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ORIGINAL ARTICLE

Effect of sago palm (*Metroxylon sagu* Rottb.) cultivation on the chemical properties of soil and water in tropical peat soil ecosystem

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Abstract Tropical peatland is a potential land resource for crop production to supply food and energy sources to increasing population. Although sago palm (*Metroxylon sagu* Rottb.) is a potential starch crop suited to this purpose, prefer control of groundwater level and fertilizer application should be done to maintain the high starch productivity. As it is also important to estimate the impact of sago palm cultivation on the environment from the view point of the sustainability, we investigated temporal changes in the chemical properties of drainage water and soil in a sago palm plantation in Indonesia. Analysis of canal water from blocks with different palm ages during a 2-year period suggested small increases in Ca, K, and Mg concentrations with time (up to 8 years). No time-dependent changes were observed in the concentrations of other nutritional/toxic elements, although the larger concentration in groundwater below sago palm than in canal water was observed for fertilizer components including B, Ca, P, and Zn. Although large portions of Al, Fe, and Zn in canal water were interacted with dissolved organic C (DOC), the leaching of DOC did not vary with the development of palm growth. Contents of nutritional elements were generally similar among soils at 1, 3, and 5 m away from a palm, among soils at 0.1, 0.3, and 0.5 m depths, and between soils in sago palm block and adjacent secondary forest, regardless of plant age. Thus, the sago palm cultivation with fertilizer and groundwater level control did not induce notable deterioration of soil and water qualities.

Keywords Dissolved organic carbon · Drainage · Fertilizer · Peat · Physicochemical properties · Trace element

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Introduction

Peatland is characterized by the accumulation of large amounts of partially decomposed plant material, low pH, high groundwater level, and low nutrient content. Because of these characteristics, peatland is unfavorable for the use as cultivated fields. Nevertheless, to supply foods balanced with the increasing population, peatland occupying 30 million ha in Southeast Asia (Radjagukguk 1997) is a potential ground for crop production. As the high groundwater level interferes with the supply of oxygen into soil,

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drainage is generally required to facilitate respiration of plant roots in peatland reclaimed for agricultural use. However, peat materials may be decomposed and subsided quickly if groundwater level is lowered (Blodau 2002), which would accelerate nutrient loss from peatland and further lower plant productivity (Laiho et al. 1999).

Sago palm (*Metroxylon sagu* Rottb.) is worthy of attention as a rare crop that can grow on tropical peat soil without drainage of groundwater and yields a great amount of starch, 164–180 kg per plant on a dry weight basis (Yamamoto et al. 2003). However, Yamaguchi et al. (1994) and Jong and Flach (1995) reported that the starch content in sago palm was larger at lower groundwater level than at higher groundwater level. Yamaguchi et al. (1994) also observed much smaller contents of micronutrients including Cu and Zn in sago palm grown in deep peat soils compared with those grown in alluvial soils. Nutrients released from peat soil may be insufficient to satisfy the growth of sago palm especially in the second and following generations. Therefore, prefer control of groundwater table and fertilizer application are required to maintain the high starch productivity, which have not been developed. Simultaneously the impact of sago palm cultivation on the environment, such as acceleration of peat decomposition, change in soil fertility, and loadings of greenhouse gasses and water-soluble nutritional/toxic elements to the atmosphere and aquatic environments, respectively, should be minimized toward the sustainable use for agriculture. There are few data (Funakawa et al. 1996; Kawahigashi et al. 2003) available to evaluate the effects of sago palm cultivation on elemental cycles in peatland ecosystem.

The reclamation of peatland has been observed to have significant changes in the rate and chemistry of water flow (Burba et al. 2001; Lu and Jaffe 2001; Vasander et al. 2003). For example, the change in the concentration of dissolved organic matter (DOM), such as fulvic acids, induces the changes in the mobility, toxicity (McCartney et al. 2003), and solubility in brackish and seawater (Matsunaga et al. 1984) of metallic elements through the formation of complexes (Küchler et al. 1994; Viers et al. 1997; Kalbitz and Wennrich 1998), and subsequently affect the population and community structure of aquatic biota (Roy and Campbell 1997; Matsunaga et al. 1998; Öztürk et al. 2002).

In the present study, we examined the effects of sago palm cultivation on the chemical properties of soil and water in an Indonesian peatland, with focusing on metallic elements. Temporal variations in the concentrations of elements in drainage (canal) system were evaluated by combining the data collected from sago palm cultivation blocks with various plant ages during a 2-year period. Changes in the chemical properties of soils were estimated using two data sets obtained from soils at different distances from sago palm plant and soils at different depths. The accumulation of elements from fertilizer or the consumption of elements by active plant absorption may result in the increase/decrease in their contents horizontally and/or vertically. Chemical properties of canal water and soil were also compared between sago palm cultivation blocks and their adjacent secondary forests. The relation of DOM to metallic elements and the chemical properties of groundwater below sago palm were also examined to discuss the behavior of fertilized and unfertilized elements as affected by the sago palm cultivation.

