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The carbon content characteristics of tropical peats in Central Kalimantan, Indonesia: Estimating their spatial variability in density

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Abstract. Clarification of carbon content characteristics, on their spatial variability in density, of tropical peatlands is needed for more accurate estimates of the C pools and more detailed C cycle understandings. In this study, the C density characteristics of different peatland types and at various depths within tropical peats in Central Kalimantan were analyzed. The peatland types and the land cover types were classified by land system map and remotely sensed data of multi-temporal AVHRR composites (1-km pixel size), respectively. Differences in the mean values of volumetric C density (CD_V) were found among peatland types owing to the variability in physical consolidation from peat decomposition or nutrient inputs, although no vertical trends of CD_V were found. Using a step-wise regression technique, geographic variables and the categories of peatland type and land cover type were found to explain 54% of the variability of CD_V within tropical peatlands in some conditions.

Abbreviations: CD_V – Volumetric carbon density; TPS – Total pore space

Introduction

Sorensen (1993) estimated the total amount of carbon (C) sequestered in peat in Indonesia at 15.93–19.29 Gt (1 Gt = 10^{15} g) assuming that C content is constant at 53.44% and bulk density of 114 kg m^{-3}. Peat deeper than 6 m was not considered, this accounts for 3–4% C mass of peatland C pools (329–525 Gt) of the world (Immirzi & Maltby 1992). In Indonesia, 3.72 Mha of the total peatland (17.85 Mha, RePPProT 1990), have had some form of development. At least 0.5 Mha have been cultivated by transmigrated farmers (Maltby &

Immirzi 1996). Furthermore, the huge 1997/98 forest fires burned, not only the surface vegetation over a large areas of peat swamp forests in Kalimantan and Sumatra but also the part of the underlying peat (Page & Rieley 1998). Owing to these drastic land system changes in recent years, an enormous amount of carbon may have been released to the atmosphere from tropical peatlands. To estimate the amount of C emission after land use change and to derive accurate C pool estimates, the more detailed knowledge of the spatial variation in C content and bulk density (BD) is needed.

In some temperate-subarctic regions variability in BD and C content among different peatland types (Botch et al. 1995) or at various depths (Howard et al. 1995) have been reported and applied for the calculation of C pool estimates. A lot of efforts have been done to clarify the spatial variability in BD (e.g. Subagjo & Driessen 1974; Driessen & Rochimah 1976) or C content (e.g. Suhardjo & Widjaja-Adhi 1976; Abdullah 1997) of the tropical peats, which are mainly wood peat as opposed to sedge and *Sphagnum* moss peat in temperate-subarctic regions (Andriesse 1988; Rieley et al. 1992). BD and C content, however, have been studied separately in the previous reports and few efforts have been done to analyze BD and C content in the same peat samples. To authors' knowledge, only Neuzil (1997) published the combined data of BD and C content of tropical peats, although the values of BD were estimated from other peat samples. Combined data on BD and C content are needed to determine the value of volumetric C density (CD_V, kg m^{-3}), which are needed to estimate spatial C mass distribution. While CD_V has been used for soils (e.g. Brown & Lugo 1990; Liski & Westman 1995; Van Dam et al. 1997) and for peats in a temperate region (e.g. Minkkinen & Laine 1998) to trace the vertical C content characteristics or to measure long-term change in C density, there have been no reports using CD_V on tropical peats. The variation in CD_V with depth are potentially very important in tropical peatlands, which are often 10 m, and sometimes up to 20 m deep (Bruenig 1990; Rieley et al. 1992).

This work has done in tropical peatlands of Central Kalimantan to analyze CD_V in various peatland types, land cover types and at various peat depths. The aim of this study is to clarify the spatial variability in CD_V in tropical peatlands and to estimate the CD_V in tropical peats from the geographical position.

