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Does Soil Fertility Decline under Smallholder Rubber Farming? The Case of a West Sumatran Lowland in Indonesia

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Abstract

In Indonesia, plantations of rubber tree (*Hevea brasiliensis*), which have been expanding rapidly in lowland areas of the Sumatra Island, are predominantly managed by smallholder farmers using a limited amount of fertilizers. The rapid growth of the rubber tree and the intensive collection of latex during an economic lifetime (ca. 25 years) of the rubber tree poses a risk of soil fertility decline in the rubber gardens, but changes in soil fertility under smallholder rubber farming have not been well assessed in this region. In the present study, we aimed to examine if the soil fertility declines under smallholder rubber farming through the assessment of the changes in the general soil fertility parameters along a chronosequence of rubber tree stands (n = 24; stand age, 3-27 years old) in a West Sumatran lowland. Our results revealed that all the parameters assessed in this study such as organic carbon, total nitrogen, available phosphorus, and exchangeable bases were found independent on the tree stand age and did not show any clear trends of decrease/increase during rubber cultivation period. These findings indicate that soil fertility decline under smallholder rubber farming system is unlikely in the study region.

Discipline: Agricultural Environment
Additional key words: chronosequence, *Hevea brasiliensis*, rubber garden, soil fertility replenishment

Introduction

Rubber tree (*Hevea brasiliensis*) is an industrial crop with high economic value because it produces milky latex as the primary source of natural rubber. This latex consists of polymers of the organic compound isoprene, with non-rubber components (ca. 6%, w/w) such as proteins, phospholipids, and ash (Kawahara & Tanaka 2009). Recently, the value of the rubber tree was raised due to the production of timber (engineered woods) for manufacturing furniture.

Indonesia is known as the world's second largest natural rubber producer, producing annually 3 million tons of natural rubber (FAO 2017). Rubber plantation was first introduced in Indonesia by the colonial Dutch East Indies in the late 19th century and as of the moment it plays a vital role in the economic growth of this country. The rubber plantation in Indonesia is predominantly managed by smallholder farmers who own less than 25 ha of land (Fox & Castella 2013), and it has more than 2 million smallholder farmers enjoying the rubber-derived income (DGEC 2017). Through policy formulation and financial support by the government, the land area under smallholder rubber farming increased by 65% over the past 30 years, and it currently accounts for 85% of the total rubber plantation area in Indonesia (IMOA 2016).

The Sumatra Island is the hotspot area of rubber plantation in Indonesia (Warren-Thomas et al. 2015). This island produces about 77% of the national rubber production (DGEC 2017). Most of rubber plantations in these regions were established by the conversion from natural forest or transitional jungle rubber agroforestry system (Pye-Smith 2011, Guillaume et al. 2015). The land conversion to industrial crop plantation (mostly oil palm and rubber tree) is the main cause underlying the loss of the original land cover, i.e., natural forest (Margono et al. 2014). In recent years, the Sumatra Island has been displaying the highest deforestation rate in the world and thus has lost almost half of its forest cover for the period of 1985-2007 (Laumonier et al. 2010). Similarly, the

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deforestation and subsequent land conversion to plantations have been seen in Kalimantan, where only 50% of the natural land cover remained in 2012 (Miettinen et al. 2011). In particular, massive deforestation was seen in the lowland area of Sumatra, where only 9% of the natural land cover was left in 2012 (Margono et al. 2014). These changes in the land use, from natural or semi-natural systems to artificial or agricultural lands, inevitably brought about a variety of environmental degradations such as enhanced carbon emission and loss of biodiversity (Danielsen et al. 2009), accelerated soil erosion and exploitation of the soil fertility (Dechert et al. 2004), and deterioration of the water quality (Klinge et al. 2004), and these environmental issues have been a serious concern worldwide as well as in Indonesia.

On the other hand, soil fertility management is a key cultural practice for sustainable latex production in rubber gardens, despite the fact that the relationship between soil fertility and latex yield is still a matter under discussion (Chambon et al. 2017). In particular, applicable and affordable ways of soil management are needed for smallholder farmers because little or no use of fertilizer (external resource) is a prevailing practice in the smallholder farming system, which suggests the exploitation of nutrients from the rubber garden soils through the latex collection and thus undermining of soil nutrient budget in the rubber gardens (Tanaka et al. 2009). In fact, many previous studies reported the depletion of soil organic matter and mineral nutrients by land use change from primary or secondary forests to rubber plantation (e.g., Li et al. 2012, de Blécourt et al. 2013, Kotowska et al. 2015, 2016, Allen et al. 2015), and the soil degradation in rubber gardens can also increase with an increase in the age of the rubber tree stand (e.g., Aweto 1987, 2001, Cheng et al. 2007). In contrast, other reports delivered inconsistent results to those previously documented: the soil fertility under rubber farming was similar to that under primary and secondary forests (e.g., Tanaka et al. 2009, Moreira et al. 2013), and little loss or even enhanced content of organic matter and some nutrients in the soil were found during rubber cultivation (Guillaume et al. 2016, N'Dri et al. 2018, Peerawat et al. 2018). These contradictory findings warrant further research on the changes in soil fertility caused by rubber plantation. Nevertheless, the study of the changes in soil fertility during rubber cultivation, in particular those under smallholder farming schemes with low resource inputs (e.g., fertilization), has been attracting much less attention compared to the study on the impacts of land use change from forest to rubber plantation, which have been accumulated significantly in the literature (e.g., Li et al. 2012, de Blécourt et al. 2013, Allen et al. 2015, Kotowska et al. 2015, 2016).