Materials and methods

Experimental site

The experiment was conducted at the National Timber and Forest Product sago palm plantation located in Tebing Tinggi Island, Riau Province, Indonesia (1°30′N, 103°40′E; Jong 2001). The mean annual maximum and minimum air temperatures in the 1996–2000 period, which were recorded at the nearest meteorological station, were 31.9 and 23.3°C, respectively. Annual precipitation was 1,700 mm with the maximum rainfall in December (222 mm) and minimum in July (79 mm). The plantation was initialized in 1996 on deep peat (Histosols) consisting of complex woody materials (100% peat). Tropical swamp forest that covered the plantation area was cleared ca 35 years ago, and thereafter the area was secondary forest.

The map of the plantation is shown in Fig. 1. The southwestern border of the plantation is approximately 2.4 km from the coast. The plantation area is divided into 20 phases. One phase consists of 20 blocks, and each block has a land area of 0.5 km^2

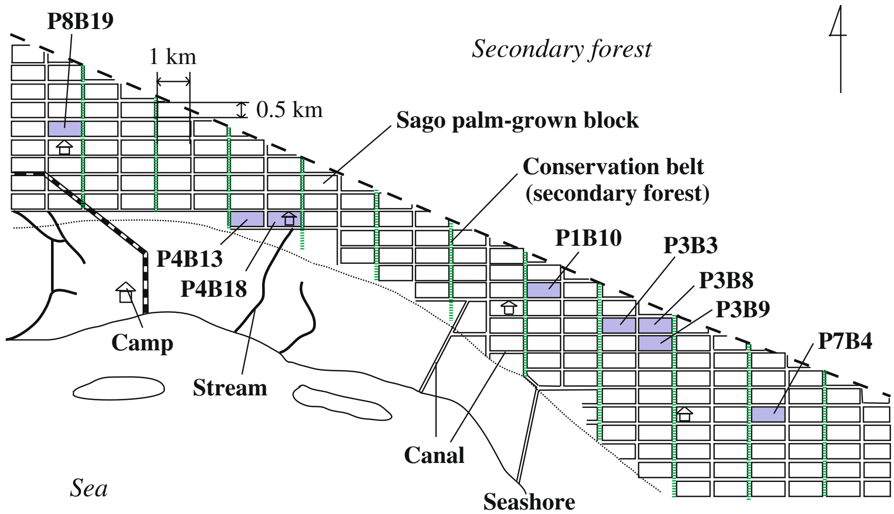

Fig. 1 Map of sago palm plantation in Tebing Tinggi, Indonesia

(0.5 × 1 km). Each block is surrounded by roads (5 m width) and facilitated with canals (5 m width). Since 1996, two phases with smaller code numbers have been established per year. Conservation belts (100 m width) of the secondary forest are maintained at two-block intervals (2 km) in the east–west direction, which also face the roads and canals. Major plant species in the secondary forests included *Cratoxylon arborescens*, *Callophyllum inophyllum*, *Shorea* spp., *Palaquium burckii*, *Eugenia* spp., *Tristania* spp., *Gonystylus bancanus*, and *Tetrameristra glabra*.

Plant density was 156 plants ha^{-1} (8 × 8 m) in Phase (P) 1 Block (B) 10 and 100 plants ha^{-1} (10 × 10 m) in the other blocks. Dolomite, urea, rock phosphate, and KCl were applied at the rates of 30–46.8, 5–7.8, 5–7.8, and 5–7.8 kg ha^{-1} year^{-1}, respectively, in the first year, and then were gradually increased to 400–624, 80–125, 40–62, and 40–62 kg ha^{-1} year^{-1} for 4-year-old sago palms. $CuSO_4$, $ZnSO_4$, and borate were also applied at the rates of 5–7.8, 5–7.8, and 2–3.1 kg ha^{-1} year^{-1} irrespective of palm age (Jong 2001). Fertilizer was applied three times a year. Dolomite was topdressed around a palm so as to draw a circle with a 10 cm width and 1 m radius, and other chemicals in granule form were introduced via four holes (10 cm depth) made at evenly spaced points on the dolomite circle. The ranges in the application rate of each chemical were derived from the difference in plant density. This manner of fertilization was expected to increase the efficiency of absorption by plants and reduce the leaching to canal. Because some of fertilizer remained in the application spot at next application, fertilizer components may be dispersed throughout a year.