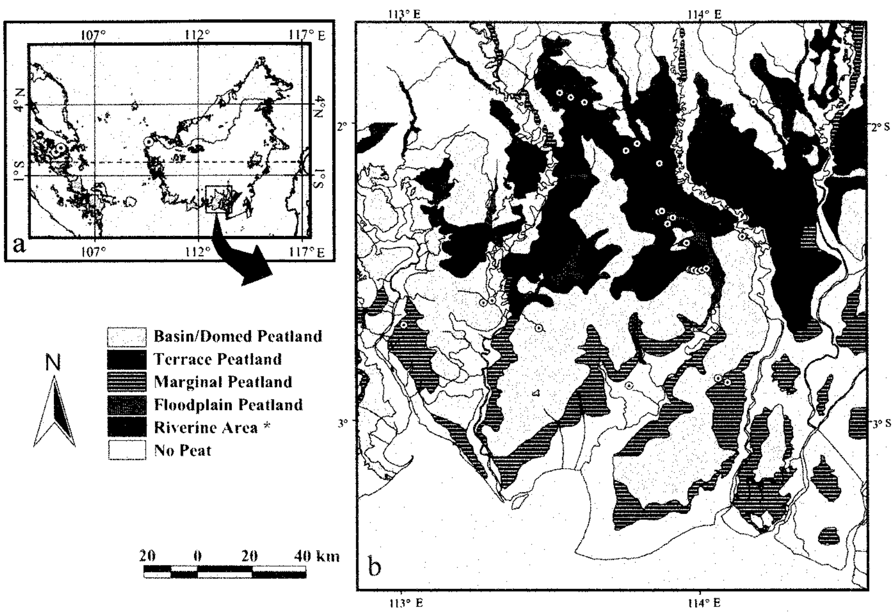

Figure 1. (a) Peatland distribution in Sumatra and Kalimantan, modified from the Digital Chart of the World (ESRI 1993). (b) Peatland type map of Central Kalimantan, modified from RePPProT (1985). The circled points indicate plots of peat core (cf. Table 2). * Riverine peatlands exists in some depression areas within riverine areas.

Materials and methods

Study sites and peatland classification

Seventy-five percent of the total Indonesian peatland area occur in Sumatra and Kalimantan (RePPProT 1990). Most of the peatlands lie in coastal lowlands within five degrees of the equator (Figure 1(a)). We selected study sites in Central Kalimantan (Figure 1(b)), which holds 15% of the total Indonesian peatland area (calculated from: ESRI 1993 and RePPProT 1990). The climate of Central Kalimantan is humid tropical; mean annual temperature varies between 25–27 °C and the mean annual precipitation varies between 2300–3000 mm (Boerema 1931; BAPPEDA 1993; Asdak 1995; Takahashi & Yonetani 1997). Evapotranspiration exceeds precipitation in less than three months per year (Neuzil 1997).

Based on the land system map of Regional Physical Planning Programme for Transmigration (RePPProT 1985), we classified the peatland types of Central Kalimantan into terrace, basin/domed, riverine, floodplain and marginal peatland (Table 1; Figure 1(b)). The study sites were located in five different peatland types (Table 2, Figure 1(b)). Data of plot PK3 (Neuzil

1997) were added as terrace peatland type (Table 2, Figure 1(b)). For comparison, some data of Riau (BK5, SK6), Sumatra and Keramat (WK3), West Kalimantan (Neuzil 1997) were also studied (Table 2, Figure 1(a)). Since the base of the peat deposits BK5, SK6 and WK3 are at ca. 0 m a.s.l., we categorized these peatlands as coastal peatlands (Table 1) according to the previous category based on the topographical location (Andriesse 1974; Anderson 1983; Rieley et al. 1996). The elevation, the distance from the nearest river and from the nearest sea coast at each study site was calculated from data by Moore et al. (1992, 1996), Supardi et al. (1993), Neuzil et al. (1993), Neuzil (1997), the map of BAKOSURTANAL (1993), and the Digital Chart of the world (ESRI 1993) (Table 2).

Different sets of forest types of tropical peatlands have been distinguished in northern Borneo and Sumatra (Anderson 1975, 1983) and Kalimantan (Shepherd et al. 1997). However, it is difficult to extend the types to our whole study areas because of the regional differences of the types (Rieley & Ahmad-Shah 1996) and of the species richness within the types (Anderson 1976). For this reason, we used multi-temporal remotely sensed data to classify land cover types of tropical peatland in Kalimantan and Sumatra. Since the classification using the thermal band indices were acceptable in the tropics (Foody et al. 1996), classification based on the ratio of T_s (surface radiation temperature) and NDVI (Normalized Difference Vegetation Index) in the period of 1992–1993, i.e. before the large scale forest fire occurred in 1994, were used in this study. The 10-days composite data (Apr. 1992–Sep. 1993; NDVI, channel-4, channel-5) of 1-km $\times$ 1-km NOAA-AVHRR (Advanced Very High Resolution Radiometer) over Sumatra-Kalimantan area were acquired from EROS (Earth Resources Observations Systems) Data Center (cf. Eidenshink & Faundeen 1994). T_s was calculated using the following equation by assuming the surface emissivity to be 0.96 (Nemani et al. 1993): $T_s = T_{c4} + 3.3(T_{c4} - T_{c5})$, where T_{c4} and T_{c5} are brightness temperature (K) of AVHRR channel-4 and channel-5, respectively. The maximum T_s and maximum NDVI ratio (T_s/NDVI) (cf. Lambin & Ehrlich 1995) was calculated for every monthly period (18 months) from the 10-days composite data, and smoothed by moving median (3 months). Five principal components (PCs) (83% of the variance) were selected after principal component analyses (PCA) were performed on those multi-temporal (16 months) data of monthly T_s/NDVI. The unsupervised classification (ISODATA algorithm) (cf. Tou & Gonzales 1974) was conducted on the PCs, then the land cover types of the study sites were determined (Table 2) after smoothing the classified map by majority filter.

Table 1. General description, mineralogy and altitude of each peatland type in the tropics.