In the present study, therefore, we aimed to address how the soil fertility status change under the rubber farming system with low- or no-input of the external resources which is largely conducted by smallholder farmers in a lowland area of West Sumatra, Indonesia through the assessment of general soil fertility parameters along a chronosequence of rubber tree stands.

Materials and methods

1. Study area

Dharmasraya District, West Sumatra Province, Indonesia (00°55′-00°57′S, 101°28′-101°32′E) was chosen for the present study, and the field survey was conducted there from August to October 2016. This site is situated 180 km south-east from the province capital Padang, and lies on a lowland landscape at an altitude lower than 120 m above the sea level and under a tropical rainforest climate (classified as *Af* in the Koppen-Geiger classification system). It has had a mean annual precipitation of ~ 2,418 mm over the past 30 years and a mean annual air temperature of 27°C with a monthly mean range of 23°C to 31°C (BMKG 2017). The soil parent material is alluvium, which originates from the Batang Hari River, and the soils are generally classified into Typic Dystrudepts (ICALRRD 2017). In the study region, the rubber trees shed their leaves once a year (May-June in a normal year) and get new leaves back within the period of 4 to 6 weeks.

At present, West Sumatra Province has a rubber plantation area of >170,000 ha out of which 41,260 ha (≈24%) are situated in Dharmasraya, known as a frontier of agricultural expansion in this region (BPS-PSB 2015). Historically, the rubber gardens in this area were mostly established by conversion from natural forests or jungle rubber agroforestry systems, and they were thoroughly managed by smallholder farmers (DGEC 2017). Although the owner farmers could not specify the names of the rubber clones planted in their gardens, a local association of rubber farmers mentioned that all farmers in this region cultivate productive clones such as GT1, PB260, IRR112, and BPM24, which were distributed by rubber development projects implemented by the Indonesian Government (Umami et al. Unpublished data). The farmers usually apply no or small amounts of fertilizers to young trees only after transplanting. Most of the gardens are subsequently managed unfertilized, although the majority of the farmers control the undergrowth vegetation by applying herbicides.

2. Soil sampling

Twenty-four rubber gardens (land area: 1.1 ± 0.4 ha) managed by 24 different smallholder farmers were selected to cover the tree age range, i.e., 3 to 27 years old, that encompasses their economic life time (25 years). Herein, the age of the rubber tree stand is referred to as the number of years after transplanting of rubber seedlings at each of the studied rubber gardens. These gardens had been managed unfertilized during the rubber tree farming, except for the first few years after the transplantation of 6- to 8-month-old seedlings (immature tree period). The annual application rates of fertilizers varied from 20 to 69 kg N ha^{-1}, 12 to 69 kg P_2O_5 ha^{-1}, and 23 to 90 kg K_2O ha^{-1}. The planting density in the studied gardens was either of 500 (area: 4 × 5 m) or 667 (area: 3 m × 5 m) tree per ha^{-1}, which was calculated based on the planting distance between the trees. All the studied gardens were maintained free from mixed cultivation with any other crops.

In the center of each rubber garden (ca. 2.5 m from the trees), soil samples were collected from freshly exposed soil profile at 0.1 m intervals up to 0.8 m in depth, using a volumetric (100 cm^3) ring sampler in triplicate from each sampling layer. A homogenized composite soil sample was air-dried and crushed to pass through a 2 mm mesh sieve prior to the laboratory analysis. Our field estimates (Japanese Society of Pedology 1997) revealed that these soils generally had clay loam texture.

