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Research Article

Evaluation of Physicochemical Properties of Sandy-Textured Soils under Smallholder Agricultural Land Use Practices in Sarawak, East Malaysia

Soo Ying Ho, Mohd Effendi Bin Wasli, and Mugunthan Perumal

Faculty of Resource Science and Technology, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

Correspondence should be addressed to Soo Ying Ho; sherylsooying@gmail.com

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A study was conducted in the Sabal area, Sarawak, to evaluate the physicochemical properties of sandy-textured soils under smallholder agricultural land uses. Study sites were established under rubber, oil palm, and pepper land uses, in comparison to the adjacent secondary forests. The sandy-textured soils underlain in all agricultural land uses are of Spodosols, based on USDA Soil Taxonomy. The soil properties under secondary forests were strongly acidic with poor nutrient contents. Despite higher bulk density in oil palm farmlands, soil properties in rubber and oil palm land uses showed little variation to those in secondary forests. Conversely, soils under pepper land uses were less acidic with higher nutrient contents at the surface layer, especially P. In addition, soils in the pepper land uses were more compact due to human trampling effects from regular farm works at a localized area. Positive correlations were observed between soil total C and soil total N, soil exchangeable K, soil sum of bases, and soil effective CEC, suggesting that soil total C is the determinant of soil fertility under the agricultural land uses. Meanwhile, insufficient K input in oil palm land uses was observed from the partial nutrient balances estimation. In contrast, P and K did not remain in the soils under pepper land use, although the fertilizers application by the farmers was beyond the crop uptake and removal (harvesting). Because of the siliceous sandy nature (low clay contents) of Spodosols, they are poor in nutrient retention capacity. Hence, maintaining ample supply of organic C is crucial to sustain the productivity and fertility of sandy-textured soils, especially when the litterfall layers covering the E horizon were removed for oil palm and pepper cultivation.

1. Introduction

In recent decades, the transition of agrarian land uses from traditional shifting cultivation to commercial cash crops systems in Sarawak, Malaysia, has been widely discussed [1–7]. Following the trends of growth in socioeconomic conditions and needs for monetary economy, the reduction and intensification of shifting cultivation practices, formerly known as the central agricultural practices, in Sarawak were highlighted by many researchers [8–11]. Nonetheless, the introduction of high-input agriculture, that is, pepper and oil palm cultivation starting in the 1960s under various government subsidy schemes is rapidly expanding among the smallholder farmers across the regions of Sarawak [4–7, 12–15]. As reported by various researchers [8–10, 12, 13, 16, 17], the initiation of permanent cash crop farmlands, shortening of fallow period, and increasing dependency to agrochemicals in management practices are the indication of intensification in agricultural land use practices in Sarawak.

Expansion of monocropping plantation and establishment of permanent forest estates or national parks have put an immense pressure on the availability of arable land for agricultural activities among smallholder farmers [2, 4, 6, 12, 18]. On the other hand, factors such as vegetation cover, soil fertility, road accessibility, and labour availability strongly influence the farmer's decision-making in site selection for crops cultivation [8, 9, 19]. Under the current regional pressure of socioeconomic condition and land use change, some farmers have no other alternatives but to conduct the agricultural activities on any available land, including the gray or white sandy-textured soils, considering that addition of fertilizers during the farming practices could solve the issues of soil fertility.

Sandy-textured soils are generally classified into Entisols or Spodosols in Malaysia, covering the soils distributed on beach ridges along the east coast of Peninsular Malaysia [20–22] as well as the sandstone plateaus and cuesta formation on dip slopes in the hilly regions of Sarawak [23–25]. The distinct characteristics of sandy soils are the occurrence of spodic horizon, being acidic, and poor cation retention capacity due to low clay contents [24]. Often, it is believed that sandy-textured soils are marginally feasible for agriculture due to their sandy texture, moisture deficiency, and concomitant infertility [26, 27]. Elsewhere in South Africa, prolonged arable cropping under sandy-textured Alfisols, which caused loss of carbon, nitrogen, and microbial biomass, was reported [28, 29]. Kumar et al. [30] reported that the sandy-textured soils in semi-arid region of India are low in organic carbon, nitrogen, phosphorus, and sulphur under groundnut cultivation for more than 5 years. While in Peninsular Malaysia, agricultural activities under sandy-textured soils, known as sandy beach ridges interspersed with swales (BRIS), are common through improved fertilizer management [31–33]. Additionally, Mohd Yusoff et al. [27] reported that soil organic matter is predominately important in BRIS soils to improve the soil fertility level throughout the cropping period.

For the case of Sarawak, the formation and characteristics of sandy Spodosols in Bintulu, Sarawak, was documented by Syuhada et al. [25]. Meanwhile, Katagiri et al. [24] investigated the properties of soil and soil-plant relationship in the heath forests under sandy-textured soils of Bako National Park. Notwithstanding, various researchers focused on the ecological study of forest vegetation from the standpoint of forest ecophysiology under sandy-textured soils at different locations within Sarawak [34–39]. Little is known on the outcome of sandy-textured soil properties under present agricultural land use practices except for the study on experimental plots of traditional shifting cultivation conducted by Kendawang et al. [40]. In their recent study, Hattori et al. [41] reported that soil fertility may be difficult to recover on steep slopes under sandy soil condition when the surface layer is destroyed by shifting cultivation. The sedentary and high-input agricultural practices might affect the soil properties under sandy-textured soils and subsequently, the agricultural productivity and soil health status. Hence, comprehensive research is of paramount importance to address the influence of recent transition in agrarian landscapes under sandy-textured soils in the regional area of Sarawak. Therefore, this study attempts to evaluate the physicochemical properties of sandy-textured soils under various smallholder agricultural land use practices in Sarawak, East Malaysia. Assessment of the effects of agricultural land use practices on sandy-textured soils deserve genuine priority to obtain baseline information for further improvement of soil management strategies at the study area or elsewhere with similar agro-ecology conditions.

2. Materials and Methods

2.1. Study Area and Sampling Sites. This study was conducted at the Sabal upland area (N 01°04′24.6″, E 110°58′08.6″), Simunjan, Sarawak, Malaysia (Figure 1), during March 2013 to October 2014. The area has been inhabited by the Iban community for the past century in three adjacent villages, namely, Kampung Sabal Kruin, Kampung Sabal Aping, and Kampung Sabal Tapang. The topography of the northern part of the area is mainly covered by undulating and rolling hills, with the slope degree ranging from 6.2° to 21.0°. The southern part of the study area rises and extended into the steep scarp of the mountainous Klingkang Range [42]. The parent material of the study area is Tertiary Silantek beds of alternating gray shales and sandstone overlain by colluvial boulders [38]. Mean annual temperature is approximately 32.5°C, while average annual precipitation is about 3,585 mm, with the short dry spell during June to August and rainy season in October to March [43]. Shifting cultivation still persists at the study area, although the number of households conducting shifting cultivation is decreasing. The intensification in shifting cultivation practices in the study area has been reported in our previous study [11]. Shifting cultivation, together with local fruits and vegetable cultivation, is considered as subsistence farming to sustain the livelihood of the local farmers in the study area. In contrast, cultivation of rubber, pepper, and oil palm are known as cash crop farming with income generating purposes. Formerly, cacao was cultivated but abandoned due to severe pest and disease infestation. The integration of these two farming practices formed complex and diverse land uses within the upland areas across the state of Sarawak [44]. The agricultural systems in the study area are basically rainfed.

