Abstract

This study discusses soil fertility under perennial cash crop farming (para rubber, *Hevea brasiliensis*; black pepper, *Piper nigrum*; oil palm, *Elaeis guineensis*) conducted by local farmers and an oil palm estate in an upland area of Sarawak, Malaysia, in comparison with the surrounding secondary forests. In the farmlands of the local farmers, rubber farming was conducted without fertilizer application, while 2 to 5 t ha^{-1} of NPK compounds were applied annually on pepper farms. Soils under rubber farming were acidic with poor nutrient contents, resembling soils in secondary forests. In pepper farms, soils were less acidic and showed high nutrient contents, especially with respect to available P and exchangeable Ca. This trend became stronger with increasing farming duration. Fertilizers applied around pepper vines appeared to migrate and spread across the fields. Bulk density and hardness of surface soils were higher in pepper farms than in secondary forests, indicating soil compaction due to field works. In the oil palm estate, annual fertilizer application rates were moderate at 0.4 to 0.8 t ha^{-1} of NPK compound fertilizers. However, the soil properties in the oil palm estate were similar to those of the small-scale pepper farms. Close to the bases of the palms where fertilizers usually are applied, the contents of exchangeable Ca and available P were high. Nutrient uptake by the dense root systems of the palms seemed to prevent excessive loss of nutrients through leaching. Loss of soil organic matter and deterioration of soil physical properties were brought about by terrace bench construction, but the soils seemed to recover to some extent over time. In conclusion, technologies such as intercropping and the appropriate allocation of different crops

to specific locations as well as the proper selection and dosage of fertilizers should be developed and adopted to improve fertilizer efficiency and prevent water pollution due to fertilizer wash-off from farmlands.

Key words: para rubber, black pepper, oil palm, soil fertility, Sarawak, upland farming

1. Introduction

In the upland of Sarawak, Malaysia, local farmers grow para rubber (*Hevea brasiliensis*) and black pepper (*Piper nigrum*) as perennial cash crops in addition to upland rice as their staple food by shifting cultivation practices. According to Cramb (2007), rubber farming was introduced at the beginning of the 20th century. It was adopted preferentially by farmers applying shifting cultivation, as it could easily be incorporated into cropping/fallow systems by planting its seedlings simultaneously or in sequence with upland rice. On the other hand, pepper farming began in the 1870s but became widespread only after the Second World War because of the high requirements for labor and agrochemical input. One characteristic of rubber and pepper production in Sarawak is that it has been conducted mainly by smallholders supported by the government's agricultural policies. Recently, with increasing need for cash income in a monetary economy, the significance of cash crop farming has increased. As a result, the shifting cultivation for rice production, formerly the most important agricultural activity and consequently, the central element of traditional local farming societies (Freeman, 1955; Jensen, 1965), changed into a mere component of a more diverse upland farming system (Crumb, 1993). This tendency toward commercialization was strengthened by various kinds of subsidy schemes provided by the Department of Agriculture of the state since the 1970s. Meanwhile, since the 1970s and 1980s, large-scale oil palm (*Elaeis guineensis*) plantations have been developed rapidly by public agencies of the federal and state governments as well as by private companies (Ngidang, 2002; Crumb, 2007). Some local farmers possess their own small-scale oil palm farm, sometimes supported by subsidies.

The total areas under perennial cash crops in Sarawak were estimated to be 156,731 ha for rubber, 12,930 ha for pepper, and 508,307 ha for oil palm in 2004, which accounted for 16.8, 1.4, and 54.5 % of the total agricultural land, respectively (Department of Statistics, Malaysia). The areas covered by rice (excluding fallow land) amounted to 60,354 ha for lowland and 66,065 ha for upland varieties. The area used for oil palm farming expanded from 116,036 ha in 1995 to 508,307 ha in 2004 while those of other crops stagnated or declined slightly.

The farmlands utilized for rice and cash crops as well as oil palm farming tend to be located along roadsides or rivers because of easy access and transportation (Hansen and Mertz, 2006), resulting in an increasing intensity of land use at such favorable sites. In the traditional shifting cultivation, upland rice was grown only once after slashing and burning of secondary forest that was more than 10 to 15 years old; afterwards, the field was turned to fallow. Nowadays, the fallow period is around 5 years and upland rice is cultivated 2 to 5 times in a row (Kendawang et al., 2005). Chemical fertilizers are widely used, especially in pepper and oil palm farming. This transformation from traditional shifting cultivation with low external input toward more sedentary farming practices with high input may affect soil fertility and, in consequence, the sustainability of the upland agricultural system.