Collection of water samples

Water samples were collected in triplicate from drainage canals along the sago palm cultivation blocks in December 2002, July 2003, and January, July, and November 2004. November, December, and January are rainy season and July is dry season, although we have not met a shower within 2 days before each sampling. Sampling was conducted in all or some blocks including P1B10 (transplantation of sago palm suckers was conducted in 1997), P3B3 and P3B8 (transplantation in 1998), P4B13 and P4B18 (in 1999), P7B4 (in 2000), and P8B19 (in 2001) at each time (Fig. 1). Total period of sago palm growth (13–15 years in peatland) is divided into three stages of rosette, trunk formation, and ripening. All the plants in this plantation were in the rosette stage throughout the research period.

Canal water along the secondary forests adjacent to P3B3 and P7B4 was also collected on the same days except for December 2002. Groundwater samples (triplicates) were collected from holes made at 1 m distance from sago palm plant in P3B3, P7B4, and P8B19 two or three times during canal water sampling days.

pH of water samples was measured in the field with a pH meter (D-24, HORIBA, Japan). The water samples brought back to the laboratory were filtrated successively through a glass fiber filter (GB-140, pore size 0.40 μm, ADVANTEC, Japan) and a hydrophilic polyvinylidene fluoride membrane (DURAPORE, pore size 0.45 μm, Millipore, USA). The filters were washed in ultra-pure water before use.

Analysis of water samples

Concentrations of Al, B, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, and Zn in the water samples were measured with an inductively coupled plasma (ICP) spectrometer (IRIS, Thermo Jallel-Ash, USA). DOC concentration was determined with a total organic C analyzer (TOC-V_{CPH}, Shimadzu, Japan).

An aliquot of canal water samples collected from the seven sago palm cultivation blocks in July 2003 and January and July 2004 (20 ml) was fractionated on a column packed with 1.5 ml of anion exchange resin (Q Sepharose Fast Flow, Amersham Biosciences, Sweden) into adsorbed and non-adsorbed fractions. The concentrations of DOC and metallic elements in the non-adsorbed fraction were determined with TOC-V_{CPH} and IRIS, and metallic elements distributed in the adsorbed and non-adsorbed fractions were regarded as organically bound and free cation forms, respectively (Kimura et al. 1998). Ultra-pure water that was passed through the resin under the same conditions as those for canal water samples was analyzed as blank. DOC was almost completely adsorbed to the resin (97 ± 4%). The amount of DOM-bound Ca could not be estimated due to the unexpectedly high recovery exceeding 100%.

Collection of soil samples

According to Miyazaki et al. (personal communication), no roots were observed >1 m distance from 1-year-old sago palms, whereas 20 and 42% of total roots were distributed between 1 and 2 m distances from 3- and 5-year-old sago palms, respectively. They also observed that the root biomass of 1- to 5-year-old sago palms were concentrated within the surface 30 cm layer. Based on these information, soil samples (triplicate) were collected from: 1) 10–15 cm depth at 1, 3, and 5 m distances from a sago palm in P1B10, P1B18 (transplantation in 1998), and P4B13 in December 2002, and 2) three layers of 10–15 (designated 10), 30–35 (30), and 50–55 (50) cm depths at 1 m distance from a sago palm plant in P3B3, P7B4, and P8B19 in July 2003. Last fertilizer application before soil sampling was September, 2002. In July 2003, three soil layers of 10–15, 30–35, and 50–55 cm depths were also collected from the secondary forests adjusting to the three blocks. Soil samples were air-dried and sieved (<2 mm) before analysis. Soil bulk density was measured separately in triplicates.

Analysis of soil samples

Total contents of Ca, Cu, Fe, K, Mg, Na, and Zn in soil samples were determined with an ICP spectrometer (Liberty 220, Varian, USA) after digestion with HF and HNO_3 in a microwave oven (Ethos 900, Milestone, Italy) according to Jones et al. (1991). Exchangeable cations were extracted from the 2002 samples with 1 mol l^{-1} ammonium acetate with pH regulated to 7 and determined with Liberty 220. pH and ash content of the soil samples collected from P8B19 and P3B3 and their adjacent forests were determined using a suspension of soil sample with distilled water mixed at 1:2.5 (w:v) and by the combustion method, respectively.

Statistical analysis

The relationships between the concentrations of elements in canal water and the duration after sago palm transplantation and those between two chemical properties of water or soil samples were analyzed using regression analysis. The significance of the differences in chemical properties between water or soil samples was analyzed using ANOVA.