Study sites were established in commercial cash crops, that is, rubber, oil palm, and pepper farmlands with the adjacent secondary forests as control plots. In the secondary forests sites, typical diagnostic heath forest vegetations such as *Crotoxylum glaucum* (Hypericaceae), *Agathis borneensis* (Araucariaceae), *Cotylelobium burckii* (Dipterocarpaceae), and *Nepenthes* sp. (Nepenthaceae) were commonly found. The selected land uses were regarded as the common commercial cash crop land uses based on farmers' preference in Sarawak. Prior to soil sampling, household interview was conducted to collect baseline information on management practices and land use history. Criteria of site selection were based on the availability of the cash crop farmlands and secondary forests located on sandy-textured soil types (*Tanah Pasir* or *Tanah Kerangas*). The age of the secondary forests and cash crop farmlands were determined based on the landowners' recalling [13]. Later, the desirable sites were selected, and the soil types were identified using a detailed soil map [45] obtained from the Department of Agriculture, Sarawak. Soil profile investigation was conducted in each land use to identify the soil series of the desirable sites. All land uses selected have a land use history of shifting cultivation practices. Information on the age and number of selected study sites of different land uses is summarized in Table 1.

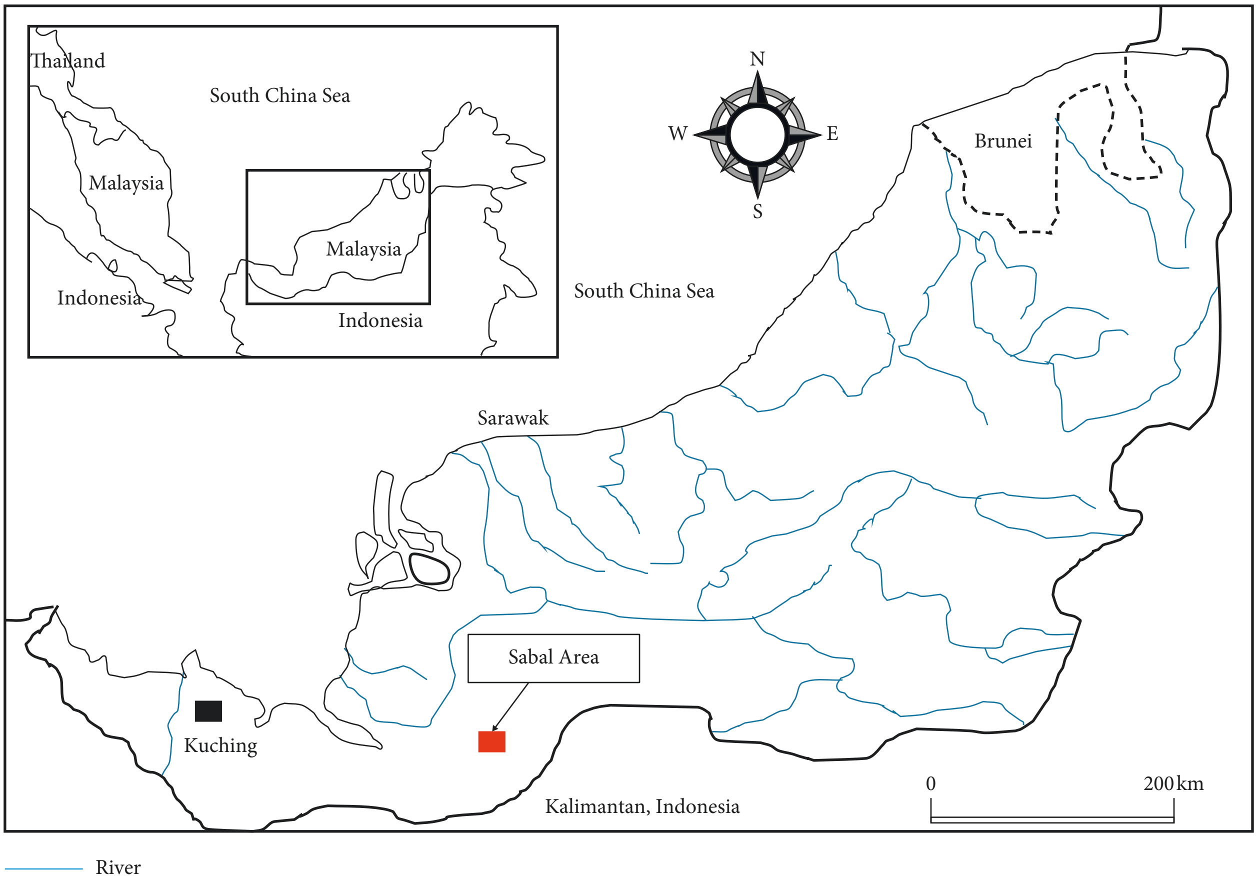

Figure 1: Map of the study area.

Table 1: Information on the selected study sites.

Land uses	Age and number of sites
Rubber (R)	Rubber of 17 to 27 years old $n = 7$
Oil palm (OP)	Oil palm of 1 to 3 years old $n = 9$
Pepper (P)	Pepper of 1 to 9 years old $n = 4$
Secondary forest (SF)	Fallow period of 35 to 50 years $n = 6$

2.2. Soil Sample Collection and Analysis. Soil sampling methods were adapted from Tanaka et al. [13]. A sampling plot of 10 m × 10 m or 20 m × 20 m was established prior to soil sampling. The information of the condition at the farmland during field survey such as planting space between the crops, size of the farmlands, and slope was recorded. Soil profile description was conducted at the study sites for the identification of soil types [46]. Subsequently, undisturbed core samples (100 $g{\cdot}mL^{-1}$) were collected from 0–10 cm depth and 30–40 cm depth in triplicates for soil bulk density determination [47]. Soil hardness was determined using Yamanaka-type push cone penetrometer. Composite soil samples were collected at the same depth from three random points at the intersection of the diagonal lines between four adjacent points (centre point). Additionally, soil samples were also collected at 0–10 cm of the fertilizing circle (fertilizing point) of pepper vines and oil palm stands, which are 30–50 cm away from the base of the vines and 1 m away from the palm stands. The collected soil samples were air-dried and crushed to pass through a sieve with 2.0 mm and 0.425 mm mesh for soil physicochemical analysis.

The analytical methods for soil analysis are as follows: soil pH was determined in water (pHw) or 1 M potassium chloride (pHk) in a soil to solution ratio of 1 : 5 using the glass-electrodes method. Electrical conductivity (EC) was measured after the pHw measurement using an EC meter (Eutech Instruments-Cyberscan Con 11). The filtrate from pHk was used for exchangeable aluminium (Al) and exchangeable hydrogen (H) analysis. Exchangeable Al and H were determined by the titration method with 0.01 M of sodium hydroxide (NaOH) and the content of exchangeable Al with 0.01 M hydrochloric acid (HCl). The soil total carbon (total C) was determined by the loss-on-ignition method [48]. Total nitrogen (total N) was determined by the Kjeldahl acid-digestion method using concentrated sulphuric acid [49]. The contents of exchangeable bases and the cation exchange capacity (CEC) were measured, respectively, after successive extraction using 1 M ammonium acetate adjusted to pH 7.0 and 10% sodium chloride (NaCl). Later, soil exchangeable bases were determined by atomic absorption spectrophotometry (AAS) for calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) (Thermo Scientific, ICE Series 3500). Available phosphorus (P) was quantified using the Bray-II method [50], where soil samples were extracted with an extracting solution, mixture of ammonium fluoride (1 M NH_4F) and hydrochloric acid (0.5 M HCl), then a colour-developing reagent was added and the available phosphorus was determined by absorbance measurement with a UV spectrophotometer at a wavelength of 710 nm [51]. Particle size distribution was determined using the pipette method with assistance of soil textural class [52]. Soil analysis was conducted at the Environmental Soil Science Laboratory, Faculty of Resource Science and Technology, Universiti Malaysia Sarawak (UNIMAS).

