fertilized and frond-stacked areas were tested using linear mixed effects (LME) models and Fisher's LSD (least significant difference) test p ≤ 0.05 (Crawley, 2008). This research also considered marginal significant difference at p ≤ 0.09 due to the research design covered the inherent spatial variability in the study region. The relationships between concentrations of cation and anion charge in soil solution across all sampling period (i.e. *n* = 12) were analyzed using Pearson correlation. While, the relationships between soil characteristics across sampling location (fertilized and frond stacked areas) and averages nutrient concentration in soil solution were assessed using Spearman's rank correlation tests.

RESULTS AND DISCUSSION

Differences in Soil Chemical Properties Between Frond Stacked, Fertilized, and Inter Row Areas in Smallholder Oil Palm Plantation

In smallholder of oil palm plantations, the rate of fertilizer application is varied depending on the capital/farmer income, the price of fertilizer, and the price of fresh fruit bunches of palm tree. Thus, this research only detected a higher exchangeable Ca, available P, and base saturation in the fertilized area than in the frond stacked and inter row areas (Table 1). This finding was consistent to the result of Carron, Auriac, et al. (2015) who reported that the circle (area that received mineral fertilizer) had higher exchangeable Ca, base saturation, and available P than the windrow (frond-stacked area) and harvest pathway (inter row area) in an industrial oil palm plantation, Riau-Sumatra. The research did not detect any differences in all parameters of soil biochemical characteristics between the frond-stacked and inter row areas, and thus this manuscript will reported and discussed about differences in soil biochemical properties between fertilized and frond stacked areas.

Soil exchangeable Ca in the frond stacked (~1.03 ± 0.3 $cmol_{charge}$ kg^{-1}) and in the fertilized (~5.80 ± 1.7 $cmol_{charge}$ kg^{-1}) areas within smallholder of oil palm plantation was higher than the values published by Carron, Pierrat, et al. (2015) for a 25-year plantation of oil palm in Riau, Sumatra (0.3 $cmol_{charge}$ kg^{-1}). Nevertheless, soil exchangeable Ca in the frond stacked area was comparable to the value recorded by Tanaka et al. (2009) for smallholders of oil palm plantation in Sarawak, Malaysia (1.07 $cmol_{charge}$ kg^{-1}). Dolomite ($CaMg(CO_3)_2$) application released Ca and Mg, resulting a higher exchangeable Ca soil in the fertilized area as compared to the frond-stacked area. This was shown by a strong and positive correlation between exchangeable Ca soil and Mg (r = 0.76; p ≤ 0.01). Furthermore, the increases of base cation (e.g. Ca and Mg) in the soil played an important role in increasing the base saturation, which is shown by: 1) the value of base saturation in the fertilized area was 2 times higher than those in the frond-stacked area, and 2) a strong positive correlation between exchangeable Ca soil and base saturation (r = 0.95, p ≤ 0.01) and the positive correlation between soil exchangeable Mg and base saturation (r = 0.67, p

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= 0.03).

The smallholder of oil palm plantation was located in a high weathered soil (Acrisol) which is characterized by a high of Al saturation (between 53 and 67 %; Hassler et al., 2015), as well as low P availability due to a high P adsorption (Al – P binding). Thus, an addition of Ca and Mg in the soil through dolomite ($CaMg(CO_3)_2$) probably replaced soil exchangeable Al in the surface adsorption and consequently decrease the soil exchangeable Al in the fertilized than frond-stacked areas (Kurniawan, 2016). In addition, replacing Al (positive 3) by Ca (positive 2) in the surface adsorption may also release P which is binded by Al (Al-P), causing a higher extractable P in the fertilized area than in the frond-stacked area. It is supported by a strong positive correlation between soil exchangeable Ca and extractable P (r = 0.81, P ≤ 0.01). Last, the application of P fertilizer such as NPK and SP-36 is another factor that increases soil extractable P in the fertilized area as compared to the frond stacked areas (Table 1).

Table 1. Soil biochemical properties in 10 cm soil depth from the fertilized, frond stacked, and inter row areas in smallholder oil palm plantations, Jambi - Sumatra, Indonesia.