Peatland type	General description	mineralogy	Altitude (m a.s.l.)
Riverine	Swampy floodplains mainly within terraces	Peat, Recent alluvium (riverine)	0–43
Terrace	Peat-covered sandy terraces	Peat, Old alluvium (sand)	5–50
Basin/Domed	Peat basins or domes	Peat	2–10
Marginal	Peat basin margins	Peat, Recent alluvium (riverine, estuarine/marine)	1–5
Floodplain	Alluvial floodplains between swamps, Permanently waterlogged plains, others†	Peat, Old alluvium (sand), Recent alluvium (riverine, estuarine/marine)	2–10
Coastal*	Coastal peatlands of the maritime fringe and deltas	Peat, Recent alluvium (estuarine/marine)	1–5

All the criteria are modified from RePPProT (1985) except for with the asterisked (*), which is modified from Rieley et al. (1996).
†The sites where temporarily (in the wet seasons) waterlogged were also categorized as floodplain peatlands even though categorized as different peatland types on the Peatland Type Map (Figure 1) (cf. Table 2).

Table 2. Characteristics of the study sites and their corresponding peatland types of Central Kalimantan and coastal peatlands in Sumatra and West Kalimantan.

Site	Latitude	Longitude	Elevation (m a.s.l.)	Peatland type	*N*	Peat Depth (m) [Min]	[Max]	Mineral layer below peat	Distance from river (km)	Distance from sea (km)	Land cover type
Lahei‡	1° 56′ S	114° 11′ E	34*	riverine	9	[1.2]	[7.5]	sand‡	0–0/5	149–150	6
Setia Alam Jaya‡	2° 19′ S	113° 54′ E	12*	terrace	3	[1.8]	[4.1]	sand‡	14–45	97–100	6, 7
Marang	2° 06′ S	113° 46′ E	18*	terrace	1	3.0		sandy clay‡	1	124	7
PK3[a]	2° 06′ S	113° 45′ E	25 (31*)	terrace	1	6.4		sandy clay	7	120	6
Petukketimpun	2° 08′ S	113° 53′ E	14*	terrace	1	1.8		sandy clay‡	1	118	6
Hampangen	1° 07′ S	113° 29′ E	37*	terrace	3	1.0		sandy clay‡	10	127	9
	1° 06′ S	113° 32′ E	37*			5.1		sand‡	11	128	6
	1° 04′ S	113° 37′ E	41*			3.1		sand‡	6	129	6
Tumbangnusa	2° 21′ S	114° 08′ E	14*	basin/doomed	1	3.7		sandy clay‡	1	99	11
Pankoh-B	2° 52′ S	114° 04′ E	20*	basin/doomed	1	5.9		clay‡	12	46	13
Pankoh-M	2° 52′ S	114° 05′ E	17*	marginal	2	[2.4]	[5.3]	clay‡	10	45	11
Tanjung Mas	2° 40′ S	113° 00′ E	13*	marginal	2	[3.8]	[4.1]	clay‡	30–36	29	7, 8
UP-SBG	2° 18′ S	113° 52′ E	12*	floodplain**	2	[0.5]	[5.0]	sandy clay‡	0	100–101	6, 8
Bakung	2° 24′ S	113° 56′ E	12*	floodplain**	1	9.7		sand‡	0	93	9
Rasau	2° 29′ S	114° 00′ E	12*	floodplain**	6	[2.5]	[4.5]	clay‡	0–0.5	86–87	8
Kajangpamali	2° 36′ S	113° 16′ E	14*	floodplain**	3	[0.5]	[5.6]	clay‡	0.5–1.1	46–48	6
Musang	2° 41′ S	113° 27′ E	16*	floodplain**	2	[2.5]	[5.2]	clay‡	0	53	6
Paduran	2° 53′ S	113° 46′ E	9*	floodplain**	1	1.2		clay‡	2	36	11
WK3[b]	1° 25′ N	109° 09′ E	9	coastal	1	6.5		clay	5	11	8
BK5[c]	1° 32′ N	102° 05′ E	9	coastal	1	8.0		clay	4	4	9
SK6[c]	1° 40′ N	102° 02′ E	14	coastal	1	13.7		clay	9	9	10

N: number of coring point.

*Values are interpolated from BAKOSURTANAL (1997). ‡observed in the field.

**The sites where temporarily (in the wet seasons) waterlogged were also categorized as floodplain peatlands even though categorized as different peatland types on the Peatland Type Map (Figure 1).

Compiled from references as follows

[a]Moore et al. (1996), Neuzil (1997). [b]Moore et al. (1992); Neuzil et al. (1993), Neuzil (1997). [c]Neuzil et al. (1993), Supardi et al. (1993), Neuzil (1997).

‡The forest type of Setia Alam Jaya site is mixed swamp forest or pole forest dominated by *Calophyllum hosei, Palaquim cochlearifolium*, *Parastemon spicatus*, and *Combretocarpus rotundatus* (Shepherd et al. 1997). The vegetation of Lahei site is dominated by *Shorea balangeran*, *Semecarpus* sp., *Buchanania* sp. (Suzuki et al. 1998).