The transformation and present situation of upland agriculture in Sarawak have been studied mostly from socioeconomic viewpoints (Best, 1988; Cookie, 2002; Ngidang, 2002; Hansen, 2005; Crumb, 2007; Ichikawa, 2007). Regarding crop production, numerous field trials have been carried out in peninsular Malaysia and Sarawak to optimize land management practices including fertilizer application (see, for example, Broughton (1977) for rubber, Raj (1972) for pepper, Agamuthu and Broughton (1985) and Khalid et al. (2002) for oil palm). The impacts of soil erosion were examined in the context of pepper farming (Hatch, 1981; de Neergaard et al., 2008), while the effects of slope terracing on soil properties were studied in rubber (Noguchi et al., 2003) and oil palm plantations (Hamdan et al., 2000). However, many of these studies have been carried out in well-controlled experimental fields of government institutions or estates and were concerned with only one particular farming practice. No attention has been paid to how different cash crop farming practices might influence soil fertility through the actual field management by local farmers.

The aim of this study was to evaluate soil fertility under different perennial cash crop farming practices (rubber, pepper and oil palm) in the Lubok Antu district of the Sri Aman division in order to provide fundamental information and perspectives for the development of appropriate and effective management systems. The hilly terrain of the study area is being used for rice and cash crop farming by local farmers. They cultivate upland rice following slashing and burning of secondary forests, and plant cash crops during or immediately after rice cropping. In addition, parts of the secondary forests have been allocated for a large-scale oil palm plantation scheme by the Sarawak Land Consolidation and Rehabilitation Authority (SALCRA) since the late 1970s. These diverse types of land use within one upland region allowed us to compare soil fertility under various farming practices to that of the surrounding secondary forests which can be regarded as a control.

2. Materials and Methods

2.1. Study area and sites

This study was conducted from 2004 to 2007 at Lubok Antu district, Sri Aman division in Sarawak. The district is located near the border with West Kalimantan, Indonesia, and has been inhabited for 400 years by the Iban people, the largest tribal group of Sarawak. Except for some riverine and swampy sites suitable for lowland rice cultivation, the study area is composed of rolling hills with an altitude below 500 m ASL. The mean annual precipitation was 2,926 mm from 1996 to 2005 with a drier season from June to August and a wetter season from September to December (Department of Irrigation and Drainage, 2005). The mean annual temperature is 26.4℃ (Meteorological Department, 2006). Soils originated from sedimentary rocks of the Palaeocene to Eocene periods.

Study sites were established in secondary forests and rubber, pepper and oil palm farms of three Iban longhouses, Karak (01º12'10'N, 111º40'51''E), Bak (01º13'04'N, 111º43'88''E) and Serau (01º02'46'N, 111º47'60''E) and at the Lemanak oil palm plantation estate of the SALCRA (01º10'80'N, 111º44'85''E; location of the estate office). The socio-economic outlines of these longhouse communities are given in Kendawang et al. (2005). In these longhouses, cacao (*Theobroma cacao*) also used to be planted as a cash crop but almost all of the fields have been abandoned due to problems such as disease infestation. The Iban landowners were asked questions about farming histories of the sites and crop management. The ages of secondary forests and cash crop farms were determined based on the owners' recalling. However, the information often was ambiguous, especially in the case of old rubber farms, when answers like, for example, 'during his (her) father's or grandfather's generation' were given. In such cases, we estimated the age based on the assumption that one generation corresponded to 25 years, and on memorable incidents. Information about the oil palm estate was provided from the Lemanak regional office of the SALCRA.

In May and June 2004, a field survey was conducted at 30 secondary forest sites, including 12 sites from 2 to 5 years of age, 9 sites from 7 to 10 years, and 9 sites from 12 to 44 years. All of the secondary forests developed after one or two rice cropping cycles in a shifting cultivation scheme. According to the landowners, the sites with forests less than 10 years old were slated for cropping. Many older forests were left unused because clearing would be too laborious, although the owners believed that the soil fertility had recovered sufficiently for rice cropping. In June 2006, 25 rubber and 24 pepper farms were surveyed; the rubber farms included 8 sites 2 to 5 years old, 9 sites 15 to 35 years old, and 8 sites 50 to 60 years old. The pepper farms included 8 sites form 1 to 4 years old, 9 sites from 7 to 10 years old, and 7 sites from 12 to 22 years old. These farmlands had been established during or after rice cropping. Although soil fertility levels had been estimated through observation of the vegetation before rice cultivation started, a systematic assessment had not taken place at the time when pepper plants or rubber trees were planted. Except for cases in which soil fertility was obviously very low resulting in poor rice yield, pepper and rubber farms were started at any sites that were disposable at the time when planting materials and labor became available through the farmer's own efforts or the subsidy program. In older rubber farms, dead rubber trees occasionally had been replaced with naturally-regenerated rubber seedlings while an improved high yielding clone had been introduced recently into newly opened farms through the subsidy program. Oil palm farms were surveyed in March 2007, but not more than nine were available because oil palms were cultivated only by the Bak community. Six of the oil palm farms were 8 years old reflecting the year when the subsidy had been provided; the other three, for which no subsidies had been provided, were 1, 4, and 17 years old.