Results

Temporal variations in chemistry of canal water from sago palm cultivation blocks

Variations in the concentrations of DOC and five elements in canal water from the sago palm cultivation blocks are shown in Fig. 2. The mean, minimum, and maximum values of the concentrations of

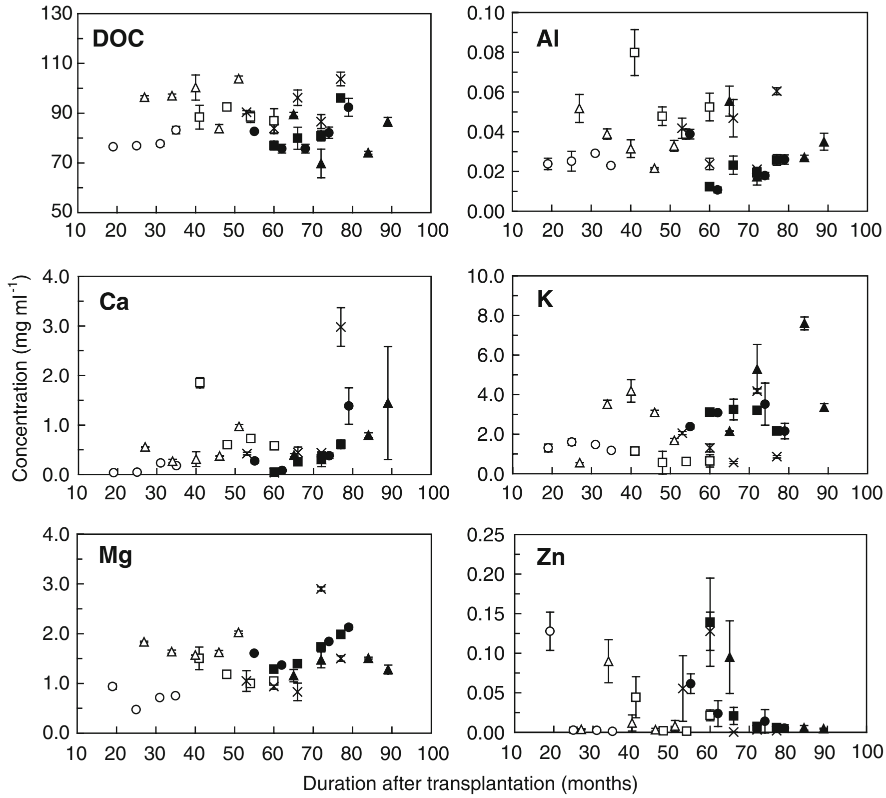

Fig. 2 Variations in concentrations of DOC, Al, Ca, K, Mg, and Zn in canal water from sago palm plantation blocks with plant age. Vertical bars indicate SE. ▲, P1B10; ●, P3B3; ■, P3B8; ×, P4B18; □, P4B13; △, P7B4; ○, P8B19

elements and pH for the seven blocks are listed in Table 1. Cu, Mo, and Cr were rarely detected, and the maximum and mean Cu concentrations were 0.031 and 0.001 mg l^{-1}, respectively. The pH of canal water from the seven blocks remained stable regardless of the duration of cultivation or the season [dry (July)/wet (November–January)], with the mean value and SD of 4.0 ± 0.3. DOC concentration, 70–104 mg l^{-1}, tended to be larger than the values reported for drainage water from European peats, 5–73 mg l^{-1} (Scott et al. 1998; Kalbitz et al. 1999). The fluctuation of DOC concentration was small and no time-dependent changes were observed.

Significant positive correlations ($P < 0.05$) with duration after sago palm transplantation were observed for the concentrations of Ca, K, and Mg (Fig. 2). Other elements did not increase irrespective of the application as fertilizer. Because the concentrations of toxic heavy metals, including Al (Fig. 2), Cd, Ni, and Pb, were always small (Table 1), sago palm cultivation did not increase heavy metal load in the surrounding water environment.

Table 2 shows the proportions of metallic elements that were bound to DOC. Because no significant differences between blocks were observed in all the elements, the data are shown as means for all the blocks. The proportion of Fe bound to DOC was largest (96 ± 3%), and this was followed by Zn (64 ± 41%) and Al (59 ± 42%). A large proportion of Fe bound to DOM in natural water is frequently observed (Sharp et al. 1982; Küchler et al. 1994). On the other hand, large proportions of K, Mg, and Na (89 to 97%) were estimated to be present as free cations. The compositional differences among the elements corresponded to differences in the binding strength to humic substances (Stevenson 1994).