2.3. Data Analysis. All results of soil analysis are expressed on oven-dry basis. For the comparison of soil physico-chemical properties among different land uses, one-way ANOVA was performed using SPSS version 17 followed by Scheffe's multiple comparison test. Paired t-test was used to compare the soil properties in fertilizing point (FP) and centre point (CP) in pepper and oil palm land uses. Multiple regression analysis was conducted to determine the dominant properties between soil total C and clay contents in contributing to soil CEC in the study area. Partial nutrient balances were estimated by means of fertilizers input by farmers, nutrient stock in soils and standing crops, and nutrient removal by harvesting. The estimation of nutrient stocks in soils was adapted from previous studies conducted by Tanaka et al. [13]. The nutrients related to oil palm and pepper crops (nutrients stored and nutrient removal) were obtained from secondary information within the studies conducted in Malaysia [53–55]. The nutrient stocks of the oil palm and pepper crops were estimated according to their age of cultivation.

3. Results and Discussion

3.1. Crop Management Practices under Agricultural Land Uses in the Study Area. The information on crop management practices collected from the household interview is summarized in Table 2.

All farmlands cultivated with oil palm, pepper, and rubber crops were previously engaged in upland rice cultivation as clearing a new farmland is rather laborious and time-consuming. Based on the interview, agrochemical products such as fertilizers, herbicides, and pesticides were widely used in cultivating crops at the study area. The source of the agrochemicals was either self-purchased [3] or subsidized by the government agency Farmers' Organization Authority. Compound fertilizers, N-P-K (17.5 : 15.5 : 10), straight fertilizer, and urea (46%) were subsidized by the government annually in aiding the local farmers for upland rice cultivation [8]. It is noteworthy that farmers also utilized the subsidized fertilizers in cash crop cultivation in the study area.

Farmers generally owned one to five rubber farmlands. The tapping frequency largely depends on the factors such as market price of rubber, labour availability, accessibility to the farmlands, and latex yield of the trees. At the time of field survey, only three study sites of seven conducted the tapping activity. The average size of the rubber farmland is 0.11 ha, ranging from 0.07 ha to 0.15 ha. The planting space between the rubber trees ranged from 1.8 m to 3.0 m, with the average of 2.65 m, giving rise to 1,675 trees$\cdot$ha^{-1}. The planting density was higher than those reported by Tanaka et al. [13] in their study at Lubuk Antu district. Likewise, there was no fertilizers input in rubber farmlands after 5 years of planting. In general, rubber land uses received least maintenance, and most farmers are likely to leave the rubber farmlands virtually unattended when no tapping activity was conducted.

One to two oil palm farmlands with a range of 0.52 ha to 2.70 ha are usually owned by a farmer. All oil palm sites are at young and unproductive stage during the field survey. The oil palm was planted in a triangular arrangement with a planting space of 8.5 m × 8.5 m, resulting in an average plant density of 160 palm$\cdot$ha^{-1}. The oil palm also received fertilizers at the rate of 151 kg$\cdot$ha$^{-1}\cdot$yr^{-1} to 469 kg$\cdot$ha$^{-1}\cdot$yr^{-1}, giving rise to an average of 89 kg$\cdot$ha$^{-1}\cdot$yr^{-1} of N, 49 kg$\cdot$ha$^{-1}\cdot$yr^{-1} of P, and 34 kg$\cdot$ha$^{-1}\cdot$yr^{-1} of K. The amount of fertilizers applied was below the recommended range of nutrient requirement for oil palm trees proposed by Ng [54] for sandy soils. All farmers in the selected study sites tended to utilize the subsidized fertilizers for upland rice in oil palm cultivation. The leftover fertilizers from rice cultivation were used in oil palm cultivation. Additionally, our findings are in agreement with those of Tanaka et al. [13] who reported that fertilizers application in oil palm farmlands largely depends on the farmer's economic condition. In smallholder farmlands, pruning activity was not as intense as compared to plantation practices. Herbicides and pesticides were also used for weed and pest control.

Farmers usually owned 1 to 2 pepper farmlands. The size of the pepper farmlands is usually small with an average of 0.05 ha. The planting space between the pepper vines was 1.5 m to 2.1 m, with an average of 1.9 m, giving rise to an average of 3017 vines$\cdot$ha^{-1}. The rate of fertilizers application was rather intense (ranged from 1,559 kg$\cdot$ha$^{-1}\cdot$yr^{-1} to 12,094 kg$\cdot$ha$^{-1}\cdot$yr^{-1}) under a localized farmland area, giving rise to 1,669 kg$\cdot$ha$^{-1}\cdot$yr^{-1} of N, 1,337 kg$\cdot$ha$^{-1}\cdot$yr^{-1} of P, 828 kg$\cdot$ha$^{-1}\cdot$yr^{-1} of K, 37 kg$\cdot$ha$^{-1}\cdot$yr^{-1} of Mg, and 37 kg$\cdot$ha$^{-1}\cdot$yr^{-1} of trace elements (TE). The rate of N-P-K application was much higher than that reported by Tanaka et al. [13] at Lubok Antu and exceeded the annual recommended dosage reported by Yap [55], which are 390 kg$\cdot$ha^{-1} of N, 62 kg$\cdot$ha^{-1} of P, and 352 kg$\cdot$ha^{-1} of K. Apart from chemical fertilizers, application of chicken manure was common in pepper cultivation at a frequency of 3 to 5 times a year. Pruning was conducted regularly, and herbicides were applied when necessary.

3.2. Soil Morphological Properties of Sandy-Textured Soils at the Study Area. Table 3 shows the representative profile description of agricultural land use practices at the study area. The soil profiles from all land uses are relatively uniform. Irrespective of land use, presence of distinct spodic horizon, resulting from the process of podzolization, was observed with bleached sandy eluvial layer (E horizon).

Table 2: Present management practices of smallholder agricultural land uses at the Sabal area.

Management practices	Crops		
	Rubber ($n = 7$)	Oil palm ($n = 9$)	Pepper ($n = 4$)
Farmland size* (ha)	0.11	2.70	0.05
Planting space* (m)	2.65	8.5	1.9
Plant density* (trees·ha^{-1})	1675	160	3017
Fertilizers application			
Source	—	Subsidized by Farmers' Organization Authority	Subsidized by Malaysia Pepper Board and Farmers' Organization Authority and self-purchased
Frequency	No fertilizers application for productive rubber trees	3 to 4 times annually	3 to 12 times annually
Annual rate* (kg·ha^{-1}·yr^{-1})	—	242	6323
*Estimated nutrients applied**			
N (kg·ha^{-1}·yr^{-1})	—	89	1669
P (kg·ha^{-1}·yr^{-1})	—	49	1337
K (kg·ha^{-1}·yr^{-1})	—	34	828
Mg (kg·ha^{-1}·yr^{-1})	—	—	37
TE (kg·ha^{-1}·yr^{-1})	—	—	37
Annual yield* (t·ha^{-1}·yr^{-1})	1.35	n.d.$^{+}$	6.62

*Average of the information obtained based on interview at all study sites. $^{+}$The oil palm planted is still at young stage (1–3 years old) and not productive at the time of field survey.

Table 3: Soil profile description of representative study sites from various agricultural land uses.