The Lemanak oil palm estate was surveyed in March, 2007. It had been established in secondary forests which belonged to longhouse territories and for which the Iban farmers asserted customary usufruct rights. No records could be obtained about landuse histories before the establishment. The total planting area of the estate is 3,230 ha divided into 7 large sectors (Phases) based on planting years. Phases are pegged out into several smaller but adjoining sectors (Blocks) belonging to individual longhouse communities. The block is the unit for crop management. Phase 1 was established in 1978 with a total planting area of 1,182 ha. Most blocks of this phase were located around the estate office and the adjacent mill on the south side of the main road (Lubok Antu road). Phases 2 (324 ha) and 3 (503 ha) were established around the Phase 1 area in 1981. The plantation expanded to the north of the road for phases 4 (1989, 339 ha), 5 (1990, 79 ha), 6 (1995, 100 ha), and 7 (1997 to 1999, 703 ha). A total of 19 sites of 4 phases were investigated in the present study: 5 sites of Phase 1, 5 sites of Phase 4, 2 sites of Phase 5 and 7 sites of Phase 7 (planted in 1997). Because of the large area of the estate, these sites were scattered over the blocks belonging not only to the surveyed longhouses but also to neighboring ones. Oil palm trees in the Phases 4, 5 and 7 were planted on terrace benches while those in Phase 1 as well as those of the Iban farmers were grown on platforms. The terrace benches were 3 to 4 m wide and followed the contours to facilitate the labor on slopes, especially the harvesting. Soil-was excavated from upper parts of a slope and moved to a lower part to produce level benches. Slopes between benches (riser banks) were occasionally covered with a portion of the soil. On the other hand, the platforms were small, leveled spaces constructed around individual palm trees. The platforms in Phase 1 were indistinguishable from natural slopes, probably due to the old age of the phase.

The slope gradients of the study sites did not vary between the farmlands and secondary forests surveyed and ranged from 0 to 30º with an overall average of 10.5º. Gravel was not found in most of the soils studied.

2.2. Soil sampling and analysis

At each site, the soil on squares of 10 × 10 or 20 × 20 m^2 was analyzed. Characteristics of the vegetation such as plant density also were recorded. Soil samples were collected at depths of 0-10 cm and 30-40 cm from 3 points within the square. While the sampling points in secondary forests were located randomly within the squares, soil samples from cash crop farming sites were collected at the intersections of the diagonal lines between four adjacent plants (center point). In case of the Phases 4, 5, and 7 in the oil palm estate, the intersections were located on riser banks. Soil samples also were collected from 0-10 cm depth in the zones adjacent to plants to which fertilizers usually are applied, that is, 30 to 50 cm from the bases of pepper vines and 1 m from palm tree stems (fertilizer circle). The fertilizer circles of the oil palm estate were located on natural slopes (old platforms) in the sites of Phase 1 and on terrace benches in the sites of Phase 4, 5, and 7. The soil samples obtained in triplicate were mixed well to yield one composite sample. The samples were air-dried and passed through a 2 mm mesh sieve for physicochemical analyses. Plant materials such as fine roots and charcoal fragments were removed carefully with tweezers. Core samples (100 mL) were collected in triplicate for determination of bulk density.

Soil pH was determined in water or 1 M KCl in a soil to solution ratio of 1:5 using glass electrodes. Total C and N contents (T-C, T-N) were analyzed using an NC analyzer (Sumigraph NC-80; Sumika Chemical Analysis Co., Osaka, Japan). The contents of exchangeable bases (Ca, Mg, K, and Na) and the cation exchange capacity (CEC) were measured after successive extraction using 1 M ammonium acetate adjusted to pH 7.0 and 10% NaCl, respectively. The amount of NH_4 replaced by Na was determined for CEC using the steam distillation and titration method, whereas the contents of exchangeable bases were determined by atomic absorption spectrophotometry for Ca, Mg, and K, and by flame photometry for Na (AA-6800; Shimadzu Corp., Kyoto, Japan). Exchangeable Al, H, and NH_4 were extracted with 1 M KCl. Exchange acidity (Al + H) was determined by titration with 0.01 M NaOH, and the content of the exchangeable Al was determined with 0.01 M HCl. The content of exchangeable H was calculated as the difference between the values of the exchange acidity and exchangeable Al. The content of exchangeable NH_4 was measured using the indophenole blue method (Mulvaney, 1996). Available phosphorus was quantified by the Bray II method (Kuo, 1996). Particle size distribution was established using the pipette method. Clay mineral composition of the soils was determined by X-ray diffraction analysis using CuKα-radiation (Shimadzu, XD-D1w). At the center points, soil hardness was examined at depths of 0–10 and 30–40 cm using a Yamanaka-type push cone penetrometer.