3. Laboratory analysis

The soil pH and electrical conductivity (EC) were determined in water at a soil-to-solution ratio of 1:5 using a glass electrode (9625-10D connected to D-74; Horiba, Ltd., Tokyo, Japan) and an EC meter (9382-10D connected to D-54; Horiba, Ltd.). The total C and N were measured by an automated NC analyzer (Sumigraph NC-22A; Sumika Chem. Anal. Serv. Ltd., Tokyo, Japan). Herein, the whole C in the soil was considered to exist thoroughly in organic forms because the soil pH was lower than 6.5 in all samples. The carbon-to-nitrogen (C/N) ratio was calculated by dividing the organic C by the total N. Available P was extracted by the Bray No. 2 method and was measured by the molybdenum blue method using a spectrophotometer (V-630; Jasco Co., Tokyo, Japan). Exchangeable bases (exchangeable Ca, Mg, and K) were extracted with 1 M neutral ammonium acetate and measured by atomic absorption spectrometry (Z-2300; Hitachi Tech., Co., Tokyo, Japan). Exchangeable acidity was extracted with 1 M potassium chloride and was measured by alkaline titration. The effective cation exchange capacity (ECEC) was calculated by summation of the values of exchangeable bases and acidity, while base saturation was computed by the occupational percentage of exchangeable bases against ECEC. All laboratory analyses in the present study were performed following the routine methods of soil analysis (e.g., IITA 1979).

4. Statistical analysis

To evaluate the profile distribution characteristics of the examined soil fertility parameters, statistical differences in their means between the soil layers were detected at a 5% significant level ($P < 0.05$) by Tukey test. Pearson's correlation coefficients were calculated to analyze bilateral relationships between the examined soil parameters.

To understand the trend of changes in the soil fertility parameters in relation to the age of the rubber tree stands, linear regression model was applied to a series of data points from which the outliers were exempted. The outliers from the data set at each soil layer (n = 24) were identified based on two criteria as follows: i) mean plus/minus three times standard deviation (SD) and ii) median plus/minus three times median absolute deviation for the normally and non-normally distributed datasets (Leys et al. 2013). Herein, the normality of the data sets were examined by the Shapiro-Wilk test. In addition, coefficient of variation was obtained for the dataset without the outliers by dividing the SD by the mean of each parameter shown in percentage.

All statistical analyses in the present study were conducted using SigmaPlot ver. 13.0 (Systat Software Inc., California).

Results

Figure 1 illustrates the changes in the examined soil fertility parameters in relation to soil depth at the study site. According to the soil assessment criteria by Eviati & Sulaeman (2009), the soils at the uppermost layer (0-10 cm; n = 24) generally had low pH (mean ± SD, 4.6 ± 0.4) and EC (5.6 ± 2.4 mS m^{-1}), high content of organic C (36.8 ± 8.7 g kg^{-1}), and a moderate level of total N (3.0 ± 0.6 g kg^{-1}) with a moderate C/N ratio (12.6 ± 2.7). Also, these soils showed a moderate status of available P (10.3 ± 5.4 mg kg^{-1}), very low to low exchangeable bases (exchangeable Ca, 0.44 ± 0.86 $cmol_c$ kg^{-1}; exchangeable Mg, 0.23 ± 0.21 $cmol_c$ kg^{-1}; exchangeable K, 0.20 ± 0.16 $cmol_c$ kg^{-1}) along with moderate ECEC (6.5 ± 0.8 $cmol_c$ kg^{-1}), and a large amount of exchangeable acidity (5.6 ± 1.5 $cmol_c$ kg^{-1}) along with very low base saturation (14.6% ± 19.4%). These parameters, except the pH, significantly decreased with increased soil depth, showing significant differences ($P < 0.05$) between some upper and lower layers. Hence, the bottom layer (70-80 cm) showed the lowest mean values for EC (0.7 ± 0.3 mS m^{-1}), organic C (4.8 ± 1.2 g kg^{-1}), total N (0.5 ± 0.1 g kg^{-1}), available P (2.4 ± 3.5 g kg^{-1}), C/N ratio (8.9 ± 1.5), exchangeable Mg (0.08 ± 0.14 $cmol_c$ kg^{-1}), K (0.06 ± 0.07 $cmol_c$ kg^{-1}), and acidity (4.5 ± 1.5 $cmol_c$ kg^{-1}), and ECEC (5.0 ± 1.6