Parameters	Fertilized Area	Frond Stacked Area	Inter Row Area
pH (1:4 H_2O)	[a]4.53 (0.18)	4.41 (0.04)	4.46 (0.04)
Soil organic Carbon (kg C m^{-2})	3.09 (0.54)	2.67 (0.46)	2.70 (0.47)
Total Nitrogen (g N m^{-2})	220.73 (32.37)	206.42 (33.99)	203.65 (35.28)
C:N ratio	13.68 (0.57)	12.76 (0.38)	13.21 (0.28)
Effective cation exchange capacity ($mmol_{charge}$ kg^{-1} soil)	86.40 (17.41)	52.27 (10.57)	52.63 (10.67)
Base saturation (%)	67.62 (12.90)$_a$	23.37 (3.26)$_b$	27.37 (4.98)$_b$
Potassium (g K m^{-2})	7.48 (3.88)	3.05 (0.79)	2.76 (0.79)
Sodium (g Na m^{-2})	3.13 (0.88)	3.00 (1.48)	2.33 (0.83)
Calcium (g Ca m^{-2})	115.63 (41.57)$_a$	17.88 (6.51)$_b$	25.92 (11.37)$_b$
Magnesium (g Mg m^{-2})	3.38 (0.74)	2.38 (0.89)	2.30 (0.94)
Aluminum (g Al m^{-2})	17.24 (7.19)	31.99 (5.10)	29.49 (3.67)
Manganese (g Mn m^{-2})	1.60 (0.86)	2.95 (1.41)	2.50 (1.21)
Iron (g Fe m^{-2})	0.52 (0.15)	0.52 (0.11)	0.54 (0.15)
Bray-extractable phosphorus (g P m^{-2})	14.84 (9.73)$_a$	0.95 (0.23)$_b$	0.94 (0.24)$_b$

Remarks: [a]Means (SE, n = 6) followed by different lower case letters indicate significant differences (at p ≤ 0.05) among sampling location (fertilized, frond stacked, and inter row) using LME models with Fisher's LSD test.

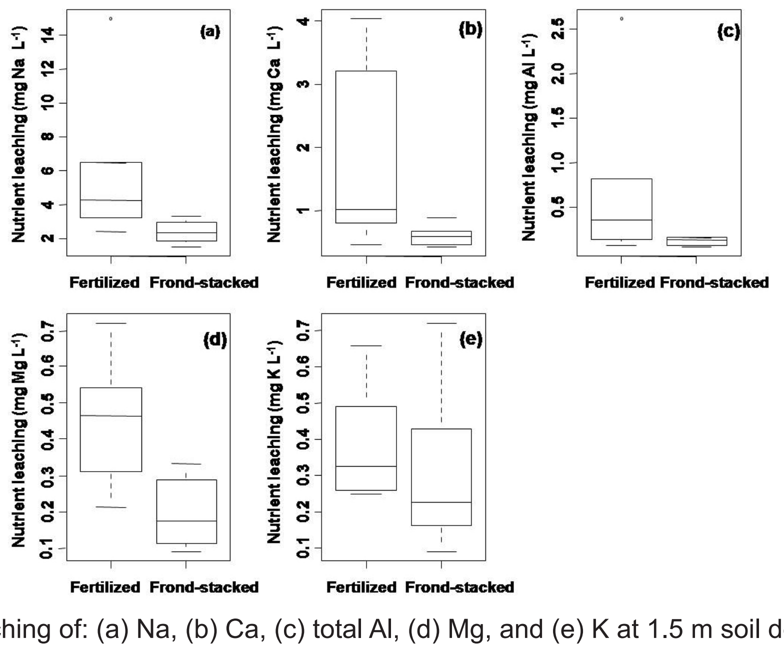

Fig. 1. Nutrient leaching of: (a) Na, (b) Ca, (c) total Al, (d) Mg, and (e) K at 1.5 m soil depth in the fertilized and frond stacked areas in smallholder oil palm plantations, Jambi, Sumatra, Indonesia.

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Nutrient Leaching from the Frond-Stacked and Fertilized Areas in Smallholder Oil Palm Plantations

Soil nutrient leaching under the fertilized area was higher than the frond-stacked area, especially for leaching losses of K, Na, Ca, Mg, and total Al as compared to the frond-stacked area (Fig. 1). The study was unable to detect significant differences of total dissolved N and organic C between fertilized and frond-stacked areas. The concentration of Ca and Mg had a positive correlation with total Al in the soil water within the fertilized and frond-stacked areas (r = 0.53 – 0.84; Table 2). Base cation leaching losses (e.g. Mg and Na) were positively correlated with base saturation (r = 0.55-0.84, p = 0.00 – 0.09). In addition, nutrient concentrations in the soil water (e.g. K) had a negative correlation with soil macro-porosity (both vertical and horizontal; r = -0.83 – -0.94, P = 0.02 – 0.06) at the top 25 cm depth of soil, especially in smallholder oil palm plantation in Sarolangun regency.