2.3. Statistical analysis

All results of soil analyses are expressed on an oven dry basis. All statistical analyses were performed using Excel Statistics ver. 2004 for Windows (SRI, Tokyo, Japan). For comparison of soil properties between sites under different crops and different durations of cultivation of one crop, the Bartlett's test of homogeneity of variance was performed. When variances had been shown to be homogenous, the Scheffe's multiple comparison after one way analysis of variance was computed. When variances were not homogeneous, the Scheffe's multiple comparison was performed following the Kruskal Wallis test. The results from the Iban's oil palm farms were omitted from this analysis because of the limited number of sites studied. However, a paired t-test was used for the oil palm farms to compare soil properties between the fertilizer circles and the center points.

3. Results

3.1. Cash crop farming in the study area

Characteristics of the crop management obtained from the vegetation and interview survey are summarized below. A detailed analysis of plant communities and growth in secondary forests can be found in our previous paper (Wasli et al., 2006).

Each landowner possessed one to nine rubber farms. The farm used for tapping and the frequency of tapping were chosen based on considerations of several factors such as labor availability, market price of rubber, accessibility of the farm, and latex yield of the trees. Spacing between adjacent rubber trees was rather constant within a site but varied between the sites from 2.0 to 6.8 m with an average of 3.9 m. This spacing resulted in an estimated average plant density of 790 trees ha^{-1}. Based on the plant densities determined in the squares and the number of the trees in the farm as given by the owners, the farm sizes were estimated to be 0.12

to 1.6 ha. The plant density and farm size were similar to those reported in a previous study conducted in the same district (Mertz and Christensen, 1997) but the plant density was higher than the 270 trees ha^{-1} reported for rubber plantations in peninsular Malaysia (Yew, 2001). Small amounts of chemical fertilizer were applied to newly planted trees only. Underbrushing was performed when the farm was used for tapping, usually about 5 years after planting.

One to three farms of pepper (in most cases, only one) were owned by one landowner. Spacing of pepper vines varied between sites from 1.6 to 2.3 m with an average of 1.9 m, resulting in a plant density of 3,400 vines ha^{-1}. The farm area was mostly smaller than 0.1 ha, with a few being smaller than 0.05 ha. The plant density and farm area were similar to those reported by Mertz and Christensen (1997). Fertilizers such as NPK compounds with various composition (for example, N-P-K-Mg-Ca, 12-5.2-14-12-5.0 %) or urea (N, 46%) were applied to the mound around pepper vine bases (about 30 to 50 cm radius) by admixing to the soil with a hoe. The type and application rate of the fertilizer depended mainly on considerations of cost-benefit ratios that change due to fluctuations of market prices of pepper and fertilizers. At the time of the survey the pepper price was in a depression, and most of the farmers insisted that they were reducing fertilizer application to just above the level that allowed pepper vines to 'survive'. The annual application rates varied widely between farmers, but were mostly between 2 and 5 t ha^{-1} with an average of 4 t ha^{-1}, applied in several doses. This average corresponds to 480-209-565-48-200 kg ha^{-1} of N-P-K-Mg-Ca for the NPK compound mentioned above. The rates applied were in the range recommended for Sarawak (Sadanandan, 2000). Pruning was done to keep the vine trailing on a wooden pole and to maintain its height at about 2.5 to 3 m. The pruning wastes were removed from the farm or used as green manure in a few cases. Irrespective of whether weeding was performed manually or by applying herbicides, herbaceous plants covered more or less of the ground in many of the farms. Other crops such as chili (*Capsicum annuum*) and egg plants (*Solanum aculeatissimum*) were occasionally intercropped.

In the oil palm estate, the trees were planted with a constant spacing of 7 to 8 m in a triangular arrangement, which resulted in a plant density of 136 palms ha^{-1}. Fertilizer types and application rates were determined based on the growth stages and the nutrient status as evaluated by foliar analysis. We obtained the records of fertilizer application since 2003. Application rates did not vary much year by year and block by block. In 2005, for example, most of the blocks of Phase 4 to 7 were fertilized once or twice, each time with about 0.4 t ha^{-1} of compound fertilizers (48-10.5-73-7.2 kg ha^{-1} of N-P-K-Mg, or 66-13-66-7.7-2.1 kg ha^{-1} of N-P-K-Mg-B). Although no information was available about the chemical form of phosphorus, it seemed to be ground rock phosphate or superphosphate (Teo et al., 1998). A few of the blocks also received 100 kg ha^{-1} of K as potassium chloride or 33-46 kg ha^{-1} of Mg-S as kieserite. The fertilizers were applied at a radius of about 1 to 2 m around the palm. Weeding was conducted thoroughly on terrace benches. Palm fronds pruned at harvest time were piled on riser banks. In Phase 1, fertilizer application and weeding had been terminated because this oldest sector was waiting for replanting. In the oil palm farms of the Iban farmers, the arrangement of the trees was similar to that of the estate but with narrower spacing. The application of chemical fertilizers depended on the farmer's economic situation.