Land use	Horizon	Depth (cm)	Boundary[a]	Colour	Texture	Structure[b]	Consistency[c]	Hardness[d] (mm)	Organic matter	Root[e]	Moisture[f]
Secondary forest (fallowed approx. 50 years)	O	0–10									
	EA	10–20	cw	7.5YR 3/2	SL	w g	ss/sp	6	High	1-4/c-m	m
	E	20–40	gw	10YR 6/2	LS	m sbk	ss/sp	16	Low	1-3/vf-f	sm
	B_h	40–70+	cw	7.5YR 3/4	SL	m sbk	ss/sp	21	High	1-2/vf	sm
N 01°04′33.1″, E 110°58′25.9″; 12°											
Rubber (cultivated approx. 17 years)	O	0–7									
	AE	7–25	gw	7.5YR 2.5/3	SL	w g	ss/sp	11	High	1-3/c-m	m
	E	25–70+	cw	7.5YR 7/1	SL	m sbk	ss/sp	20	Low	1-3/vf	sm
N 01°04′31.3″, E 110°58′31.3″; 10.4°											
Oil palm (cultivated for 1 year)	O	0–2									
	EA	2–25	cw	10YR 6/6	LS	w m	ns/np	17	Low	1-2/vf-f	sm
	E	25–45	dw	7.5YR 6/2	SL	w g	ss/sp	20	Low	1/vf	sm
	B_h	45–70+	cw	10YR 3/3	SL	m sbk	ss/sp	21	High	n	sm
N 01°04′35.7″, E 110°57′55.9″; 12.6°											
Pepper (cultivated for 1 year)	O	0–2									
	E_1	2–15	cw	7.5YR 6/2	LS	w g	ns/np	13	Low	1-3/vf-f	sm
	E_2	15–40	cw	7.5YR 7/1	SL	w sbk	ns/np	19	Low	1-2/vf-f	sm
	B_h	45–70+	dw	10YR 6/2	SL	m sbk	ss/sp	24	Low	n	sm
N 01°04′30.7″, E 110°58′20.8″; 11.4°											

[a]Abbreviations used for boundary (distinctness and topography): Distinctness: a, abrupt; c, clear; g, gradual; d, diffuse. Topography: s, smooth; w, wavy; i, irregular; b, broken. [b]Abbreviations used for structure (grade and type): Grade: ns, no structure; w, weak; m, moderate; s, strong. Type: m, massive; g, granular; sbk, subangular blocky. [c]Abbreviations used for consistency (stickiness and plasticity): Stickiness: ns, not sticky; ss, slightly sticky; s, sticky; vs, very sticky. Plasticity: np, not plastic; sp, slightly plastic; p, plastic; vp, very plastic. [d]Measured by Yamanaka-type push cone penetrometer. [e]Abbreviations used for roots (size and abundance): Size: 1, very fine; 2, fine; 3, medium; 4, course. Abundance: n, none; vf, very few; f, few; c, common; m, many. [f]Abbreviations used for moisture: sm, slightly moist; m, moist.

In secondary forest and rubber land use, surface accumulation of thick litterfall layer and peaty mor humus (raw humus) is found with a depth of 7 cm and 10 cm in rubber land use and secondary forests, respectively. Conversely, thinner layer of O horizon with 2-cm depth is discovered in oil palm and pepper land uses, ascribable to the removal of the litter layer due to crop cultivation. The layer of mor humus is absent in both land uses. Besides, dense, well-developed root mat can be seen in secondary forest and rubber land use with abundance of various root sizes, ranging from very fine to coarse, penetrating up to 70 cm into subsurface layers. In contrast, root mat development was rather poor in both oil palm and pepper land uses, mainly characterized by few to very few fine to medium roots, up to 45 cm of the profile and absent towards the deeper soil solum.

The surface horizons showed a mixture of eluvial (bleached sand) deposits with A horizon giving rise to EA or AE horizon, with respect to the dominance of A or E features of the pedons, ranging between 7 cm and 25 cm at all land uses except for the case of pepper land use. The soil texture fell within the class of sandy loam or loamy sand based on the "feel" method. In all study sites, E horizon, including E_1 and E_2 horizon, varies in terms of depth between 2 cm and 70 cm, generally characterized by the sandy loam or loamy sand soil texture. Subsequently, the darker humus-enriched subsurface horizon, B_h horizon, was found underlain the eluvial horizon in secondary forests, oil palm, and pepper land uses. At the surface layer, the structure of the soils was generally weak with massive to granular structure. In contrast, weak to moderate subangular blocky structure was observed moving down the soil profiles.

The colour of the mixture of EA or AE horizon was usually darker, ranging from very dark brown (7.5YR 2.5/3), dark brown (7.5YR 3/2) and brownish yellow (10YR 6/6) in rubber land use, secondary forest, and oil palm land uses, respectively. Continuous supply of fresh organic materials in the form of litterfall and peaty mor humus contributed to the darker colour of surface horizon, especially for the case of rubber and secondary forest land uses. The spodic E horizon is pale in colour, characterized by pinkish gray (7.5YR 6/2), light gray (7.5YR 7/1), and light brownish gray (10YR 6/2) at all land uses.

Judging from the presence of spodic and albic horizon discovered within 100 cm of the surface and the humus pan underlain beneath the E horizon, the soils are classified under the Podzols group in Sarawak soil classification [56]. The parent materials of Podzols originated from alluvial materials on old terrace deposits during the Pleistocene period sedentary materials of sandstones or conglomerates from the Tertiary age [56–58]. Cementation and induration of the sand grains were enhanced during the periodical drying of the soils [57]. Wood and Beckett [59] also reported that induration towards deeper soil profile depth and resting upon an impermeable humus pan with either compact or less compact characteristic is one of the morphological attributes in *Kerangas* soil features. As mentioned in the study by Teng [56], soils of Podzols group under Sarawak soil classification are tentatively correlated with Spodosols order under USDA Soil Taxonomy [60]. It is noteworthy that all land uses selected for this study exhibit relatively similar profile description with the representatives' profile but varies in the depth of spodic E horizon and the presence of B_h or B_{hs} horizon.

3.3. Soil Physicochemical Properties under Various Smallholder Land Use Practices. The average values of soil physicochemical properties at various agricultural land uses are presented in Table 4. Table 5 shows the comparison of selected soil physicochemical properties at 0–10 cm depth of centre point (CP) and fertilizing point (FP) in oil palm and pepper land uses.

In general, the soils were relatively sandy at all land uses, ranging from 57.9% to 87.2% and 49.4% and 49.4% to 87.2% in surface and subsurface soils, respectively. At all study sites, soil pHw was strongly acidic with the value less than 5.00 at the surface soil and less than 5.40 at the subsurface soil. Meanwhile, the soil total C content showed higher level in surface layer than the subsurface layer, ranged between $9.8\,g{\cdot}kg^{-1}$ to $34.5\,g{\cdot}kg^{-1}$ and $2.3\,g{\cdot}kg^{-1}$ to $19.6\,g{\cdot}kg^{-1}$, respectively. Comparatively, the soil total N was $0.55\,g{\cdot}kg^{-1}$ to $2.03\,g{\cdot}kg^{-1}$ and $0.21\,g{\cdot}kg^{-1}$ to $0.80\,g{\cdot}kg^{-1}$ at the surface and subsurface layers, respectively. The contents of exchangeable bases (K, Mg, and Ca) were found higher at the surface soils than the subsurface layer. At all land uses, Ca was the dominant soil exchangeable bases in both layers. Soil exchangeable Al depicted lower levels on the surface layer and higher levels at the subsurface layer. The soil CEC values did not vary widely among the land uses, generally low with less than $7.00\,cmol_c{\cdot}kg^{-1}$ and less than $5.00\,cmol_c{\cdot}kg^{-1}$ at the surface layer and subsurface layer, respectively. Judging from the fact that effective CEC (sum of exchangeable cations, i.e., K, Mg, Ca, Na, and Al) is lower than CEC values, a certain amount of variables of negative charges occurred in the soils [61]. Conversely, the available P varied widely at all land uses, generally higher in the surface soil layer than the subsurface soil layer, ranging from $0.9\,mg{\cdot}kg^{-1}$ to $98.7\,mg{\cdot}kg^{-1}$ at the surface layer and $0.1\,mg{\cdot}kg^{-1}$ to $11.9\,mg{\cdot}kg^{-1}$ at subsurface layer. On the other hand, the values of bulk density ranged between $0.83\,g{\cdot}mL^{-1}$ to $1.35\,g{\cdot}mL^{-1}$ and $1.24\,g{\cdot}mL^{-1}$ to $1.80\,g{\cdot}mL^{-1}$ in surface soils and subsurface soils, respectively. The soil hardness for surface and subsurface soils was 6 mm to 22 mm and 14 mm to 23 mm, respectively.