The concentration of Na and K in our measurement (~ 0.18 ± 0.05 $mmol_{charge}$ L^{-1} soil for Na and 0.01 ± 0.00 $mmol_{charge}$ L^{-1} soil for K) was comparable to the values from the depth 30 cm of soil within tropical forest and cropland (0.04 $mmol_{charge}$ L^{-1} for Na and 0.03-0.06 $mmol_{charge}$ L^{-1} for K) (Fujii, Funakawa, Hayakawa, Sukartiningsih, & Kosaki, 2009). The concentration of potassium in soil water under the frond-stacked (0.29 ± 0.06 mg K L^{-1}) and fertilized area (0.40 ± 0.04 mg K L^{-1}) were lower than the value from Tung, Yusoff, Majid, Joo, & Huang (2009) who measured concentration of K in soil solution at 1.2 m depth of soil under a mature oil palm plantation (26 years old) in Acrisol, Serawak – Malaysia. The values of Ca and Mg (~ 0.06 ± 0.03 $mmol_{charge}$ Ca L-1 and 0.03 ± 0.01 $mmol_{charge}$ Mg L^{-1}) were also comparable to those in soil solution at 30 cm depth of soil within tropical forest and crop land in East Kalimantan, Indonesia (0.04-0.08 $mmol_{charge}$ Ca L^{-1} and 0.03-0.04 $mmol_{charge}$ Mg L^{-1}) (Fujii, Funakawa, Hayakawa, Sukartiningsih, & Kosaki, 2009). However, no previous study can be used to compare the base cation concentration (e.g. Na, Ca, and Mg) in soil water within oil palm plantation.

Table 2. Correlation (Pearson test, n = 12) among nutrient concentration (mg L^{-1}) in soil solution (1.5-m depth) from different sampling areas in oil palm plantation.

Element	NH_4^+-N	NO_3^--N	Total N	DOC	Na	K	Ca	Mg	Total Al	Total P	pH
Frond stacked area											
DON	-0.17	0.44	0.60*	0.03	-0.25	0.14	0.04	-0.07	0.36	0.13	-0.29
NH_4^+-N		-0.11	0.59*	0.34	0.28	0.06	0.02	0.02	-0.04	0.06	0.28
NO_3^--N			0.57*	0.17	0.25	0.29	0.11	0.03	0.26	0.65*	0.09
Total N				0.33	0.17	0.24	0.08	-0.01	0.27	0.30	0.09
DOC					0.11	0.14	-0.08	0.06	-0.18	0.07	0.48
Na						0.20	0.48†	0.51†	0.43	-0.21	0.07
K							-0.14	-0.08	0.11	0.01	0.28
Ca								0.94**	0.82**	-0.30	-0.57*
Mg									0.78**	-0.32	-0.49*
Total Al										-0.25	-0.54*
Total P											0.08
Fertilized area											
DON	0.02	0.03	0.17	0.17	-0.14	0.04	0.25	0.35	0.58*	0.20	-0.21
NH_4^+-N		-0.01	0.14	0.26	0.29	0.70**	0.52†	0.58*	0.45	0.13	-0.16
NO_3^--N			0.98**	-0.28	0.11	0.19	-0.62*	-0.13	-0.18	0.65*	-0.15
Total N				-0.21	0.14	0.29	-0.49†	0.01	-0.03	0.68**	-0.20
DOC					0.13	0.35	0.22	0.52†	0.39	-0.35	-0.13
Na						0.40	-0.13	0.07	-0.04	0.04	-0.16
K							0.15	0.27	-0.01	0.04	0.18
Ca								0.44	0.53†	-0.27	0.07
Mg									0.84**	0.19	-0.64*
Total Al										0.08	-0.71**
Total P											-0.15

Remarks: *, ** - significant at p ≤ 0.05 and p ≤ 0.01, respectively, † show marginal significant at p ≤ 0.09