Comparisons of chemistry of canal water in sago palm cultivation block with groundwater in the same block and canal water in the adjacent secondary forest

Figure 3 compares the concentrations of six elements between canal water and groundwater at the same

Table 1 Minimum, maximum, and mean values of pH and concentrations of elements and dissolved organic carbon (DOC) in canal water from seven blocks transplanted with sago palms at different times

Element/pH	Minimum (mg l^{-1})[a]	Maximum (mg l^{-1})[a]	Mean (mg l^{-1})[a]
pH	3.5	4.7	4.0
DOC	69.8	103.8	86.6
Al	0.011	0.080	0.033
B	0.004	0.086	0.028
Ca	0.36	2.98	0.58
Cd	<0.001	0.175	0.032
Fe	0.020	0.110	0.041
K	0.56	7.60	2.46
Mg	0.47	2.90	1.40
Mn	0.001	0.019	0.005
Na	6.00	41.5	17.8
Ni	0.002	0.036	0.004
P	0.007	1.41	0.24
Pb	<0.001	0.005	<0.001
Zn	<0.001	0.128	0.030

[a] Except for pH

sago palm cultivation blocks. The concentrations of B, Ca, P, and Zn were significantly larger in groundwater than in canal water at P7B4 (transplantation in 2000) and/or P3B3 (transplantation in 1998). Similar trends were not observed at P8B19 (transplantation in 2001). On the contrary, Na concentration was larger in canal water than in groundwater at all the blocks.

Figure 4 compares the concentrations of DOC and five elements in canal waters between the sago palm cultivation blocks and their adjacent secondary forests. The concentrations of Zn, Ca, and P as well as Al and B (data not shown) at P7B4 were smaller than those at the adjacent forest, while no significant difference or an opposite trend was observed at P3B3. These observations indicated that the sago palm cultivation may increase the concentrations of

Table 2 Mean proportions of metallic elements in organically bound form in canal water

Mean/SD[a]	Al	Fe	K	Mg	Mn	Na	Zn
Mean (%)	59	96	11	3	23	5	64
SD (%)	42	3	19	17	38	17	41

[a] Standard deviation

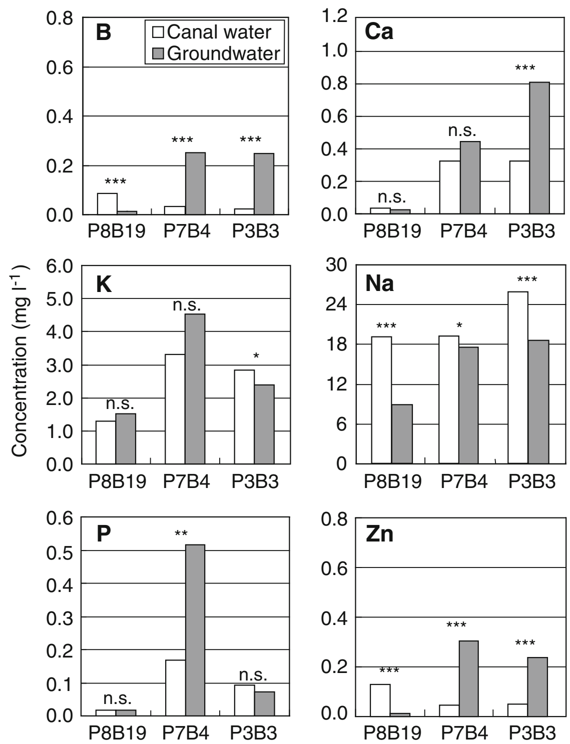

Fig. 3 Comparison of mean concentrations of six elements between canal water and groundwater. n.s., not significant

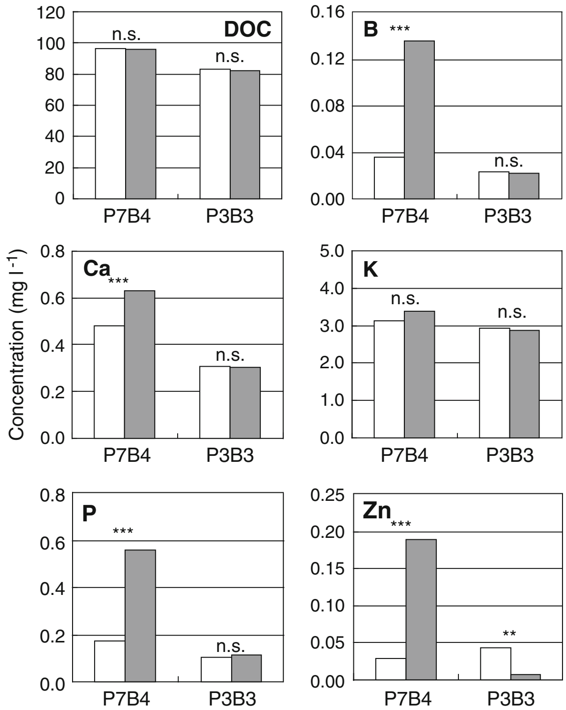

Fig. 4 Comparison of mean concentrations of DOC and five elements between canal waters from sago palm cultivation blocks (P7B4 and P3B3) and those from adjacent secondary forests. Open columns, sago palm cultivation blocks; closed columns, secondary forests. n.s., not significant

elements that were included in fertilizer in groundwater below sago palm but generally did not have significant effects on the chemical properties of canal water.