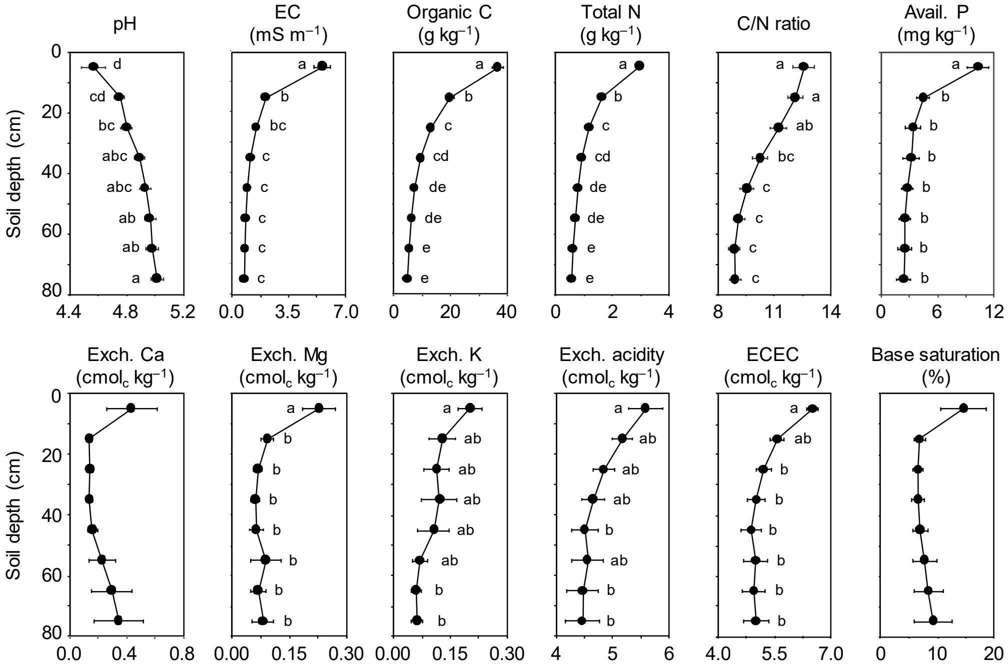

Fig. 1. Changes in the soil properties in relation to the depths of the soil at the study site

Error bars indicate standard errors at each soil layer. Different letters indicate significant difference ($P < 0.05$) between the soil layers.

cmol$_c$ kg^{-1}). An opposite tendency was observed for the pH, which exhibited a significant increase with a decrease in the soil depth, while no significant change in relation to the soil depth was observed for exchangeable Ca and base saturation.

Figure 2 shows scatter plots and a correlation matrix among the examined soil parameters in this study. The soil pH was negatively correlated with EC, organic C, total N, available P, and exchangeable acidity, but positively correlated with exchangeable Ca, Mg, and K to a significant degree ($P < 0.05$). Organic C had a significantly positive correlation with EC, total N, available P, exchangeable Mg, K, and acidity, and ECEC. Significantly positive correlations were also found between exchangeable Ca, Mg, and K.

Figure 3 shows the changes in the examined soil fertility parameters at the three selected soil layers, i.e., the surface (0-10 cm), subsurface (20-30 cm), and bottom layers (70-80 cm), in relation to the age of the rubber tree stands at the study site, while Table 1 shows relevant information such as model parameters of the linear regression model fitted to the datasets from which outliers (if any) were exempted. The soil pH varied to a low extent at all three layers as indicated by the low coefficients of variation (4.0%-6.0%) and did not show any significant trend of the change (decrease or increase) over the economic life time of the rubber trees. Likewise, both organic C and total N contents remained at a relatively constant level without any significant trend of change over the economic life time of the trees, although slightly higher variations were observed for both organic C (23.8%-26.3%) and total N (18.8%-22.5%) contents. Exchangeable acidity and ECEC were also found in a low content at the surface (exchangeable acidity, 16.5%, n = 23; ECEC, 11.9%, n = 24) and subsurface layers (exchangeable acidity, 18.3%, n = 24; ECEC, 19.2%, n = 24), while they showed a slightly higher variability at the bottom layer (exchangeable acidity, 33.5%, n = 24; ECEC, 23.9%, n = 22). The remaining parameters, i.e., EC, available P, exchangeable Ca, Mg, and K, and base saturation, also showed a similar behavior; no significant trend of change over the economic lifetime of the rubber trees. On the other hand, these parameters had a higher variability than the above mentioned soil parameters, i.e., pH, organic C, EC, exchangeable acidity, and ECEC, regardless of the exclusion of outliers.

Discussion

The soils at the study sites generally had a strongly acidic reaction (low pH) with moderate contents of total N and available P but very low contents of exchangeable bases, based on the soil assessment criteria in Indonesia (Eviati & Sulaeman 2009) (Fig. 1). The majority of the soil samples showed pH values which fell within the suitable range (i.e., 4.5-6.0) for rubber thee growth (Verheye