In terms of soil texture at all land uses, no statistical difference was observed at the surface soil layer, indicating the homogeneity of soil-forming processes and the similarity of parent materials. Hence, the differences in terms of soil properties at various agricultural land uses could be attributed to variations in management practices at the study area.

The soil pHw in secondary forest land use was acidic with an average value of 4.59 at the surface layer and 4.95 at the subsurface layer. The soils under secondary forests were low in sum of bases (no significant differences) than pepper land uses, however, higher than rubber and oil palm land uses. Additionally, soils under secondary forests were less compact with low values of soil bulk density and soil hardness. Correlations were found between fallow age and soil properties such as soil exchangeable Al ($r = -0.911$, $P < 0.01$), soil exchangeable Ca ($r = -0.826$, $P < 0.05$), and soil available P ($r = -0.911$, $P < 0.05$) at the surface soil layer. Meanwhile, at the subsurface soil layer, the correlations between fallow age and soil exchangeable Al ($r = 0.960$, $P < 0.01$), base saturation ($r = -0.972$, $P < 0.01$), and soil total C ($r = 0.872$, $P < 0.05$) were observed. With increasing fallow age in secondary forest, the soil acidity (exchangeable Al) increased with decrease in nutrient availability (exchangeable Ca and available P, base saturation) at the surface and subsurface soil layers. As mentioned by few researchers [62, 63], soil exchangeable Ca has a direct effect on reducing soil acidity. Prolonged fallow period often resulted in the acidic condition in soils due to uptake by the standing vegetation and leaching under the

Table 4: Surface and subsurface soil physicochemical properties at various agricultural land uses.

Soil physicochemical properties	Secondary forest (SF) $n = 6$	Rubber (R) $n = 7$	Oil palm (OP) $n = 9$	Pepper (P) $n = 4$
Surface soil (0–10 cm)				
pHw	4.59 ± 0.15^a	4.53 ± 0.07^a	4.57 ± 0.14^a	4.76 ± 0.20^a
pHk	3.52 ± 0.24^a	3.59 ± 0.26^a	3.49 ± 0.18^a	3.86 ± 0.11^a
EC ($\mu S \cdot cm^{-1}$)	26 ± 3^a	27 ± 5^a	38 ± 5^b	26 ± 7^a
Total C ($g \cdot kg^{-1}$)	18.0 ± 3.1^a	16.3 ± 4.9^a	19.5 ± 7.3^a	19.6 ± 4.5^a
Total N ($g \cdot kg^{-1}$)	1.20 ± 0.19^a	0.99 ± 0.34^a	1.37 ± 0.35^a	1.30 ± 0.40^a
C/N	15.1 ± 2.1^a	16.7 ± 2.0^a	13.9 ± 2.1^a	15.4 ± 2.0^a
CEC ($cmol_c \cdot kg^{-1}$)	4.13 ± 0.56^a	3.80 ± 0.68^a	4.42 ± 0.99^a	4.70 ± 0.68^a
Exch. K^+ ($cmol_c \cdot kg^{-1}$)	0.11 ± 0.01^a	0.09 ± 0.02^a	0.08 ± 0.03^a	0.10 ± 0.02^a
Exch. Mg^{2+} ($cmol_c \cdot kg^{-1}$)	0.13 ± 0.03^a	0.10 ± 0.01^a	0.13 ± 0.06^a	0.19 ± 0.10^a
Exch. Ca^{2+} ($cmol_c \cdot kg^{-1}$)	0.43 ± 0.10^{ab}	0.27 ± 0.04^a	0.30 ± 0.18^{ab}	0.52 ± 0.13^b
Exch. Al^{3+} ($cmol_c \cdot kg^{-1}$)	0.46 ± 0.36^a	0.30 ± 0.16^a	0.39 ± 0.21^a	0.55 ± 0.08^a
Sum of bases[a] ($cmol_c \cdot kg^{-1}$)	0.70 ± 0.10^{ab}	0.49 ± 0.08^a	0.68 ± 0.23^{ab}	0.92 ± 0.32^b
Effective CEC[b] (%)	1.16 ± 0.34^{ab}	0.79 ± 0.21^a	1.08 ± 0.32^{ab}	1.47 ± 0.30^b
Al saturation[c] (%)	35.9 ± 18.2^a	8.3 ± 1.6^a	35.7 ± 14.2^a	38.3 ± 8.4^a
Available P ($mg \cdot kg^{-1}$)	3.7 ± 2.0^a	8.3 ± 1.6^a	19.4 ± 10.6^a	65.9 ± 29.7^b
Clay (%)	15.9 ± 7.9^a	10.0 ± 2.3^a	11.1 ± 4.6^a	13.8 ± 1.8^a
Silt (%)	11.9 ± 2.0^a	9.3 ± 4.4^a	10.8 ± 9.1^a	13.2 ± 7.6^a
Sand (%)	72.2 ± 8.4^a	80.7 ± 5.7^a	78.1 ± 7.9^a	73.0 ± 7.0^a
Bulk density ($g \cdot mL^{-1}$)	1.05 ± 0.10^a	1.09 ± 0.16^{ab}	1.23 ± 0.07^{ab}	1.26 ± 0.06^b
Hardness[d] (mm)	12 ± 4^a	13 ± 2^a	15 ± 1^a	20 ± 3^b
Subsurface soil (30–40 cm)				
pHw	4.95 ± 0.21^{ab}	5.07 ± 0.19^{ab}	5.19 ± 0.10^b	4.83 ± 0.23^a
pHk	3.94 ± 0.20^{ab}	4.29 ± 0.18^b	4.00 ± 0.24^{ab}	3.83 ± 0.32^a
EC ($\mu S \cdot cm^{-1}$)	11 ± 2^a	12 ± 2^a	12 ± 2^a	23 ± 7^b
Total C ($g \cdot kg^{-1}$)	6.8 ± 3.1^a	12.3 ± 5.7^a	8.4 ± 4.1^a	10.6 ± 1.4^a
Total N ($g \cdot kg^{-1}$)	0.40 ± 0.14^a	0.48 ± 0.15^a	0.54 ± 0.14^a	0.46 ± 0.10^a
C/N	16.6 ± 4.8^a	25.1 ± 6.0^a	15.4 ± 5.3^a	23.8 ± 6.7^a
CEC ($cmol_c \cdot kg^{-1}$)	1.67 ± 0.83^a	1.91 ± 0.56^a	1.82 ± 0.71^a	2.00 ± 0.69^a
Exch. K^+ ($cmol_c \cdot kg^{-1}$)	0.02 ± 0.01^a	0.02 ± 0.01^a	0.02 ± 0.01^a	0.04 ± 0.02^a
Exch. Mg^{2+} ($cmol_c \cdot kg^{-1}$)	0.08 ± 0.02^b	0.06 ± 0.02^{ab}	0.04 ± 0.03^a	0.07 ± 0.01^{ab}
Exch. Ca^{2+} ($cmol_c \cdot kg^{-1}$)	0.28 ± 0.01^{ab}	0.24 ± 0.03^{ab}	0.19 ± 0.07^a	0.36 ± 0.16^b
Exch. Al^{3+} ($cmol_c \cdot kg^{-1}$)	0.49 ± 0.36^a	0.37 ± 0.20^a	0.43 ± 0.20^a	0.60 ± 0.17^a
Sum of bases[a] ($cmol_c \cdot kg^{-1}$)	0.48 ± 0.03^{ab}	0.37 ± 0.05^{ab}	0.30 ± 0.13^a	0.51 ± 0.17^b
Effective CEC[b] (%)	0.96 ± 0.37^a	0.74 ± 0.23^a	0.73 ± 0.18^a	1.10 ± 0.26^a
Al saturation[c] (%)	44.3 ± 18.9^a	47.0 ± 12.4^a	57.5 ± 20.0^a	53.9 ± 11.3^a
Available P ($mg \cdot kg^{-1}$)	1.4 ± 1.0^a	6.2 ± 3.1^b	3.1 ± 1.6^{ab}	4.3 ± 2.0^{ab}
Clay (%)	13.6 ± 8.8^a	11.8 ± 4.1^a	13.1 ± 5.5^a	15.2 ± 3.8^a
Silt (%)	16.6 ± 3.2^{ab}	10.2 ± 3.7^a	13.0 ± 7.3^{ab}	22.4 ± 9.7^b
Sand (%)	69.8 ± 9.5^{ab}	78.0 ± 6.3^b	73.9 ± 7.9^{ab}	62.5 ± 9.2^a
Bulk density ($g \cdot mL^{-1}$)	1.64 ± 0.09^a	1.47 ± 0.15^a	1.56 ± 0.12^a	1.55 ± 0.07^a
Hardness[d] (mm)	17 ± 2^a	18 ± 2^a	20 ± 2^a	19 ± 1^a