Methodology

Peat samples were collected from undisturbed (virgin or secondary forested) peatlands in July–August 1997–1999. The geographic location of the sampling points was determined by GPS. Peat cores were taken from the surface to the base of peat layer using half cylinder type Eijkelkamp peat core sampler (cf. Neuzil et al. 1997) with a bulk capacity of 400 cm^3. However, it was impossible to sample the entire peat layer from one bore hole because of the presence of hard woody materials or fragmented samples which might be disturbed by the sampler. Thickness of peat layer was also measured with the sampler. Intact parts of cores were divided into samples of 40 cm^3 pieces and sealed in plastic bags for analysis. The samples were weighted, oven-dried at 90 °C over 24 hours, and stored for the analysis. Water content (WC) of a fresh peat sample was determined after measuring dry peat mass. Dry bulk density (BD) was calculated by dividing dry peat mass by fresh volume of the sample. Loss on ignition (LOI) of dry mass was measured after 550 °C (ca. 5 h) combustion by electric muffle furnace. C content (CC) of dry mass was measured by CHN Elemental Analyzer (Elementar Vrio EL). Total pore space (TPS) was estimated by the equation: $TPS = 1 - BD \times (LOI/SD_P + (1 - LOI)/SD_A)$ (cf. Driessen et al. 1976). We assumed the specific density of peat (SD_P) and ash component (SD_A) to be 1430 kg m^{-3} and 2650 kg m^{-3}, respectively (Driessen & Rochimah 1976). Volumetric C density (CD_V) was calculated by the equation: $CD_V = BD \times CC$. Sandy or clayey layers recognized in the field, we categorized these layers separately as such. Material with LOI lower than 65% was also attributed to as sandy/clayey layers (cf. Sorensen 1993) even though we did not categorize them as such in the field. Material with LOI lower than 50%, occurred only near the bottom of peat layers and was defined as mineral subsoil (cf. Immirzi & Maltby 1992). Large quantities of undecomposed woody fragments are present heterogeneously in tropical peats (cf. Anderson 1964; Yonebayashi et al. 1992). We categorized layers as ‘woody’ for 40 cm^3 samples that contain wood debris more than 50% wood debris by volume. Sampling depths were normalized by setting the peat thickness at each sampling points at 1.0 to facilitate comparison of vertical CD_V trends among peatland types (Figure 3). ANOVA (Sheffé’s test) was used to determine differences between mean values of CD_V among peatland types. Step-wise multiple regression analysis was conducted to estimate CD_V from the Geographic factors, peatland types and land cover types except for riverine peatland, which location is specific and not consecutive to the other peatland types (cf. Figure 1(b)).

Results

Input of sand or clay significantly changes the peat characteristics, by decreasing WC, TPS and CC, and increasing BD and CD_V. Yet mean CD_V value of sandy/clayey layers is not significantly different from that of floodplain peatland (Table 3, Figure 4). Sandy/clayey peat layers may occur throughout the peat column in riverine peatland, while they occur only near the bottom (normalized depth > 0.6) in other peatland types (Figure 2).

Woody peat sample occurred throughout the peat column except near the surface (Figure 2). From the number of samples (*n*, Table 3), woody peat sample was common in marginal (84%) and basin/domed (53%) peatland, and less in terrace (16%) and floodplain (12%) peatland. There was no information about the existence of woody layer at coastal peatlands (Neuzil 1997). There were no peats defined as woody layer at riverine peatland, although small pieces of wood debris were observed in the field. Without distinguishing these woody layers, no significant relationships within each peatland type were found between volumetric C density (CD_V) of pure (not woody) peat layers and normalized peat depth except for riverine peatland ($r = –0.37$, $P < 0.05$; Figure 3). Woody layers and pure peat layers have similar values of WC, TPS, BD, and CD_V in basin/domed and marginal peatland, but showed clear differences ($P < 0.05$) between woody layers and pure layers of terrace and floodplain peatland (Table 3; Figure 4).

Mean value of TPS and CD_V were significantly different between terrace-floodplain peatland type and coastal-marginal peatland type. Difference of mean CC value was only significant between terrace and floodplain peatland. No significant different mean values of WC and BD among peatland types were found (Table 3).

The strong relationships, which have been previously reported (e.g. Päivänen 1976), between peat BD and TPS ($r^2 = 0.95$) and between CD_V and TPS ($r^2 = 0.85$), were also found in this study (Figure 5). The coefficient of determination of CD_V versus BD was lower ($r^2 = 0.72$). The variables of peat thickness, peatland type, land cover type, and geographic factors (altitude of peat layer, distance from nearest river and sea) explained 54.0% (or, with adjusted r^2 statistics, 50.8%) of the variability of CD_V, although woody layers of terrace and floodplain peatland were not taken into consideration (Table 4).

Table 3. Peat characteristics of different peatland types in Central Kalimantan and coastal peatland. Values are the mean ±S.D. Values followed by the same letter are not significantly different at the $P < 0.05$ significance level. ANOVA was not conducted to the values with parentheses.