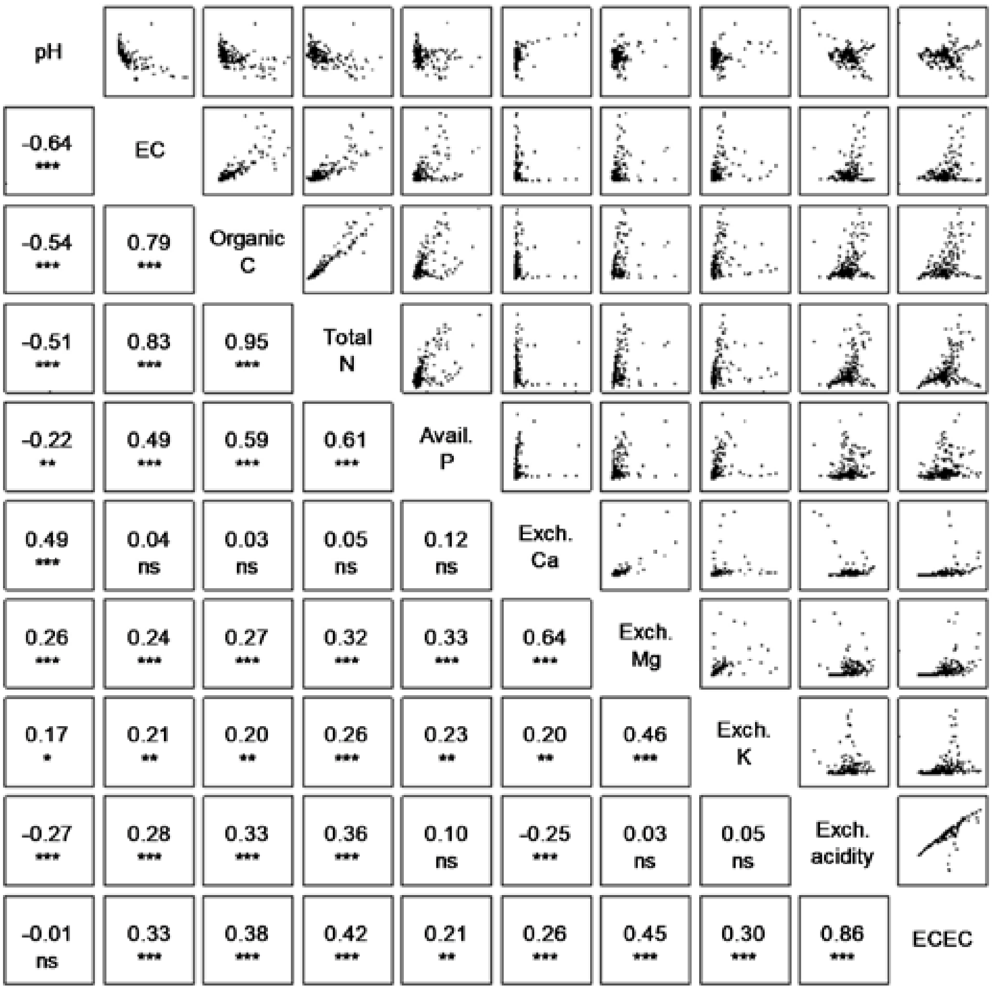

Fig. 2. Scatter plots and correlation matrix of the examined soil properties at the study site
*, **, and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

2010), except for some of the soil layers (n = 11; mostly surface layers), which had pH values lower than 4.5. The pH values observed in the present study were comparable with those in the soils under the rubber cultivation in some other countries such as 4.4 ± 0.5 (0-15 cm) in Southern India (Eappen et al. 2005) and 4.5 ± 0.1 (0-10 cm) in Jambi, Central Sumatra (Allen et al. 2015), a neighboring location to our study site, but considerably lower than 5.6 ± 0.4 (0-10 cm) in Southern Nigeria (Aweto 1987) and 5.4 ± 0.6 (0-20 cm) in Southwestern China (Li et al. 2012). Meanwhile, all exchangeable bases (Ca, Mg, and K) were found at very low amounts and the relatively high content of exchangeable acidity throughout the soil profile. The acidic reaction as well as the high level of exchangeable acidity and very low base saturation status of the soils suggest a strong and prolonged leaching process under tropical humid climate (e.g., Abe et al. 2009). Regardless of the strong leaching process, however, signs of eluviation of clay and thus its illuviation into the subsoil were not observed during the field survey, as indicated by the lack of clay cutan (clay film on the ped surface) and no abrupt change of the soil texture among the subsoil layers. This description of the soil profile is also supported by the profile data on ECEC; no significant increase in ECEC in the subsoil layers, which often correlates positively with the clay content (e.g., Abe et al. 2009), was observed.