Values are means ± standard deviation; values in the same row followed by different letters indicate significant differences at 5% levels using Scheffe's multiple comparison test. [a]Sum of exchangeable K^+, Mg^{2+}, Ca^{2+}, and Na^+; [b]sum of exchangeable bases and exchangeable Al; [c]exchangeable Al in percent of ECEC; [d]measured using Yamanaka-type push cone penetrometer.

humid tropical climate [64–66]. On the other hand, the soil acidity could be attributed to the release of organic acids within the thick accumulation of litterfall layer and peaty mor humus (approximately 10 cm) in secondary forests.

Similarly, the soils under rubber land uses were acidic at the surface and subsurface soils, with the soil pHw slightly higher than that of secondary forests in the subsurface layer. At the surface layer, soil total C, soil total N, and sum of exchangeable base contents were the lowest as compared to other land uses. Contrary to our expectation, the correlation between cultivation age, acidity, and nutrient contents was not found in rubber land uses.

Soil properties under oil palm land uses showed little variation from secondary forests and rubber land uses, except for the soil bulk density and soil hardness. Additionally, the contents of available P are more abundant in oil palm land uses than those of secondary forest and rubber land uses. For the comparison of fertilizing point (FP) and centre point (CP), no distinct differences were observed between soil acidity (soil pHw) and soil nutrient contents (exchangeable K, exchangeable Mg, exchangeable Ca, and available P). However, the contents of soil total C, soil total N, and soil C/N ratio were higher, and soil bulk density was lower at the fertilizing point (FP). Chew and Pushparajah [67] reported that high soil total

Table 5: Comparison of selected soil physicochemical properties at 0–10 cm depth of centre point (CP) and fertilizing point (FP) in oil palm and pepper land uses.

Soil physicochemical properties	Oil palm CP $n = 9$	Oil palm FP $n = 9$	Pepper CP $n = 4$	Pepper FP $n = 4$
Soil depth (0–10 cm)				
pHw	4.57 ± 0.14	4.73 ± 0.66	4.76 ± 0.20	$5.60 \pm 0.78^{*}$
Total C ($g{\cdot}kg^{-1}$)	19.5 ± 7.3	$25.5 \pm 6.8^{*}$	19.6 ± 4.5	24.7 ± 3.5
Total N ($g{\cdot}kg^{-1}$)	1.37 ± 0.35	$2.16 \pm 0.57^{**}$	1.30 ± 0.40	$2.06 \pm 0.40^{**}$
C/N	13.9 ± 2.1	$12.0 \pm 2.3^{*}$	15.4 ± 2.0	$12.1 \pm 1.5^{**}$
Exch. K^{+} ($cmol_c{\cdot}kg^{-1}$)	0.08 ± 0.03	0.48 ± 1.27	0.10 ± 0.02	0.85 ± 1.26
Exch. Mg^{2+} ($cmol_c{\cdot}kg^{-1}$)	0.13 ± 0.06	0.31 ± 0.53	0.19 ± 0.10	1.41 ± 1.81
Exch. Ca^{2+} ($cmol_c{\cdot}kg^{-1}$)	0.30 ± 0.18	0.46 ± 0.50	0.52 ± 0.13	$1.76 \pm 1.02^{**}$
Exch. Al^{3+} ($cmol_c{\cdot}kg^{-1}$)	0.39 ± 0.21	0.34 ± 0.24	0.55 ± 0.08	$0.15 \pm 0.13^{**}$
Available P ($mg{\cdot}kg^{-1}$)	19.4 ± 10.6	27.2 ± 40.5	65.9 ± 29.7	$693.9 \pm 531.5^{*}$
Bulk density ($g{\cdot}mL^{-1}$)	1.23 ± 0.07	$1.11 \pm 0.14^{**}$	1.26 ± 0.06	$1.16 \pm 0.05^{*}$

Values are means ± standard deviation; **significant differences at $P < 0.05$ using paired t-test; *significant differences at $P < 0.1$ using paired t-test.

C contents at the fertilizing point could be ascribable to the fallen male blossom, which continuously increases the organic matter contents at the fertilizing point. Moreover, the freshly supplied organic matter from palm root exudates could be another reason of high total C at the fertilizing point. Meanwhile, Tan et al. [68] reported that a lower soil pHw value was observed in the weeded circle (fertilizing point) than the harvesting path (centre point) of an oil palm plantation in central Pahang due to nitrification. However, the soil pHw at the fertilizing point is higher than that at the centre point. Additionally, the bulk density at the fertilizing point showed lower compaction as compared to the centre point. Presence of extensive palm roots, which penetrate through the surface soils, and the regular supply of organic materials from the vegetative palm parts resulted in a lower compaction at the fertilizing point than the centre point. Additionally, the exposure of bare lands (the canopy of oil palm is not formed yet) to rainfall at the centre point is another possible reason for higher soil compaction. The surface soils will become more compact after the removal of the root mat from the forest cover and the surface soils are exposed to rain [69, 70].

Soils under pepper land uses were generally less acidic with the presence of significantly higher sum of bases in both surface and subsurface layers. Nonetheless, the available P was also significantly higher as compared to other land uses at the surface soil layers. The application of organic manures as soil conditioners could result in high retention of available P in tropical soils. According to Verma et al. [71], acidic tropical soils have high rate of P fixation due to high Al and Fe oxide concentrations. The application of manures in such soils reduces P fixation but increases the available P pool due to release of organic acids and other microbial products that modified soil pH (H_2O) during decomposition. Likewise, chelation of Fe and Al (hydr)oxides by organic acids and competition of PO_4^{3-} with organic anions for anion adsorptions sites could be another factor that contributes to such conditions [72]. Soil bulk density and soil hardness were also significantly higher as compared to secondary forest in surface soils of pepper land uses, suggesting soil compaction from regular farm work and crop maintenance activities under a localized farmland area [13]. The differences between soil properties at the fertilizing point and centre point could be observed except for soil total C, soil exchangeable K, and soil exchangeable Mg. Significantly high level of available P was observed at the fertilizing point of the pepper land uses, indicating the accumulation of unused P by the pepper vines.