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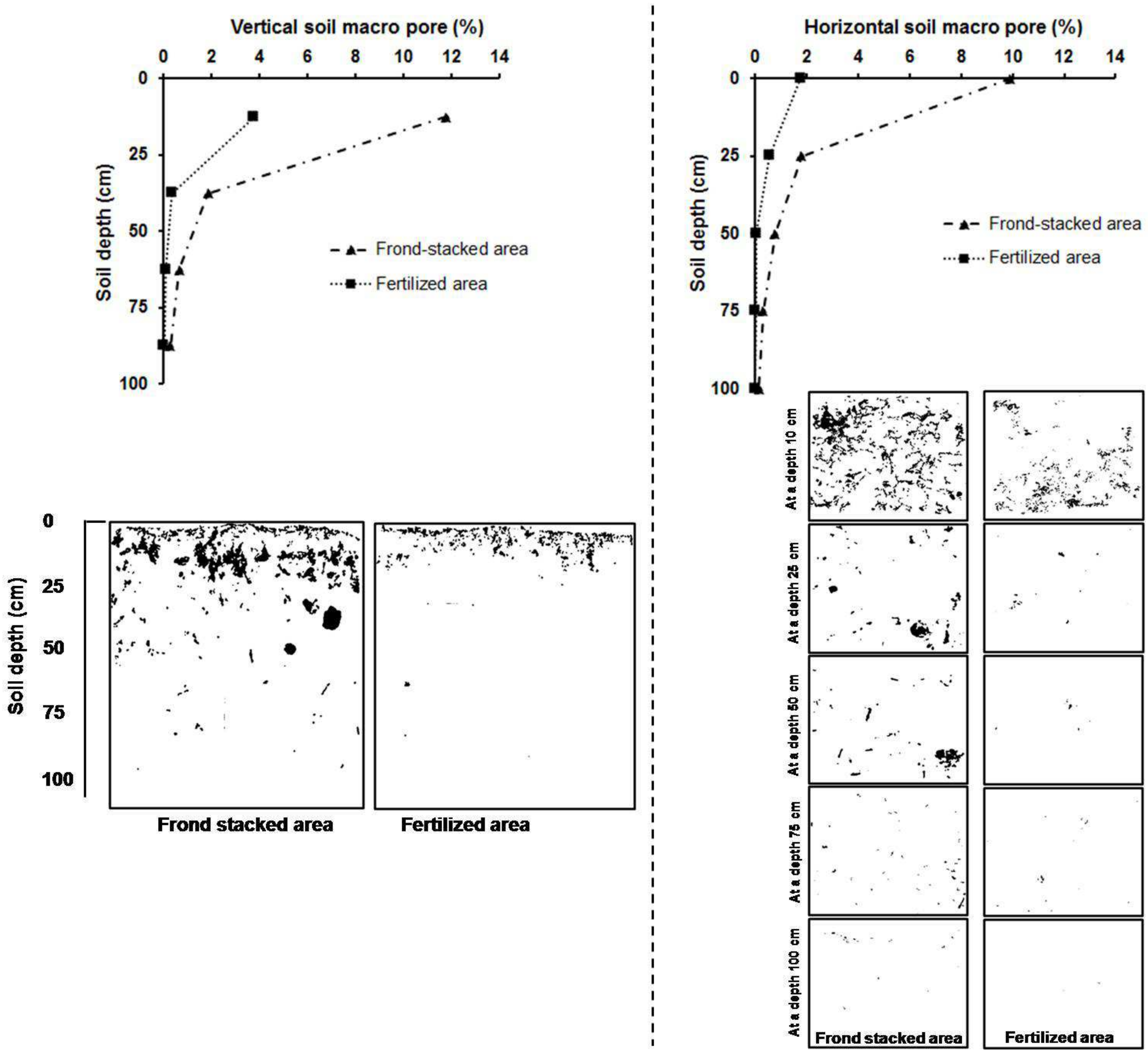

Fig. 2. Vertical soil macro pore (left) and horizontal soil macro-pore (right) between frond-stacked and fertilized areas in 100 cm soil depth in smallholder oil palm plantations, Jambi, Sumatra, Indonesia

The result showed that the application of fertilizer and lime played an important role on nutrient concentration in the soil solution. The application of inorganic fertilizer (e.g. NPK, KCl, and borate; see Materials and Methods) results in higher K and Na leaching losses in the fertilized area than in the frond-stacked areas which received only prune frond (Fig. 1 a and e). The application of dolomite (Ca Mg $(CO_3)_2$) increased Ca and Mg concentrations in soil water under the fertilized area (Fig. 2 b and d). The high concentration of Ca and Mg in soil water replaced soil exchangeable Al from the soil adsorption site, releasing Al in the soil water (Fig. 1c). This was supported by the positive correlation of Ca and Mg with total aluminum concentration in the soil water both in the fertilized and frond stacked areas (Table 2). In addition, a higher total Al in the fertilized than in the frond stacked areas probably also caused by the application of mineral N fertilizer which may have increased the solubility of Al in soil solution. The replacement of Al in the surface adsorption by Ca and/or Mg increased soil exchangeable Ca and base saturation (Table 1).