Horizontal variations in contents of metallic nutritional elements in sago palm soils

Soil bulk density ranged from 0.12 to 0.17 g cm^{-3}, which was similar to the reported values for other tropical peat soils grown with sago palm (Funakawa et al. 1996; Kawahigashi et al. 2003) and did not differ between the different distances from sago palm plant. Total contents of Ca, K, and Mg in the soil samples ranged between 0.37–2.51, 0.24–0.46, and 1.10–1.53 g kg^{-1}, respectively (Fig. 5). Those for Fe, Cu, and Zn were 125–394, 0.0–1.2, and 1.2–4.3 mg kg^{-1}, respectively (Fig. 5). Similar (K and Mg) or greater values (Ca, Fe, Zn, and Cu) have been reported for other Indonesian (Kawahigashi et al. 2003) or Malaysian (Funakawa et al. 1996) peat soils grown with sago palm. No significant differences were observed in the contents of nutritional metals with respect to the distance from sago palm, except for Mg in P4B13 (1 m > 3 m) and Zn in P1B18 (1 m > 5 m).

The contents of Ca, K, and Mg in the exchangeable form were larger in soils with larger contents of total Ca, K, and Mg, respectively ($P < 0.005$). However, the proportion of these elements present as the exchangeable form differed from each other. Exchangeable Ca accounted for 32 ± 6% of total Ca with an exception, while exchangeable Mg accounted for 58 ± 7% of total Mg (Fig. 5). The proportion of exchangeable K in total K was large especially at 1 and 3 m, 97 ± 4%. Significant decreases with increasing the distance from sago palm were observed only in exchangeable K in P1B10 (oldest block) and exchangeable Mg in P4B13 and P1B18 (younger blocks).

Vertical variations in chemical properties of sago palm soils and adjacent forest soils

In respective soil profiles, root mat was observed in the surface 5-cm layer. Below 15 cm depth, no weed roots and little less-humified organic matter were observed. Bulk density of three layers at 10, 30, and 50 cm depths was in the range of 0.11–0.16 g cm^{-3}. Ash content and pH of soil samples were smaller/lower in the 30 and 50 cm depth layers than in the 10 cm depth layer ($P < 0.005$; Fig. 6). Soil pH was also higher in the sago palm soils than in the forest soils ($P < 0.005$). Total contents of Ca, K, and Mg in the sago palm soils ranged between 0.11–1.81, 0.11–0.61, and 0.61–2.45 g kg^{-1}, respectively, which tended to be larger at 10 cm depth than at the deeper depths in P3B3 (Table 3). Contents of Ca and Mg correlated positively to the ash content ($P < 0.005$). There were no differences in the Ca, K, and Mg contents between the sago palm and secondary forest soils.

The Fe, Zn, and Cu contents in the sago palm soils were 81–338, 2.8–7.3, and 0.0–1.5 mg kg^{-1}, respectively (Table 3). The Fe content tended to be greater at 10 cm depth than at the deeper depths in both the sago palm and secondary forest soils and showed a positive correlation to the ash content ($P < 0.005$). Similar tendency or correlation was not observed for the Cu and Zn contents.