3.4. Role of Soil Total C under Sandy-Textured Soils. Based on multiple regression analysis, the soil total C was found as the dominant contributor of soil CEC with the equation of $CEC = 0.251\ \text{Clay} + 0.729\ \text{total C}^{**}$ ($R^2 = 0.778$) on the surface layers. Such interrelationship, therefore, indicated that maintaining sufficient levels of soil total C during the cropping period is vital to sustain the soil fertility and crop productivity for agricultural land uses at sandy soils. Figure 2 shows the relationship between soil total C and the major soil properties at the surface layer. It was found that the soil total C has a direct relationship with soil nutrients and fertility at the surface layer, indicating that soil total C acts as the nutrient reservoir for the standing vegetation under sandy-textured soils. The naturally poor nutrient retention in sandy-textured soils was due to low clay contents and sandstone parent materials [24]. Katagiri et al. [24] reported that the amount of nutrients was very low under sandy-textured soils of heath forests resulted from the low supply of organic matter returned by litterfall and the rapid decomposition caused by high temperature. Unlike the remnant forests under clayey soils, the nutrients found in heath forests are poor under long fallow period (more than 35 years at the study area). Stark and Jordan [73] reported that 99% of the dissolved nutrients available to soils are sequestrated by the thick root mats under infertile sandy soils of tropical forests. Thus, the dissolved nutrients were stored within the thick litterfall (O horizon) and root mat layer before the nutrients were leached into the spodic E horizon [40]. Such a condition, therefore, explained the low availability of nutrients and acidic properties of soils under secondary forests and rubber land uses in the study sites. According to Syuhada et al. [25], the accumulated thick layer of litterfall contributed to the formation of organic acids through microbial decomposition. Moreover, the presence of organic acids is likely to enhance the

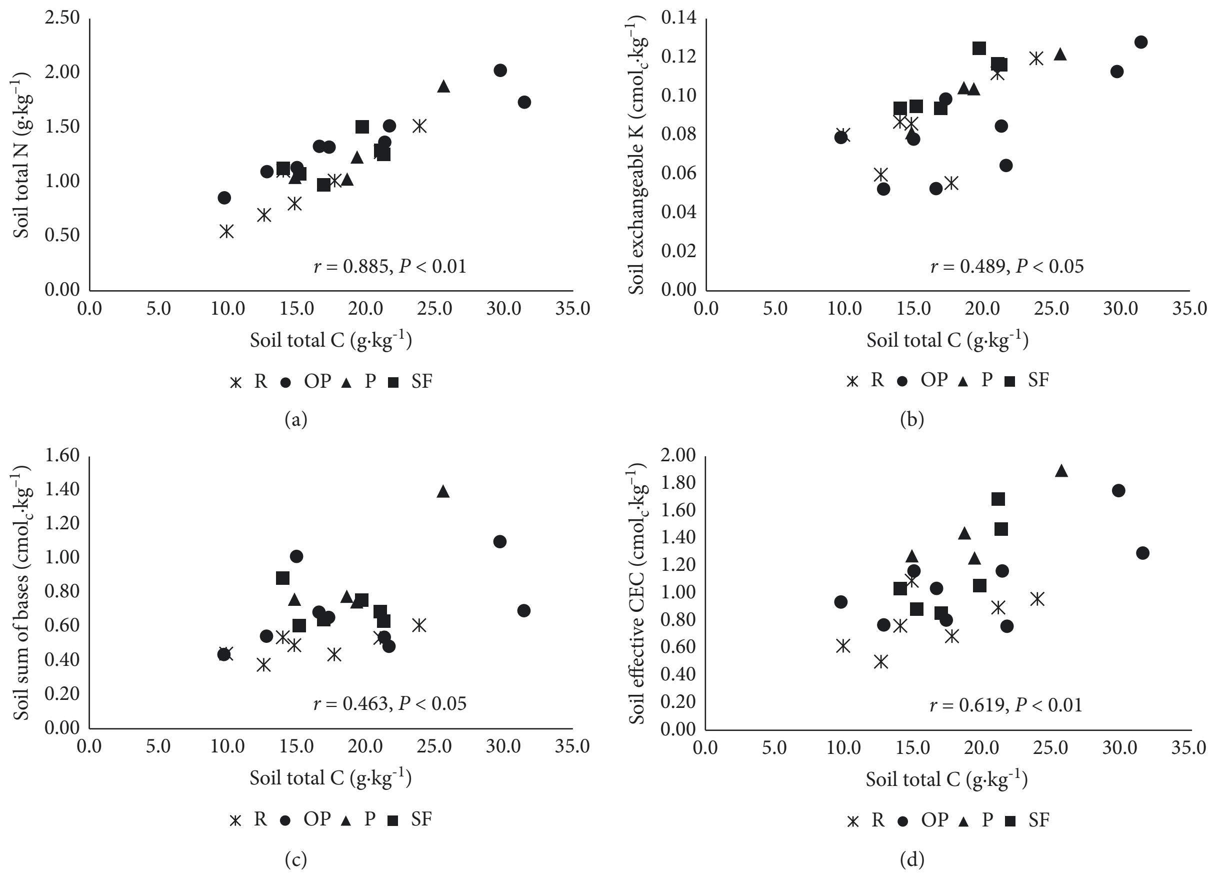

Figure 2: Relationships between soil total C and soil total N, soil exchangeable K, soil sum of bases, and soil effective CEC at the surface soil layer.

weathering of silicates and minerals to release cations [25] for the uptake of the standing vegetation. Hattori et al. [41] further reported that the removal and destruction of the thick layer of litterfall and root mat may accelerate the leaching process of nutrients and limiting the recovery of the secondary forest under sandy-textured soils. Under intensified oil palm and pepper cultivation, development of O layer was very thin. Hence, the main challenge is to ensure the efficient use of nutrient applied under agricultural cultivation in sandy-textured soils on a limited coverage of organic litterfall layer to ease the nutrient uptake of the cultivated crops. Especially for the case of pepper farmlands, most farmers clean-weeded the farmlands regularly, as shown in Figure 3 (approximately 3 to 5 times annually), which resulted in periodical removal of O horizon, limiting the plant litter input under such agricultural land uses. The dissolved nutrients easily leach and accumulate over the spodic or albic layers of B_h horizon and later lost through the lateral flows, especially during the rainy season. Few researchers [27, 33] suggested that the application of organic fertilizers such as chicken manure and compost is encouraged for farming practices under sandy-textured BRIS soils at Peninsular Malaysia. The organic soil conditioners applied in the oil palm and pepper land uses in the study sites were in the form of frond stacks and chicken manures, respectively; further study on the extend of the interactions of these organic fertilizers regarding the uptake of nutrients in relation to crop productivity under intensive agricultural practices at sandy-textured soils is required.

3.5. Partial Nutrient Balances of Oil Palm and Pepper Cultivation under Sandy-Textured Soils. Partial nutrient balances were estimated in each oil palm and pepper land use with reference to nutrient stocks stored in soils (0–40 cm) and crops, nutrient removal from harvesting, and input from fertilizers. Nutrient balance estimation act as an instrument to provide indicators for the sustainability of agricultural land use practices and importance for nutrient management [74, 75]. According to Sanchez and Palm [76], soil nutrient stocks is the reserve of N, P, and K, which can be made available to the plant in the next 5 to 10 years. Table 6 shows the nutrient stocks of oil palm and pepper land uses, in comparison to secondary forests (control) at the study area.

The soil nutrient stocks under oil palm and pepper land uses did not vary widely compared to secondary forests land uses. Under intensive farming with fertilizers input in oil palm and pepper land uses, the soil nutrient stocks (except for N) showed little variation to soil nutrient stocks under secondary forests, suggesting the poor ability of nutrient retention in the sandy-textured soils. Subsequently, partial nutrient budgeting comparing fertilizers input, crop uptake, and soils (0–40 cm) were estimated. However, it was

(a) (b)

Figure 3: Pepper cultivation (1 year old) under sandy-textured soils at the Sabal area.

Table 6: Soil nutrient stocks in various agricultural land uses.