3.2. Soil physicochemical properties

Table 1 gives average values of physicochemical properties of soils from various farming conditions and secondary forests. Table 2 compares some of the surface soil properties at the center points and fertilizer circles of pepper farms and the oil palm estate in terms of farming history. Regarding the classification of pepper farms in Table 2, the age up to four years represents immaturity, seven to 10 years corresponds to the middle of the productive phase, and 12 to 22 years corresponds to or exceeds the productive life span of pepper vines (10 to 15 years) in Sarawak (Sadanandan, 2000). In Table 2, the properties of the oil palm farms of the Iban are also compared between sampling points.

In each landuse type, clay contents of the surface and subsurface soils showed significant correlations with soil properties such as T-C and exchangeable bases (data not shown), indicating that the clay content is an important determinant of the soil fertility status in the study area. Variation in the clay contents was relatively high for each land use type. However, no significant differences were found in the clay contents of surface soils between land use types (Table 1) and between the age classes defined for each land use type (data not shown). On the other hand, Brunn et al. (2006) compared soil properties and upland rice yields of several sites after fallow periods of different lengths in Sarawak and pointed out that the variation in slope gradients in the sites (3 to 15°) might affect soil nutrients and carbon levels, and confound the evaluation. In the present study, however, no correlations were not found between soil properties and slope gradients measured at the soil sampling points. Therefore, the differences in soil properties can be ascribed principally to the influences of the type of land use and its duration.

Soils under secondary forests were relatively clayey. The clay mineral composition was dominated by kaolin minerals, followed by quartz and chlorite and, to a lesser extent, illite, gibbsite, goethite, and hydroxyl-interlayered vermiculite. The soils showed pH (H_2O) values around 4.1 at the surface and 4.3 in the subsurface layer. The contents of exchangeable bases were low while that of exchangeable Al were high, resulting in a high value of Al saturation. The level of available P was very low. With increasing fallow duration, the surface soils tended to become more acidic and lower in exchangeable Ca and Mg (data not shown; not statistically significant). The average Al saturation of the surface soils was 90 % in forests less than 5 years old and 95 % in forests over 12 years. The soils were classified as Typic Dysrudepts in the USDA soil classification system (Soil Survey Staff, 2006).

No substantial differences were found between the soil properties in secondary forests and rubber farms (Table 1). The soils in rubber farms were acidic with poor nutrient contents. They tended to be acidified and lower in exchangeable bases with increasing age of the stand (data no shown; not statistically significant).

In pepper farms of the Iban farmers, the surface as well as subsurface soils were less acidic with higher contents of exchangeable bases and available P than soils in secondary forests.

The T-C contents of soils in pepper farms were low compared with other types of land use (not statistically significant), resulting in the lowest C/N ratios. As shown in Table 2, the surface soils became less acidic and nutrients were accumulated with increasing farm age. Bulk density and hardness of the surface soils were higher in pepper farms than in secondary forests, indicating compaction of the surface soils. However, there was no apparent correlation between soil compaction and farm age.

The soils in oil palm farms owned by individual farmers showed similar physicochemical properties as those in pepper farms.

In the oil palm estate, soil properties also resembled those found in pepper farms of local farmers. Compared with secondary forests, the soils were less acidic and richer in nutrients except for available P at the center points; here, P levels were as low as in secondary forests. However, the T-C and T-N contents were not significantly different from those in the secondary forests. The contents of exchangeable Ca and Mg at the center points were higher in Phase 7 (9 years) sites than in Phase 1 (28 years) and Phase 4 - 5 (17 and 16 years) sites, while there were no differences in the fertilizer circles. Although the T-C and T-N contents, C/N ratio, and CEC in the center points were not significantly different between the phases, their values in the fertilizer circles were highest in Phase 1. There were no appreciable differences in the contents of available P between the phases. At the center points, the soils were harder compared with secondary forests. The soils in Phase 1 showed the greatest hardness. The bulk density in the fertilizer circles was highest in Phase 7, while there were no differences in bulk density at the center points between the phases. On riser banks in some of the sites of Phases 4, 5 and 7, a new A horizon of 3 to 5 cm thickness was observed above the original A horizon which had been buried during the construction of the terrace benches. A dense fabric of secondary and tertiary palm roots was found all over the fields of Phases 1, 4 and 5 at soil depths between 0 and 30 cm.