Peatland Type	n	n_{SC}	Water content	Carbon Content	Total pore space	Dry bulk density	Volumetric carbon density
			(fresh mass)	% (dry mass)	(fresh volume)	kg m^{-3}	
Riverine	31	26	87.9 ± 3.2^{a}	55.5 ± 4.2^{bc}	92.1 ± 1.8^{efg}	117 ± 27.5^{h}	64.5 ± 14.0^{jk}
Terrace*	67	1	88.5 ± 3.3^{a}	56.7 ± 5.1^{b}	92.1 ± 1.8^{fg}	124 ± 31.3^{h}	71.5 ± 17.3^{j}
(woody)	(11)		(91.2 ± 1.6)	(58.9 ± 5.7)	(93.5 ± 1.5)	(95.6 ± 21.7)	(56.3 ± 13.8)
(pure†)	(56)		(88.1 ± 3.3)	(56.4 ± 5.0)	(91.0 ± 2.0)	(130 ± 19.7)	(74.4 ± 16.3)
Basin/Domed	15	0	91.1 ± 2.1^{a}	57.0 ± 4.5^{bc}	93.3 ± 1.5^{def}	98.4 ± 22.3^{h}	55.8 ± 8.7^{kl}
(woody)	(8)		(91.0 ± 2.3)	(55.9 ± 4.4)	(93.3 ± 1.5)	(99.2 ± 25.6)	(54.6 ± 10.9)
(pure†)	(7)		(91.2 ± 1.7)	(58.3 ± 4.4)	(93.2 ± 1.2)	(97.4 ± 17.8)	(57.2 ± 4.9)
Marginal	32	3	91.3 ± 1.9^{a}	56.6 ± 3.9^{bc}	93.8 ± 1.5^{de}	94.9 ± 25.2^{h}	53.6 ± 12.5^{kl}
(woody)	(27)		(91.3 ± 2.0)	(55.9 ± 3.8)	(93.9 ± 1.6)	(95.1 ± 27.2)	(53.1 ± 13.5)
(pure†)	(5)		(91.6 ± 0.5)	(60.3 ± 1.5)	(93.7 ± 0.3)	(93.4 ± 6.5)	(56.2 ± 3.8)
Floodplain	57	2	87.9 ± 2.9^{a}	52.5 ± 8.0^{c}	90.4 ± 2.9^{g}	141 ± 35.1^{h}	72.9 ± 16.2^{ij}
(woody)	(7)		(89.9 ± 1.4)	(50.4 ± 10.3)	(92.9 ± 1.0)	(114 ± 17.7)	(57.2 ± 13.0)
(pure†)	(50)		(87.6 ± 2.9)	(52.8 ± 7.6)	(90.1 ± 2.6)	(145 ± 35.3)	(75.1 ± 15.3)
Coastal**	29	0	90.9 ± 2.3^{a}	57.3 ± 2.8^{b}	94.2 ± 0.8^{d}	84.1 ± 11.5^{h}	48.7 ± 6.3^{l}
Sandy/Clayey layer		32	78.8 ± 10.7	44.3 ± 8.0	88.4 ± 2.5	264 ± 163	83.6 ± 18.7^{i}
Woody peat (total)	(53)		(91.0 ± 2.0)	(55.8 ± 6.1)	(93.6 ± 1.5)	(98.6 ± 25.6)	(54.5 ± 13.2)

n: number of samples; n_{SC}: number of sandy/clayey layer samples.
†Samples without woody, sandy, clayey peat layers.
*Some data (n = 9) are adapted from Neuzil (1997); **All the data are adapted from Neuzil (1997).

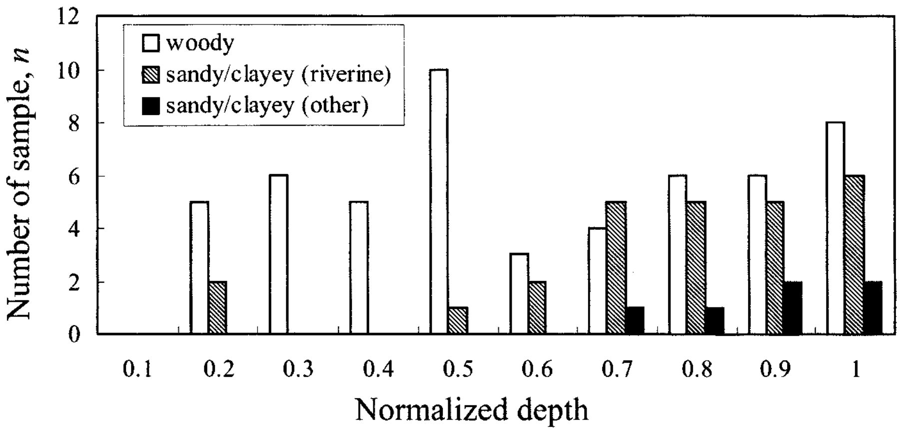

Figure 2. Vertical frequency of occurrence of woody peat samples (n = 32), and of sandy/clayey peat samples within riverine peatland (n = 16) and at other peatland types (n = 6).