Soils (0–40 cm)[a]	Total N ($kg\cdot ha^{-1}$)	Available P ($kg\cdot ha^{-1}$)	Exchangeable K ($kg\cdot ha^{-1}$)	Exchangeable Mg ($kg\cdot ha^{-1}$)	Exchangeable Ca ($kg\cdot ha^{-1}$)
Secondary forest (SF)	3220	24	92	64	336
Oil palm land use (OP)	4671	58	71	56	300
Pepper land use (P)	4216	32	97	59	278

[a]Average values for all sites. Amounts of nutrients in soils were calculated as the sum of the value determined for 0–10 cm depth and three times the value determined for 30–40 cm depth. For the surface soils in oil palm farmlands and pepper farmlands, the average of the values determined for the centre point and fertilizing point samples was used.

noteworthy that N concentration in soils was calculated based on the estimation of total N, thus resulting in high amount of N in soils in the land uses, as organic matter could be another source in contributing N in soils of these farmlands. Tables 7 and 8 show the estimated partial nutrient balances in both oil palm and pepper land uses.

There is variability in terms of P accumulation under oil palm land uses. Study sites 3, 8, and 9 received slightly excess fertilizers as the nutrient applied did not retain in soils nor the standing crops. The nutrient balance of P could be observed in study sites 1, 2, 4, 5, and 6 whereby the nutrients applied did not exceed or deficit from the nutrient stored in soils and crops. Study site 7 showed higher soil P stocks at the surface layer. Compared to the secondary forests, soil K stocks in most oil palm sites (study sites 3 to 9) were low. Such conditions, therefore, suggest possible insufficient K input from fertilizers due to the vigorous uptake of the oil palm with increasing age. Meanwhile, K applied from fertilizers are likely to be lost through leaching from the sandy soils.

Comparatively, both soil P stocks and soil K stocks in pepper land uses were low despite high amount of fertilizers input from all study sites. Taking into account the removal of nutrients from crop harvesting and nutrients stored within the pepper plant, the surplus of fertilizers applied in P and K still far exceeded the nutrient uptake and removal (harvesting) of the pepper vines. However, the applied nutrients did not remain in the soils (0–40 cm). Such condition is an indication that sandy soils could not hold the unused nutrients by the pepper vines. Although the yield of pepper fruits is good with an annual production of 6.62 tonnes, the inability of soils to hold nutrients is a concern as the dissolved P and K derived from the fertilizers is likely to leach downward into the spodic horizon or loss from surface runoff. Mohd Yusoff et al. [27] pointed out that the loss of K nutrients was due to the lower selectivity of the variable negative charges derived from soil organic matter for monovalent cations rather than divalent cations. Loss of P fertilizers to environment may contribute to ground water contamination at the water bodies located nearby the pepper farmlands [77].

The existence of agronomic constraints in managing the oil palm cultivation which lead to lower achievable yield in smallholder oil palm cultivation than plantations has been highlighted [78]. In their studies, Woittiez et al. [79] addressed the issues of nutrient deficiency, with emphasis on K under smallholder oil palm cultivation in Indonesia. Deficiency of K could lead to reduced productivity of fresh fruit bunches (FFB). Additionally, Kosno and Subardja [80] reported that poor growth performance of oil palm is possible under sandy Spodosols due to restricted root penetration through the hard albic and spodic horizon. Application of slow-release fertilizers and organic fertilizers has been recommended to reduce the loss of nutrients through leaching and runoff [80, 81]. Nonetheless, Tao et al. [82] reported that reducing fertilizer rate resulted in a higher nutrient use efficiency of K, compared to treatments with increased fertilizers frequency. However, some researchers [80, 83] suggested that the environmentally vulnerable sandy-textured soils Spodosols should be localized for conservation purposes rather than agriculture purposes or else, it will inflict financial loss to smallholder farmers. The recovery and restoration of the soil fertility on sandy soils after destruction is rather difficult [41]. For this purpose, judicious steps should be carefully planned in managing

Table 7: Partial nutrient budgeting comparing fertilizer input, crop uptake, and soils (0–40 cm) for P and K in each oil palm land use.

		P				K			
Oil palm farmlands	Age (years)	Fertilizers input (kg·ha^{-1})	Stored in crops (kg·ha^{-1})	Stored in soils 0–10 cm (kg·ha^{-1})	Stored in soils 10–40 cm (kg·ha^{-1})	Fertilizers input (kg·ha^{-1})	Stored in crops (kg·ha^{-1})	Stored in soils 0–10 cm (kg·ha^{-1})	Stored in soils 10–40 cm (kg·ha^{-1})
1	1	32	1	12	37	21	16	79	9
2	1	32	1	13	34	21	16	91	8
3	1	73	1	7	37	47	16	33	40
4	2	23	10	12	28	15	158	64	8
5	2	24	10	20	37	15	158	38	31
6	2	24	10	19	39	15	158	37	29
7	2	55	8	145	20	46	135	53	7
8	2	91	10	9	20	67	158	23	26
9	3	85	10	9	28	62	201	39	28

Table 8: Partial nutrient budgeting comparing fertilizer input, crop uptake, crop removal, and soils (0–40 cm) for P and K in each pepper land use.

		P					K				
Pepper farmlands	Age (years)	Fertilizers input (kg·ha^{-1})	Stored in crops (kg·ha^{-1})	Removal from crop output (kg·ha^{-1})	Stored in soils 0–10 cm (kg·ha^{-1})	Stored in soils 10–40 cm (kg·ha^{-1})	Fertilizers input (kg·ha^{-1})	Stored in crops (kg·ha^{-1})	Removal from crop output (kg·ha^{-1})	Stored in soils 0–10 cm (kg·ha^{-1})	Stored in soils 10–40 cm (kg·ha^{-1})
1	1	1264	9	0	11	10	583	65	0	61	31
2	1	590	13	0	11	12	421	93	0	51	58
3	5	1959	30	11	12	22	1293	370	107	51	20
4	8	1535	30	6	13	34	1014	370	62	55	63

smallholder oil palm and pepper cultivation on sandy-textured soils to minimize the risk of soil degradation.

4. Conclusions

The present study revealed that the properties of sandy-textured soils were influenced by smallholder agricultural land uses. Soil total C was found to be the determinant in sustaining soil fertility. Maintaining adequate levels of soil total C throughout the cropping period is the main challenge for agricultural land use practices under sandy-textured soils. Over-application of P and K fertilizers is observed under pepper cultivation at sandy soils. Considering the size of the farmlands, the pepper land uses are usually smaller, localized, and manageable by individual farmers, and with patches of secondary vegetation in the surrounding land uses, the impact on the soils is greatly reduced. In contrast, the oil palm land uses generally cover a larger area size. Hence, even a small change in soil properties has a great impact on the soil productivity. Therefore, sustaining the nutrient balances in soils and fertilizers input could be an option to monitor the health status of poor sandy-textured soils under intensive oil palm and pepper cultivation at the Sabal area. Integrated nutrient management with constant addition of organic fertilizers as soil ameliorants is required to increase the nutrient retention capacity for agricultural practices under sandy-textured soils. This study, however, was conducted at a limited age group for oil palm and pepper land uses. A wider age group with higher number of study sites is necessary to draw robust conclusions. On-farm experiments are required to fill the research gap on the nutrient management, with respect to fertilizers use and nutrient deficiencies among the independent smallholder agricultural land use practices under sandy soils in these regions. Nonetheless, addressing the nutrient loss from smallholder agricultural practices under sandy-textured soils in Sarawak is another critical research gap to be filled. The fine-tuning of site-specific soil management recommendations is crucial towards holistic conservation of smallholder agroecosystems under sandy-textured soils in the marginal areas of Sarawak.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The earlier version of the work was reported in an unpublished master dissertation entitled "Assessment on the Soil Fertility Status of Lands under Upland Farming Practices at Sabal, Sarawak, Malaysia."

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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