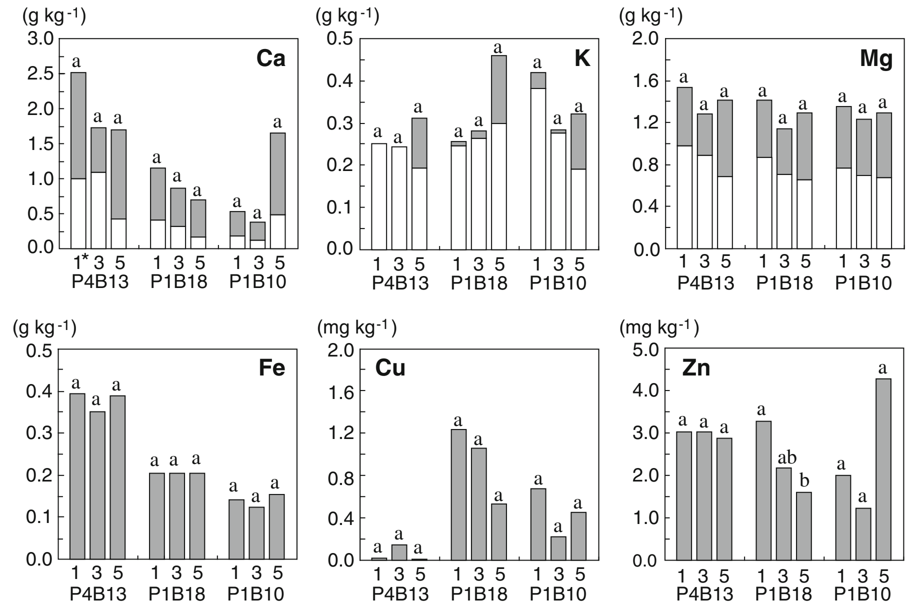

Fig. 5 Contents of total and exchangeable elements in 10–15 cm layer soils at different distances from sago palm plant. Open bar indicate the amount in exchangeable form, and open plus closed bars indicate total amount. Same character indicates the lack of significant difference in the total content within each block at $P < 0.05$. * Distance (m) from sago palm

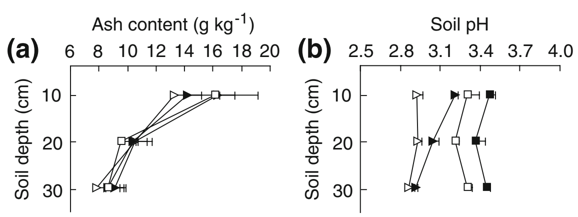

Fig. 6 Ash contents (**a**) and pH (**b**) of sago palm soils with different plant age (P8B19 and P3B3) and their adjacent secondary forest soils (P3SF and P8SF). ▲, P3B3; △, P3SF; ■, P8B19, □, P8SF. Vertical bars indicate SD

Discussion

Schroth et al. (2000) observed that the contents of P, K, Ca, and Mg in the available form in the surface layer (0–10 cm) of a mineral soil were larger at 2.5 m than at 1 m distance from oil palm (*Elaeis guineensis*). They attributed these differences to the active absorption of nutrients by palm roots, because of larger root density at 1 m than at 2.5 m distance from oil palm. Similar trend was rarely observed in the present study (Fig. 5). Supplement from fertilizer, which could not lead to the larger nutrient contents compared with forest soils (Table 3), and effective return from litter fall were possible causes.

In peat soil planted with sago palm, portions of components from intensive fertilizer application were expected to be accumulated at the application point, gradually dissolved in soil water, and moved to groundwater and drainage canal. Significant horizontal dispersion was probably scarce (Fig. 5). Based on the combination of data obtained from six blocks in 2002 and 2003 (Table 3; Fig. 5), the variations in the content of any element in soil did not correspond to the duration after transplantation. Hence, the spatial variations of chemical properties of soils within the sago palm plantation area could be a major cause of the variations in the contents of nutritional elements among the blocks. No significant differences from the adjacent forest soils (Table 3) agreed to this. Same trends are probably observable in the amounts of bio-available or relatively transportable major nutrients, because there were significant correlations between the contents of total Ca, K, and Mg and those in the exchangeable form.

The difference in the proportion of Ca, K, and Mg present as exchangeable form (Fig. 5) suggested the smaller mobility of Ca than K and Mg, which was reflected in the rate of decrease in their contents with soil depth (Table 3). The concentrations of Ca, K, and Mg in canal water relative to the total contents of

Table 3 Contents of nutritional elements in sago plam soils and the adjacent secondary fores soils at different depths