Discussion

Characteristics of volumetric carbon density

From the correlations of CD_V versus TPS (r^2 = 0.85) and BD (r^2 = 0.72), the different CD_V values among peatland types could be explained by differences in TPS. This indicates that only physical consolidation contributes to the value of peat CD_V. Inputs of mineral components due to rises flooding may have caused the physical consolidation on the peats of floodplain and riverine peatland. This aspect agree well with Parton et al. (1987) and Brown and Lugo (1990), who have reported that soil texture, particularly the silt plus clay content, and biotic factors play a role in the differences in C density among soil types. The degree of physical consolidation in pure peat layer may seem smaller in terrace than floodplain peatland (Figure 4). However, similar mean values and the 95% confidence intervals ($\pm$1.96 $\times$ SE) of CD_V were due to the higher carbon contents in terrace peatland (Table 3). These results suggest that the formation of C consolidation in terrace peatland, which is thought to be ombrogenous (Neuzil 1997; Shepherd et al. 1997), is different from that in floodplain peatland. Since it is difficult to apply the soil taxonomy for tropical peats (Vijarnsorn 1986), we have not done any test to check the degree of peat decomposition. However, it is clear from the lower TPS (Table 3, Figure 4) and the lower frequency (16%) of woody layers (Table 3) that terrace peat is more decomposed than coastal, marginal, and basin/domed peat, which are also ombrogenous (cf. Neuzil 1997).

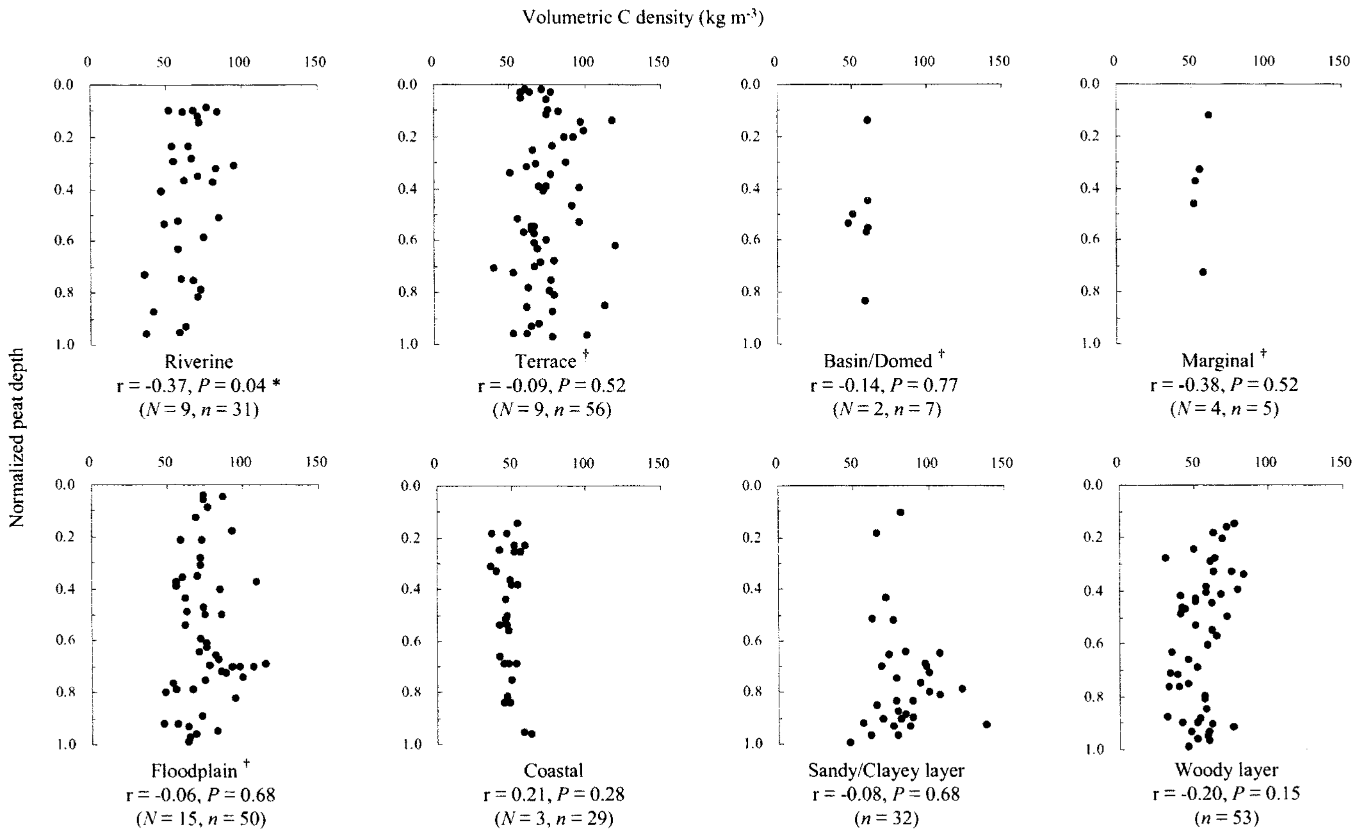

Figure 3. Variations in volumetric C density with normalized peat depth for all peatland types († without woody layer), sandy/clayey layer, and woody layer. r: correlation coefficient of volumetric carbon density versus normalized peat depth; P: p-value; N: number of coring points; n: number of samples.