A negative correlation between soil macro-porosity (both vertical and horizontal, r = -0.83 to -0.94) and nutrient concentration in soil water might explain the lower leaching losses under the frond-stacked as compared to the fertilized area and it was probably because of a high soil macro-porosity in the fond-stacked area. The addition of organic matter (e.g. palm frond) might increase soil organism activities to create a channel in the soil, resulting in a higher soil macro-porosity and infiltration rate. If the water move rapidly to the deeper layer and less contact with the surface adsorption, it will result a low concentration of nutrient in the soil water. The measurement of soil macro-porosity using methylene blue dye (see in materials and methods) in three replicate plots within Sarolangun regency showed that the vertical and horizontal soil macro-porosity was 2-8 fold higher in the frond stacked than in the fertilized areas (Fig. 2). This finding is consistent to Banabas, Turner, Scotter, & Nelson (2008) who reported that the frond pile zone had higher infiltration due to an increasing of soil macro-porosity from the effect of palm frond addition. Therefore, the higher soil macro pores (vertical and horizontal, Fig. 2) together with a lower soil nutrient stock (e.g. P, Ca, and Base saturation; Table 1) in the frond stacked than in the fertilized area result lower leaching losses of Ca, K, Na, Mg, and total P.

Quantifying Nutrient Leaching Fluxes and their Consequences on Soil Management Practices in Oil Palm Plantations

For a better understanding of nutrient leaching losses in a certain area and their relationship to soil management practices, this study calculated nutrient leaching fluxes by multiplying concentrations of nutrient in soil water from each sample collection with a total of drainage water (two weeks or four weeks) at 1.5 m depth. The total drainage water fluxes were calculated from cumulation of daily drainage water fluxes, which was estimated using the modelling of Expert-N (Priesack, 2005). This study considered to use an Expert N model since it was used successfully in the previous research of soil nutrient leaching from the conversion of montane forest to agricultural land in Sulawesi, Indonesia (Dechert, Veldkamp, & Brumme, 2005). Then, to validate the output of the Expert-N model, the result of soil matrix potential was compared to the field measurement (at 30 and 60 cm depth of soil). The output of the Expert N model was accepted if soil matrix potential at each depth between the modelled and field measurement had strong positive correlations (Pearson correlation coefficients of 0.79 to 0.96, all $p \leq 0.01$) and the paired of t-test was not significantly different (all $p \geq 0.21$, n = 10 for 30 cm depth and n = 9 for 60 cm depth) (Kurniawan, 2016).

In the fertilized area, leaching losses (kg ha^{-1} $year^{-1}$) of total dissolved N, total P, K, Ca, and Mg (~12.6 ± 5.2; 0.07 ± 0.01; 5.94 ± 1.11; 7.52 ± 0.98; and 2.74 ± 0.39, respectively) were 14–26 % of N fertilizer, 8–14 % of K fertilizer, and 65 % and 28 % of Ca and Mg input from dolomite, whereas total P leaching losses were only < 1% compared to P input from inorganic fertilizer (see materials and methods; Allen, Corre, Tjoa, & Veldkamp, 2015). In the frond-stacked area, leaching fluxes (kg ha^{-1} $year^{-1}$) of total dissolved N, total P, K, Ca, and Mg (3.49 ± 0.62, 0.12 ± 0.07, 3.63 ± 0.94, 7.52 ± 0.98, and 2.74 ± 0.39, respectively) were ranged between 2.4 to 25.6 % of those returned from the pruned frond (Kotowska, Leuschner, Triadiati, & Hertel, 2016). The loss of N through leaching was higher than N loss by emission from the same palm tree plot (1 – 1.1 kg N ha^{-1} yr^{-1}; Hassler et al., 2015). The total of dissolved N losses in this study was higher than N leaching at 1.2 m depth in mature oil palm plantations (26-year old) on Acrisol, Malaysia with NPK fertilizer treatment (Tung, Yusoff, Majid, Joo, & Huang, 2009). However, Tung, Yusoff, Majid, Joo, & Huang (2009) measured N leaching losses only in 150 days over fertilization, whereas the leaching fluxes in this study was calculated for 315 days, and it was problematic for comparison. A low P loss through leaching from inorganic fertilizer input was due to the high of P fixation by aluminum, which is common in Acrisol soil (Al saturation 53-67 %: Hassler et al., 2015). In addition, leaching fluxes of Ca and Mg in the fertilized area of this study was comparable to leaching fluxes of Ca and Mg in the fertilized area of mature oil palm plantations (22 year old), in Nigeria (~46 ± 13 kg Ca ha^{-1} $year^{-1}$, 8.8 ± 2.1 kg Mg ha^{-1} $year^{-1}$; Omoti, Ataga, & Isenmila, 1983). By combining the nutrient output through harvest export, high leaching losses of Ca and Mg resulted a negative net balance of Ca and Mg in oil palm plantation which contributed to 73 % decreases of soil nutrient stock (especially for Mg) in the top of 1m depth of soil (Kurniawan, Corre, Utami, & Veldkamp, 2017).