4. Discussion

4.1. Soil fertility under secondary forests

The soils under secondary forests in this area were characterized by a more acidic nature and lower contents of exchangeable bases in spite of similar levels of clay, T-C, and available P, compared with values reported previously for secondary forests in shifting cultivation systems (Andriesse and Koopmans, 1984; Tanaka et al., 2007) and selectively-logged secondary forests (Tanaka et al., 2004, 2005) in Sarawak. Tanaka et al. (2007) studied soil fertility in secondary forests at 1 to 40 years after rice cropping in the Mujong river region of Sarawak which the Iban inhabited for about 100 years. While topographic and geological conditions in that region resembled those of our study area, the cycle of shifting cultivation consisted of a single generation of rice followed by about 10 years of fallow. The soils were less acidic with a pH of around 5.0 and possessed much higher contents of exchangeable bases than those characterized in the present study. The soil characteristics presented in this study might be a result of nutrient loss from the soils due to prolonged agricultural land use during the longer settlement history of the sites.

The soils at the early stages of secondary forest tended to be less acidic with higher contents of exchangeable Ca and Mg. This could be ascribed to the remaining effects of ash (Juo and Maru, 1996), suggesting that a small ash input under intensified shifting cultivation with a shorter fallow period could still improve soil fertility to some extent. Although the farmers sometimes used chemical fertilizers (mainly urea) in upland rice farming as supplements for small amounts of ash, the application rates did not exceed 100 kg ha^{-1} (46 kg N ha^{-1} in case of urea) and the resulting rice yield was only about 500 to 1000 kg ha^{-1} (Kendawang et al., 2005). In contrast, Bruun et al. (2006) studied sifting cultivation systems in Niah, Sarawak, where cropping intensities were low since the first clearing 30 to 80 years ago. They reported that rice yields after 0 to 38 years of fallow ranged from 169 to 3,466 kg ha^{-1} with an average of 1,780 kg ha^{-1}. Furthermore, compared with cases in which large amounts of ash were added to soils through burning practices (Andriesse and Schelhaas, 1984; Tanaka et al., 2004, 2005; Bruun et al., 2006), the soils in the present study often showed lower levels of exchangeable bases and were more acidic even in the pepper farms and oil palm estate in spite of the application of chemical fertilizers, while the levels of available P were comparable or higher. These facts imply that because the study region had low soil fertilities (probably due to longer or more intensive agricultural land use) and sufficient ash effects could not be expected any more, more efficient fertilizer application methods are required for sustainable production of upland rice and cash crops.

4.2. Soil fertility under rubber farming by local farmers

Tables 3 and 4 show estimates of nutrient stocks in crops and soils, and annual nutrient budgets, respectively. Data related to crops are cited from previous studies conducted in Sarawak and peninsular Malaysia. The stocks in the soils are the average of all sites of a given type of land use. They were calculated as the values found for 0-10 cm depth plus three times the values found for 30-40 cm, assuming that the nutrient concentrations of the soil layer at 10-30 cm depth were equal to those at 30-40 cm. For the surface soils (0-10 cm) of the pepper farms and oil palm estate, the average of samples from center points and fertilizer circles were used in the calculation. It should be noted that this calculation probably underestimates soil nutrient stocks because the nutrient contents at 30-40 cm depth were generally lower than at 10-30 cm depth.

The soil properties in the rubber farms were similar to those in the secondary forests, indicating that the influences of rubber farming led to similar developments with respect to soil fertility as those that occurred during secondary forest formation, in spite of the differences in species composition and the diversity of vegetation. In rubber plantations in peninsular Malaysia, Noguchi et al. (2003) reported deteriorated soil physical properties due to topsoil removal and soil compaction caused by mechanical construction of terrace benches and plantation works. In contrast, our results indicate that rubber tapping activities on the natural slopes of the Iban’s rubber farms did not cause significant soil compaction. Rubber latex yields depend on farmers’ tapping activities: the annual yield in smallholdings in Malaysia is reported to be 800 to 900 kg ha^{-1} (Hartemink, 2003), while 880 kg ha^{-1} were produced from a 2.2 ha rubber farm by one household in the permanent smallholder rubber agroforestry systems in Sumatra, Indonesia (Wibawa et al., 2005). Cramb (1993) reported about 500 kg per household in an Iban community in Sarawak. Tables 3 and 4 suggest that nutrient removal from soils by tapping is not negligible and is likely to cause nutrient depletion in soils within about 10 years of continuous tapping. However, the enthusiasm of the farmers for tapping largely depends on the market price of rubber, and activities often come to a halt during low price-periods, which might contribute to the conservation of soil fertility.