The soil organic C content (36.8 ± 8.7 g kg^{-1}) at the surface layer found at the study site (Fig. 1) was relatively high compared to those previously reported in rubber gardens of other countries, i.e., 10.8 ± 0.6 g kg^{-1} (0-10 cm) in Southern Nigeria (Aweto 1987), 8.7 ± 1.8 g kg^{-1} (0-15 cm) in Southern India (Eappen et al. 2005), and 15.6 ± 1.7 g kg^{-1} (0-20 cm) in Southwestern China (Li et al. 2012), but was comparable to those documented in the neighboring locations (Jambi Province) to our study site, i.e., 31.1 ± 4.4 g kg^{-1} (0-10 cm) (Allen et al. 2015) and 36.0 ± 12.0 g kg^{-1} (0-5 cm) (Guillaume et al. 2016). This higher level of soil organic matter found at our study site may be attributed to the higher biomass production rate of the rubber trees (Umami et al. Unpublished data)

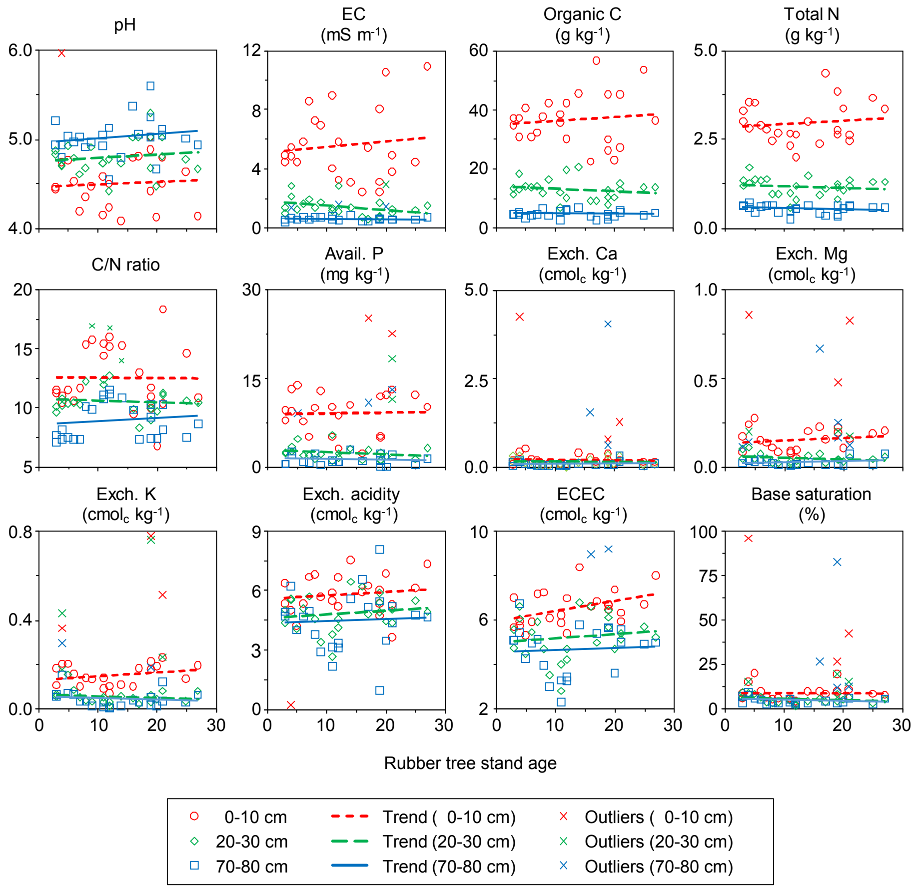

Fig. 3. **Changes in the soil properties at three different soil layers (surface, 0-10 cm; subsurface, 20-30 cm; bottom, 70-80 cm) in relation to the ages of rubber tree stands at the study site**

Table 1. Number of observations (n), coefficient of variation (CV), model parameters, coefficient of determination (R^2) and P-value of the linear regressions at three different soil layers, i.e., surface (S), 0-10 cm; subsurface (SS), 20-30 cm; bottom (B), 70-80 cm; in relation to the ages of the rubber tree stands at the study site