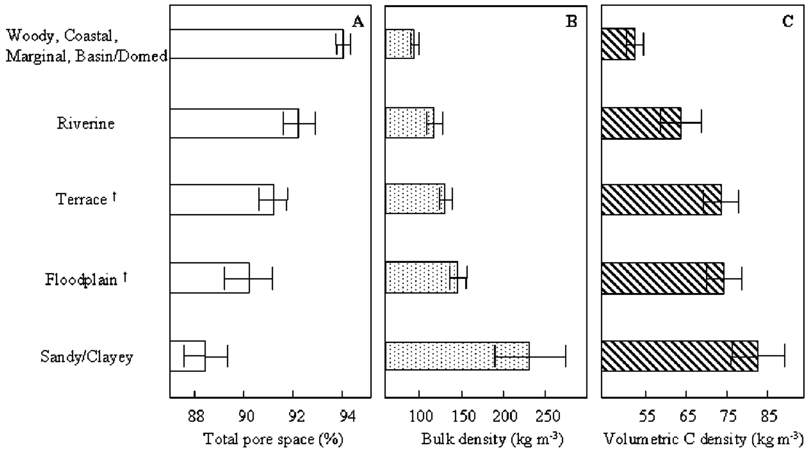

Figure 4. Mean (±95% confidence interval) total pore space (A), bulk density (B), and volumetric C density (C) of peats between peatland types of riverine, floodplain, terrace († without woody layer), sandy/clayey layers and a combined category of basin/domed, marginal and woody layers.

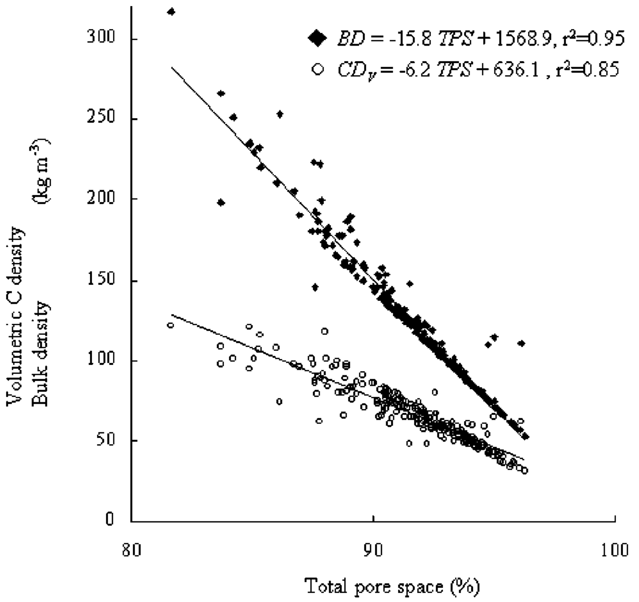

Figure 5. Scatter diagram of volumetric C density and bulk density against total pore space.

Table 4. Regression model using stepwise regression procedure, with a variability of volumetric C density of 54.0% (adjusted 50.8%).

Variable	Coefficient	S.E.	Standardized estimate of coeff.
Constant	49.89	4.75	
Distance from seacoast (km)	−0.13	0.11	−0.30
Distance from river (km)	−0.8	0.80	−0.15
Altitude (m)	1.09	0.32	0.42
Thickness of peat (m)	−0.016	0.0063	−0.25
Floodplain peatland*‡	36.67	5.62	0.92
Terrace peatland*‡	25.10	9.25	0.65
Basin/domed peatland*	12.44	8.28	0.19
Coastal peatland*	18.03	5.46	0.37
Land cover type 7*	9.37	3.30	0.22
Land cover type 8*	−7.59	3.40	−0.18
Land cover type 9*	−9.62	4.83	−0.13
Land cover type 13*	20.22	8.90	0.20

$r^2 = 0.540$; r^2 (adjusted) = 0.508.
$F(12,169) = 16.544$, $P < 0.001$.
*Peatland types and land cover types were included as dummy variables (1: included, 0: not included).
‡Woody peat layers were not taken into consideration for the regression model.

The variances on the values of CD_V, BD, and TPS within a combined category of woody layer, coastal, marginal, basin/domed peatland were smaller than the other well-consolidated peatland categories (Figure 4). This result can be explained from the vertical heterogeneity in degree of decomposition. The existence of woody layers, with an extremely low degree of decomposition, enlarges the variances of the CD_V and other peat physical characteristics within the well-consolidated peatlands (Table 3).

From studies in temperate peatlands (e.g. Howard et al. 1995; Robinson & Moore 1999) where BD increases with increasing peat depth, we expected CD_V to increase with increasing peat depth. However, we found no such relationships except in riverine peatland (Figure 3). Driessen and Rochimah (1976) reported that decomposition of Kalimantan peats has virtually stopped below depths of 60–80 cm and that the subsoils contain less decomposed material than the surface layers unlike most peats in temperate regions. This may explain the absence of woody layer near the surface, i.e. normalized depth < 0.1 (Figure 2), and the negative correlation coefficients between the variables of normalized peat depth and CD_V within the most of the peatland types, although the correlation was not significant ($P > 0.05$) except for riverine peatland.