Thus, rubber farming could be regarded as a sustainable component without external input in the upland farming system of the Iban agriculture as long as the tapping intensity is low enough to not deplete the soils. In fact, jungle rubber farming in Indonesia has been considered a form of agroforestry or enriched fallow management which can replace unsustainable upland farming systems and rehabilitate *Imperata*-dominated, degraded grasslands (Grist et al., 1998; Penot, 2007). However, the tapping activities of Iban farmers are increasing because of the favorable current market price of natural rubber. In addition, a high-yielding clone is being planted with support from government subsidies while rubber wood is cut as timber and firewood because of a lack of other suitable species. These changes may affect nutrient budgets and require fertilizer input to maintain soil fertility.

4.3. Soil fertility under pepper and oil palm farming by local farmers

In the pepper farms, the soils at the center points as well as in the fertilizer circles were less acidic and showed higher contents of nutrients except for N, compared with secondary forests. This trend increased with increasing duration of farming. The subsurface soils also were richer in nutrients than secondary forest soils. Nutrient input by fertilizer application, especially P and Ca, far exceeded the output by harvesting and pruning (Table 4). These results indicate that appreciable amounts of P and basic cations applied as fertilizers migrated from the fertilizer circles and distributed across the fields. The C/N ratios of surface and subsurface soils were low because of lower T-C contents, which might be ascribed to the decomposition of soil organic matter and the relatively small addition of fresh organic matter from pepper plants to the soils. However, no appreciable N accumulation occurred in the soils in spite of the high input of fertilizer N. Although the form of fertilizer N applied was urea or ammonium sulfate, the levels of exchangeable NH_4-N were not significantly different from those in the other types of land use. The T-N contents did not differ significantly between the land use types. These results suggested that excess fertilizer-N is rapidly nitrified despite the acidic soil conditions, and is lost by leaching and runoff although a portion of the fertilizer N might be fixed by the illite that is a minor component of the clay minerals. Further detailed monitoring will be required to characterize short-term N dynamics in these soils.

The surface soils were harder and the bulk density was larger than under the other types of land use, reflecting soil compaction caused by farm work. Hatch (1981) studied soil erosion in a pepper farm located on a slope of 25° at Semongok Agricultural Research Center in Sarawak.

He reported that soil erosion during the first year after the establishment amounted to 62.7 t ha^{-1} while erosion under primary and secondary forests was negligible. Contrarily, in small pepper farms in the Miri and Serian Divisions of Sarawak, Neergaard et al. (2008) used ^{137}Cs measurements to show that soil erosion on 30 to 35º slopes was limited with an estimated 35 % of the surface soils lost over 40 years. Although the low content of T-C reported in the present study might reflect the loss of soil organic matter due to surface soil erosion, the field observation detected little evidence of soil erosion in most locations. This result might be explained by the fact that pepper farms of local farmers had only small parcels of sloping land that were surrounded by secondary forest, resulting in low velocities of runoff water and consequently, low rates of soil erosion. In addition, slopes were gentle (10.5º on average) with undulating microtopographies, and the ground mostly was covered by herbaceous plants which probably provided additional protection from soil erosion.

Although sufficient information could not be obtained due to the limited number of sites, the effects of Iban oil palm farming practices on soil fertility did not seem to differ from those described for pepper farms.

For small local pepper and oil palm farming, methods of fertilizer application and crop should be altered. Because of large accumulations of available P in the soils, the input of fertilizer P can be reduced. In order to improve fertilizer efficiency, increase crop production, and prevent soil erosion, intercropping should be encouraged. Since most of the roots of pepper vines distribute within a 30 cm radius around the plants (Ravindran et al., 2000), nutrient competition can be avoided if appropriate secondary crops are selected. Taking into account fertilizer N dynamics as discussed above, leguminous crops appear promising although legumes are not commonly cultivated by Iban farmers (Christensen and Mertz, 1993). In addition, pruning waste should be used as green manure to return organic matter and nutrients to soils.

4.4. Soil fertility in the oil palm estate

In the oil palm estate, the contents of available P and exchangeable Ca were high in the fertilizer circle. This could be ascribed to the application of rock phosphate or superphosphate. There was no significant difference in the contents between Phase 1 and the other phases, suggesting that the residual effect of the P fertilizer persisted for several years after the application (at least since 2003 when we obtained the fertilizer application records). At the center points, the level of exchangeable Ca was high but that of available P was low, compared to secondary forest soils. In addition, the level of exchangeable Ca was higher in Phase 7 than in Phase 1 and Phases 4 - 5. These findings for Ca and P at the center points of the oil palm estate differed from those from the pepper farms discussed above. This might be related to nutrient release from the frond piles through decomposition and nutrient uptake by palm roots as well as the general property of tropical soils to fix P rapidly. Oil palm fronds contain 5 times more Ca than P on a weight basis (Corley and Tinker, 2003). Khalid et al. (2000) also reported a high level of exchangeable Ca and a low level of available P from frond piles after 23 years of oil palm plantation. According to field observations, the density of palm roots in Phase 7 (the latest planting sector) was sparse at the center points, which might result in decreased uptake of Ca as compared to other phases.