Parameter	Layer	n	CV (%)	*a*[†]	*b*[†]	R^2	P value	Parameter	Layer	n	CV (%)	*a*[†]	*b*[†]	R^2	P value
pH	S	23	6.0	$2.7E^{-03}$	4.5	$5.0E^{-03}$	0.749	Exch. Ca	S	21	69.7	$-2.1E^{-03}$	0.2	$1.2E^{-02}$	0.642
	SS	24	4.0	$3.6E^{-03}$	4.8	$1.8E^{-02}$	0.532		SS	24	70.2	$-1.3E^{-03}$	0.2	$8.1E^{-03}$	0.675
	B	24	4.3	$5.1E^{-03}$	4.9	$3.0E^{-02}$	0.422		B	21	66.6	$1.2E^{-03}$	0.1	$1.8E^{-02}$	0.567
EC	S	24	42.9	$3.7E^{-02}$	5.1	$1.3E^{-02}$	0.603	Exch. Mg	S	21	40.1	$1.6E^{-03}$	0.1	$3.4E^{-02}$	0.424
	SS	23	41.3	$-3.2E^{-02}$	1.8	$1.5E^{-01}$	0.068		SS	21	50.6	$-1.0E^{-03}$	0.1	$8.5E^{-02}$	0.201
	B	21	18.6	$-5.4E^{-04}$	0.6	$1.2E^{-03}$	0.883		B	18	69.3	$7.8E^{-04}$	0.0	$9.3E^{-02}$	0.220
Organic C	S	24	23.8	$1.3E^{-01}$	35.1	$1.2E^{-02}$	0.619	Exch. K	S	21	30.7	$1.8E^{-03}$	0.1	$7.4E^{-02}$	0.232
	SS	24	26.3	$-8.6E^{-02}$	14.2	$3.3E^{-02}$	0.397		SS	20	53.9	$-8.2E^{-04}$	0.1	$3.8E^{-02}$	0.411
	B	24	24.4	$-6.2E^{-03}$	4.9	$1.5E^{-03}$	0.859		B	22	82.7	$-1.1E^{-03}$	0.1	$4.5E^{-02}$	0.342
Total N	S	24	18.8	$9.7E^{-03}$	2.8	$1.6E^{-02}$	0.556	Exch. acidity	S	23	16.5	$1.8E^{-02}$	5.6	$1.7E^{-02}$	0.549
	SS	24	21.1	$-4.9E^{-03}$	1.2	$2.1E^{-02}$	0.504		SS	24	18.3	$1.9E^{-02}$	4.6	$2.4E^{-02}$	0.471
	B	24	22.5	$-2.8E^{-03}$	0.6	$2.8E^{-02}$	0.438		B	24	33.5	$1.1E^{-02}$	4.3	$2.8E^{-03}$	0.807
C/N ratio	S	24	21.6	$-3.6E^{-03}$	12.6	$9.4E^{-05}$	0.964	ECEC	S	24	11.9	$4.5E^{-02}$	5.9	$1.8E^{-01}$	0.040
	SS	21	10.4	$-1.7E^{-02}$	10.8	$1.4E^{-02}$	0.612		SS	24	19.2	$1.9E^{-02}$	5.0	$1.8E^{-02}$	0.533
	B	24	17.3	$2.8E^{-02}$	8.6	$1.7E^{-02}$	0.541		B	22	23.9	$8.4E^{-03}$	4.5	$3.1E^{-03}$	0.804
Avail. P	S	22	38.2	$1.1E^{-02}$	8.9	$5.4E^{-04}$	0.918	Base saturation	S	21	51.2	$-3.6E^{-03}$	8.9	$3.3E^{-05}$	0.980
	SS	22	48.0	$-4.0E^{-02}$	2.9	$6.3E^{-02}$	0.258		SS	21	42.0	$-9.1E^{-02}$	6.4	$9.1E^{-02}$	0.184
	B	21	70.9	$-8.3E^{-03}$	1.3	$5.0E^{-03}$	0.760		B	20	42.2	$-8.3E^{-02}$	5.5	$1.1E^{-01}$	0.161

[†] The model parameters *a* and *b* are included in the linear regression model: $Y = a \cdot X + b$. Here, X and Y are independent (i.e., age of rubber tree stand) and dependent (i.e., soil parameter at each layer) variables, respectively.

due to a tropical humid climate without dry period (Vogt et al. 1986), and the types of rubber clones (Umami et al. Unpublished data) than those in Southern Nigeria (Aweto 1987), Southern India (Eappen et al. 2005), and Southwestern China (Li et al. 2012). The higher biomass production would eventually result in the higher input of organic matter into the soil through the litter fall and root purging.

As commonly seen in the soil, the total N content was highly correlated with the organic C (Fig. 2), and thus the total N in the surface soil (0-10 cm) was found to be relatively high (3.0 ± 0.6 g kg^{-1}) (Fig. 1). The nitrogen cycle in the soil is closely related to that of C, as often indicated by the significant correlations of organic C (hence with total N) and C/N ratio with gross N mineralization and microbe-associated N (e.g., Allen et al. 2015). The relatively high total N associated with high organic C and moderate C/N ratio (12.6 ± 2.7) suggests that the studied soil has a moderate N availability.

The low availability of P in the studied soil can be primarily attributed to its acidic nature, as most of mineral P in the soil would exist in unavailable forms due to the sorption on hydrous oxides and/or precipitation with iron, manganese, and aluminum (Brady & Weil 2007). However, similar to the usual conditions in natural ecosystems, in the smallholder rubber farming system with low external input, P can be provided to the plant almost exclusively by organic matter mineralization. This may be attested by the significantly positive correlation between organic C and available P (Fig. 2).