The current fertilizer application around the palm stem in smallholder oil palm plantations resulted a temporary increase in nutrient concentrations. If these concentrations exceed the nutrient uptake of the palm tree, they would increase nutrient leaching and have a potential impact to the quality of ground

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water, a nutrient use and soil nutrient stock of oil palm plantations. Improving fertilization practices (e.g. synchronize the dose of fertilizer with nutrient demand of palm tree) would probably reduce nutrient leaching losses. Another soil management practices that may reduce nutrient leaching losses can be conducted through stacking pruned fronds close to the fertilized area. These practices could reduce leaching losses in the fertilized area by increasing the nutrient uptake from mineralization, as well as nutrient immobilization, since the application of oil palm frond might increase soil organism mass (Allen, Corre, Tjoa, & Veldkamp, 2015).

CONCLUSION AND SUGGESTION

The study showed that higher leaching losses of K, Na, Ca, Mg and total Al in the fertilized area than in the frond stacked area were mainly caused by the application of inorganic fertilizer and liming. In addition, the application of organic matter (e.g. oil palm frond) increase soil macro-porosity, which is probably caused by soil organism activity, resulting in a decrease of nutrient leaching losses due to bypass flow. Improving soil management practices through synchronizing rate of fertilizer application with nutrient output (e.g. harvest export) and frequency of fertilizer application may decrease soil nutrient leaching losses and optimize nutrient use in oil palm plantation.

ACKNOWLEDGEMENT

The measurement of soil biochemical properties and nutrient leaching was financed by the Deutsche Forschungsgemeinschaft (DFG) as part of the project A05 in the framework of the German-Indonesian Collaborative Research Center 990: Ecological and Socioeconomic Function of Tropical Lowland Rainforest Transformation Systems. Soil macro porosity measurement was funded by Directorate General of Higher Education (DIKTI) through DIPA Universitas Brawijaya No: 023.04.2.414989/2014 and SK Rektor Universitas Brawijaya No 157, April 10, 2014. S. Kurniawan received post-graduate scholarship from the Indonesian Directorate General of Higher Education. We are especially grateful to our assistants (Christanti Agustina, Fahrurrozy and Khairul Anwar). The authors thank the village leaders, local plot owners, PT Humusindo, PT REKI, and Bukit Duabelas National Park for granting us access and use of their properties. We also acknowledge subprojects A03 (Meijide et al. unpublished data) and the Indonesia Meteorological, Climatological and Geophysical Agency for climatic data and subproject B06 (Rembold et al. unpublished data) for leaf area index data. We thank Dirk Böttger, Andrea Bauer, Kerstin Langs and Martina Knaust (Georg-August University Göttingen, Germany) for their assistance with field instruments and laboratory analyses. This study was conducted using the research permits (215/SIP/FRP/SM/VI/2012 and 44/EXT/SIP/FRP/SM/V/2013) recommended by the Ministry of Research and Technology of Indonesia (RISTEK), and the collection permits (2703/IPH.1/KS.02/XI/2012 and S.13/KKH-2/2013) recommended by the Indonesian Institute of Sciences (LIPI) and issued by the Ministry of Forestry of Indonesia (PHKA).

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