Volumetric carbon density of terrace peatland in relation to the geomorphic history

From the topographic characteristics of each peatland type (Table 1, Table 2), the peatlands stretch continuously from Java Sea thorough coastal, marginal to basin/domed and terrace peatland toward ca. 100 km inland of Kalimantan (Figure 6). Sieffermann et al. (1988) reported the existence of high peatland, developed on podzolic terraces and formed earlier (ca. 10000–5000 before present: BP) than the other peatlands (ca. 6000–2000 BP; i.e. after the Daly's transgression) that were described by e.g. Andriesse (1974), Tejoyuwono (1979), and Anderson (1983). This type of peatlands developed on white sandbars was also described in Brunei (Furukawa 1988; Bruenig 1990) or Sumatra (Furukawa 1994). High peatlands occur in low altitude watershed positions (10–30 m a.s.l.) between major river systems (Rieley et al. 1996). These topographic characteristics of high peatlands coincide with those of terrace peatland (Table 1), although the distribution of high peatlands does not match completely with the map (Figure 1) of terrace peatlands (cf. Sieffermann et al. 1988). However, the sampling plots of Marang, PK3, Petukketimpun and Hampangen are within the high peatland area (cf. Sieffermann et al. 1988), the sampled cores of terrace peatland in this study might reflect the characteristics of older peats. Sieffermann et al. (1988) indicated that these old terrace peat deposits stopped accumulating ca. between 5000–2500 BP and are in the process of decomposition. Hence, the C consolidation from the longer decomposition period may attribute to the greater CD_V value of terrace peatland. On the other hand, the better drainage of the terrace peatlands, from their higher topographic position and higher permeability of mineral subsoils, may be another possibility of the higher CD_V (cf. Minkkinen & Laine 1998). However, no differences in the structure of the peat dome, the slope, and the water table (cf. Rieley et al. 1996; Takahashi & Yonetani 1997) between terrace peatlands and the other ombrogenous peatlands have been found, so the effect of longer anaerobic decomposition seems to be more acceptable reason for the higher CD_V value of terrace peats.

Estimating volumetric carbon density from geographic factors

The main objective of this study was to estimate the variability of tropical peat CD_V in Central Kalimantan. For this purpose, geographic factors that might relate to the CD_V value were used as variables for a step-wise multiple regression analysis (Table 4). The most important geographic variable was

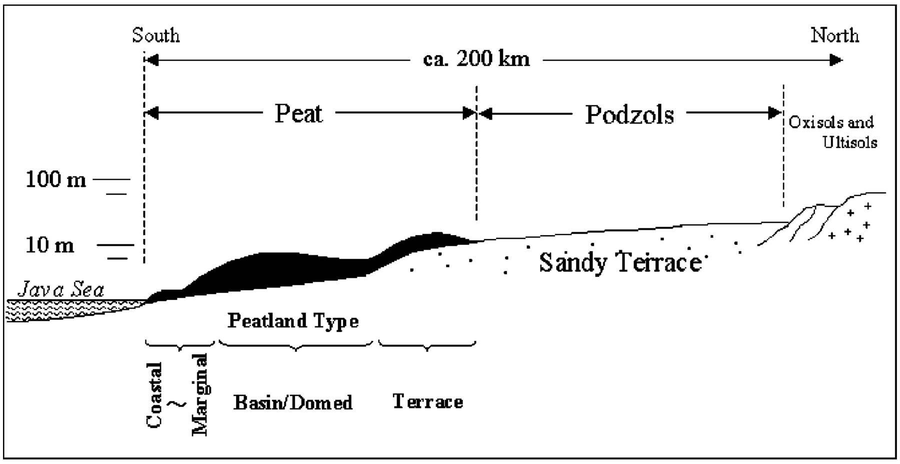

Figure 6. Schematic model for longitudinal section of Central Kalimantan (modified from: Sieffermann 1990) superimposed by the distribution of peatland types (cf. Table 1).

altitude of the peat layer, which derived by subtracting the depth of sampling peat layer from the elevation of the location, within one area of combined category of peatland types and land cover types, which were included as dummy variables in the model. Negative coefficient of the variable of distance from river agrees with the fact that lower value of BD near the top of peat dome (e.g. Driessen & Rochimah), which develop between rivers. It is clear from the regression model that decision of peatland type is the most important factor in estimating CD_V. Decision of land cover type is also found to be an important factor to estimate CD_V value. The reason for this is probably that differences in vegetation is a good indicator for the CD_V differences due to the mineral richness and increase of effective capillary pore system from TPS increase (Päivänen 1976). In this study, land cover types classified by the remotely sensed data were used as an index of the vegetation differences. Although the verification of the land cover type by the ground truth data could not be done, we found that the CD_V differs among vegetation types as well as peatland types. The regression model (Table 4) can explain 54% of the variability in the value of CD_V. However, the model cannot predict the woody layers in terrace (16% frequency) and floodplain (12% frequency) peatland. If all the woody layers are included for the step-wise regression model, coefficient of determination (r^2) would by down be 44.9% (or, with adjusted r^2 statistics, 41.0%).

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