All soil fertility parameters examined at the surface, subsurface, and bottom layers were found to be independent on the age of the rubber stand (Fig. 3) and did not show any significant trend of change during the period which encompasses the economic lifetime of the rubber tree. This result indicates that a soil fertility decline is unlikely to happen under the smallholder rubber farming system, in spite of local farmers hardly using fertilizers while intensively harvesting latex in this period. These findings are not in agreement with those of previous studies (e.g., Aweto 1987, 2001, Cheng et al. 2007, Liu et al. 2018), which reported a depletion of soil nutrients with an increase in the age of the rubber tree stand. In contrast, our results are in accordance with those documented by other previous researches (e.g., Guillaume et al. 2016); there is no significant decline in the soil fertility in relation to the rubber tree stand age. Soil fertility decline simply occurs when the output of nutrients exceeds their input during the cultivation period (Hartemink 2003). Major export of nutrients from the rubber gardens occurs by the collection of latex by tapping the rubber trees. Although the information on the latex yield and nutrient contents in the latex is not available in this study, a previous study in Malaysia (Tanaka et al. 2009) reported that the tapping (latex collection) may result in the annual export of 7 kg N ha^{-1}, 3 kg P ha^{-1}, 10 kg K ha^{-1}, and 3 kg Mg ha^{-1} in the rubber garden. No clear trend of soil fertility change (decline or improvement) found in the present study implies that the current output level of these nutrients is balanced with their input level and that the soil fertility remains in a steady state over the period of the rubber tree's economic life time at the study site. Considering that local farmers commit rubber cultivation to no- or low-input of external resource, natural mechanisms of soil fertility replenishment are likely to have worked to maintain soil fertility during the rubber cultivation. In this regard, we suggest two major mechanisms as follows: i) the maintenance of soil organic matter content and ii) the contribution of flash floods.

Regarding mechanism i), the significantly positive correlations of organic C with macronutrients, i.e., exchangeable Mg and K as well as with total N and available P (Fig. 2), suggest that major plant nutrients in the soil are associated with soil organic matter, and thus that keeping soil organic matter at a constant level is the fundamental key for soil fertility maintenance in the smallholder farming systems. In this regard, a previous study of ours (Abe et al. Unpublished data) revealed that the soil organic C stock at the study site was maintained on a relatively constant level over the economic lifetime of rubber trees. Similar results have been documented elsewhere as follows: N'Dri et al. (2018) found similar or even higher contents of soil organic C and total N in 25-year-old rubber gardens, compared with those at 7-year-old gardens in Cote d'Ivoire, and Peerawat et al. (2018) reported no significant change in the contents of organic C, available P, exchangeable Ca, Mg, and K, and cation exchange capacity over the rubber's economic lifetime in eastern Thailand. In practice, soil organic matter management is often identified as a key practice in soil fertility maintenance in the smallholder farming system in tropical regions (Coleman et al. 1989), although the rubber farmers in our study site have no specific strategy for managing the soil organic matter for the moment.

With respect to mechanism ii), flash floods occasionally occurring after heavy rain events (a few times a year in recent years) can provide the soil with additional nutrients through the deposition of sediments and to a lesser extent through the flood water, both of which contain the nutrients, although the extent of nutrient addition depends on the frequency of flood occurrence, deposited river-borne sediments, irrigation water quality, local topography, and agricultural practices in the surrounding environments (Hirst & Ibrahim 1996).

In this regard, however, further study is needed to clarify the contribution of flash floods to the soil fertility status in the study region.

Conclusion

In the present study, we examined the changes in the soil fertility status along a chronosequence of rubber tree stands in a lowland area of West Sumatra, Indonesia. Our results revealed that there was no significant trend of changes in the soil fertility parameters during the economic lifetime of these trees and, thus, soil fertility decline under the smallholder rubber farming system is unlikely even though local farmers hardly use or do not use at all fertilizers while intensively harvesting latex during the economic life time of the rubber tree. These findings suggest that the continuous uptake of macronutrients by the rubber trees did not result in the exploitation of nutrients to an extent to overbalance nutrient cycle in the soil nor thus in soil degradation. The strongly positive correlations found between organic C and most of the examined macronutrients suggest that the dynamics of these macronutrients were associated with soil organic matter, which were maintained on a relatively constant level over the economic life time of the rubber trees in the study site (Abe et al. Unpublished data). In addition, we suggest that there is another natural mechanism of soil fertility replenishment; the supply of nutrients from the alluviums during flash floods, which occur after a big shower of rainfall, also contribute to the replenishment of some nutrients being exploited through the uptake by rubber trees and the collection of latex under the smallholder management practices in the study site.

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