Aweto (1995) reported that the organic carbon stock of the soil in an oil palm plantation was lower than that in an adjacent primary forest. However, in the present study, the levels of T-C and T-N at the center points in the oil palm estate were comparable to those under secondary forests. Moreover, no significant differences between the phases were found in T-C and T-N at the center points. A new A horizon had developed above the buried original A horizon on riser banks in several sites of Phases 4, 5, and 7. These results suggest that soil organic matter at the center points (riser banks) were maintained at a similar level as in secondary forests, probably because of the supply of fresh organic matter through the decomposition of the frond piles. On the other hand, the soils in the fertilizer circles of Phase 1 (without terracing) showed higher contents of T-C and T-N with a higher C/N ratio than those of Phases 4 - 5 and Phase 7 (with terrace benches). However, no differences were found in these parameters between Phases 4 - 5 and Phase 7. Hamdan et al. (2000) compared soil physicochemical properties on terrace benches and original slopes in newly established oil palm plantations in peninsular Malaysia. According to their study, the terrace benches were composed of saprolitic materials corresponding to the C horizon of the original soils. The level of organic C of the surface layer at the terrace benches was very low (less than 1 g kg^{-1}) while the level at the original slopes was similar to that in the present study. It is suggest that the level of soil organic matter in terrace benches could be rapidly recovered to some extent through a supply of fresh organic matter from palm roots.

Hamdan et al. (2000) and Noguchi et al. (2003) discussed the deterioration of soil physical properties in terrace benches in oil palm and rubber plantations, respectively, that occurred due to day-to-day farm work as well as to disturbances during the establishment of the estate. In the present study, the bulk densities in the fertilizer circles were found significantly higher in Phase 7 than in Phases 4 - 5, reflecting the deterioration of soil physical properties by terrace bench construction and its alleviation with increasing farming duration. On the other hand, the surface soils at the center points were harder than those in secondary forests, while no difference was found in the bulk density. The soils in Phase 1 showed the greatest hardness in the absence of differences in bulk density between the phases. The results regarding soil hardness and bulk density at the center points might be attributable to the increasing volume of palm roots within a given volume of soil after planting, which resulted in soil compacting and hardening without significant changes in soil bulk density.

Judging from the nutrient budgets given in Table 4, the application rates of fertilizer N, P, K and Mg in the oil palm estate appear to be appropriate. Thus, in contrast to the pepper farms of the Iban, the loss of nutrients added as fertilizers seemed to be low. However, since the estate is incomparably larger than any pepper farm, measures to prevent nutrient loss and soil erosion should be taken carefully. Noguchi et al. (2003) emphasized the low water permeability of terrace benches and the occurrence of flooding after heavy rain, which is consistent with our field observations on rainy days. The oldest fields of Phase 1 will be replanted soon. In

Malaysia, the residues of the previous stand generally are returned to the soil by felling and crushing with bulldozers and other machines before replanting in order to improve fertilizer efficiency and to avoid burning. The biomass of oil palm plants of 27 years in a peninsular Malaysia plantation was reported to be 67.8 t ha^{-1} (Corley and Tinker, 2003); in this particular stand, the nutrient stock in the plants could be higher than the values cited in Table 3. However, our study revealed that significant amounts of nutrients still remained in the soils of Phase 1, especially in the fertilizer circles. Therefore, nutrient stocks in the soils also should be taken into account in the replanting management.

5. Conclusions

Our study showed that soil fertility was affected by different cash crop farming managements. The soil properties under rubber farming could be regarded as identical to those under secondary forests. In contrast, significant nutrient accumulation in soils due to fertilizer application occurred in the pepper and oil palm farms of the Iban farmers and in the oil palm estate. Technologies such as appropriate selection and dosage of the fertilizers applied and intercropping should be developed and adopted to improve fertilizer efficiency and prevent water pollution by fertilizers washed off of farmlands. However, loss of soil nutrients from fields on slopes probably is unavoidable under the climatic conditions of Sarawak. Although farmlands of local farmers and oil palm plantations have coexisted for some time in the study area, the location of farmlands and cropping design are determined by individual households and the estate separately. However, the cooperation of communities and estates in land use planning would appear desirable. For example, pepper and oil palms should not be planted on lower slopes close to rivers to prevent the influx of eroded material into the water. Rather, these farmlands should be located on slopes above upland rice and rubber farms to use washed-off nutrients efficiently. Previous studies of socioeconomic aspects have revealed that the Iban are flexible in combining shifting cultivation and cash crop farming practices which are components of upland agriculture that complement each other to contribute to the Iban's livelihood (Crumb, 1993; Wadley and Mertz, 2005). From the viewpoint of soil fertility management, the appropriate allocation of different crops to specific locations will contribute to the sustainability of the upland farming system with less external input and less impact on the surrounding environment.

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