Block	Soil depth (cm)	Ca (g kg^{-1})		K (g kg^{-1})		Mg (g kg^{-1})		Cu (mg kg^{-1})		Fe (mg kg^{-1})		Zn (mg kg^{-1})	
		Sago palm	Forest	Sago palm	Forest	Sago palm	Forest	Sago palm	Forest	Sago palm	Forest	Sago palm	Forest
P3B3	10	0.96 ab	1.05 a	0.30 ab	0.40 a	1.06 ab	1.05 a	1.12 a	1.00 a	95 a	90 a	5.0 a	6.1 a
	30	0.20 ab	0.07 b	0.20 b	0.20 b	0.87 b	0.73 b	1.13 a	0.86 a	93 a	68 bc	6.4 a	5.6 a
	50	0.12 b	0.06 b	0.17 b	0.18 b	0.76 b	0.75 b	1.47 a	1.24 a	81 ab	56 c	7.3 a	6.9 a
P7B4	10	1.81 a	0.28 a	0.61 a	0.67 a	2.45 a	1.46 a	0.55 ab	0.29 b	338 ab	350 a	3.2 a	2.9 ab
	30	0.54 a	0.03 ab	0.49 a	0.51 a	1.76 a	1.26 a	0.67 a	0.44 ab	238 abc	215 bc	2.8 ab	2.5 ab
	50	0.28 a	0.06 a	0.22 a	0.32 a	1.47 a	1.30 a	0.40 ab	0.60 ab	139 c	173 c	3.0 ab	2.2 b
P8B19	10	0.72 a	0.74 a	0.53 b	0.28 b	0.86 a	0.97 a	0.00 a	0.53 a	213 a	135 ab	3.4 a	3.5 a
	30	0.14 a	0.05 a	0.34 b	0.47 b	0.63 ab	0.69 b	0.06 a	0.10 a	119 b	110 b	6.4 a	1.9 a
	50	0.17 a	0.04 a	0.16 b	0.61 a	0.61 b	0.62 b	0.26 a	0.85 a	124 ab	99 b	4.5 a	8.6 a

Values not followed by the same letter differ within each block (including both landuse types) at $P < 0.05$

those elements in soil were also likely to follow the same order (Figs. 2, 5; Table 3). However, an increase with duration after transplantation was detected not only in the K concentration but also in the Ca and Mg concentrations in canal water (Fig. 2). On the other hand, the Ca and K concentrations in canal water at sago palm cultivation blocks did not beyond those at the secondary forests (Fig. 4). This was also applicable to Mg (data not shown). Therefore, additional loads of metal elements in the surrounding water environment due to chemical fertilizer application may have happened but small.

Statistical analysis of the chemical properties of canal water indicated a negative correlation between pH and Al concentration for the seven blocks ($r = -0.52$; $P < 0.05$). In contrast, pH showed a positive correlation with Na concentration ($r = 0.65$; $P < 0.005$). Na was not applied to the field and its concentration was higher in canal water than in groundwater (Fig. 3). A possible cause of higher pH and higher Na concentration in canal water is the inflow of seawater during high tide. On the other hand, Al concentration in canal water from sago palm cultivation blocks also showed a positive correlation with DOC concentration ($r = 0.641$; $P < 0.01$). Actually, Al concentration was high in blocks from which large amounts of DOC leached out, i.e., P7B4, P4B13, and P4B18 (Fig. 2). On the other hand, pH had no significant effect on DOC concentration ($r = -0.217$). These observations suggest that both pH and DOC concentration were associated with Al load in the surrounding environment, which may be reflected in the smaller mean value and the larger SD in the proportion of Al present as organically bound form than in that of Fe (Table 2). Because time-dependent increase in DOC concentration in canal water was not observed, the increase in the concentrations of polyvalent cations having strong affinity to DOM with the development of sago palm growth was not expected.

As for Zn in river water, both of strong and weak associations with DOM have been reported (Küchler et al. 1994; Pettersson et al. 1997; Linnik 2000). According to Burba et al. (2001), the proportion of Zn that was bound to DOM in the water extract from German peat increased abruptly between pH 3.8 and 4.3. The large mean value and the large deviation in the proportion of Zn that was bound to DOM in canal water (Table 2) might be due to the variation in pH. However, the total concentration of Zn in canal water showed no correlation with water pH ($r = -0.04$). Therefore, the interaction with DOM may not be a strong factor regulating the Zn release from peat soil.

The accumulation of Cu and Zn from fertilizer application and the acceleration of Fe loss under sago palm cultivation were generally not observed. The increase in any minor nutritional element in canal water was also not detected. Possible reasons for the small or no enrichment of fertilizer components in soil include efficient absorption by plants and strong adsorption to soil organic matter at fertilizer application points. The former was disproved by the lack of significant differences in the contents of major and minor nutritional elements in sago palm leaves among treatments with various compositions of chemical fertilizers in a field experiment conducted in the same plantation (Ando et al. 2007). The latter may be applicable to polyvalent cations that can form stable complexes with humic substances such as Cu and Fe. Another possible reason is the temporary increase in the concentration of fertilizer components after the application, followed by sufficient dilution. The positive correlations ($P < 0.005$) observed between K and P ($r = 0.691$) and between B and Zn ($r = 0.729$) in the canal water may support this hypothesis for the fertilized elements that do not form stable complex with peat humic substances.

Conclusions

Comparisons of various data sets from soil and water samples disproved the notable effects of sago palm cultivation in a tropical deep peat soil on soil chemical properties and surrounding water environment for 6 or 8 years, although fertilizer application may have contributed to maintain the amounts of nutritional elements in soil and resulted in small increases of them in groundwater and canal water.

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