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Drainage and land use impacts on changes in selected peat properties and peat degradation in West Kalimantan Province, Indonesia

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Abstract. Degradation of tropical peats is a global concern due to large Carbon emission and loss of biodiversity. The degradation of tropical peats usually starts when the government drains and clears peat forests into open peats used for food crops, oil palm and industrial timber plantations. Major properties of tropical peat forests are high in Water Contents (WC), Loss on Ignition (LOI) and Total Organic Carbon (TOC), and low in peat pH, Dry Bulk Density (DBD), and Total Nitrogen (TN). In this study, we investigated impacts of drainage and land use change on these properties. We collected peat samples from peat forests, logged over peat forest, industrial timber plantation, community agriculture, and oil palms. We used independent t-tests and oneway ANOVA to analyze mean differences of the research variables. We found that peat pH, DBD, and TN tend to increase. A significant decrease of C/N ratio in oil palm and agriculture sites importantly denotes a high rate of peat decompositions. Water contents, LOI, and TOC are relatively constants. We suggest that changes in pH, DBD, TN and atomic C/N ratio are important indicators for assessing tropical peat degradation. We infer that land use change from tropical peat forests into cleared and drained peats used for intensive timber harvesting, oil palms and industrial timber plantations in Indonesia has greatly degraded major ecological function of tropical peats as Carbon storage.

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1 Introduction

Land use change and tropical peat degradation are commonly discussed from a perspective of Carbon emission (Page et al., 2004; Hooijer et al., 2010; Miettinen and Liew, 2010). Most studies in tropical peats were based on remotely sensed data (Jaenicke et al., 2008), and general models of Carbon emissions associated with land use change and peat degradation (Page et al., 2004). A study focusing on direct measurements of peat properties associated with drainage and land use changes is not common. Therefore, we conducted this study by investigating peat properties in peat forests, industrial timber, oil palm plantations, and community agriculture. We aim to discuss impacts of drainage and land uses on selected peat properties and peat degradation in West Kalimantan Province, Indonesia. We also suggest important indicators of peat properties that could be used to indicate tropical peat degradation due to drainage and land use change. We also believe that global climate change leading to more

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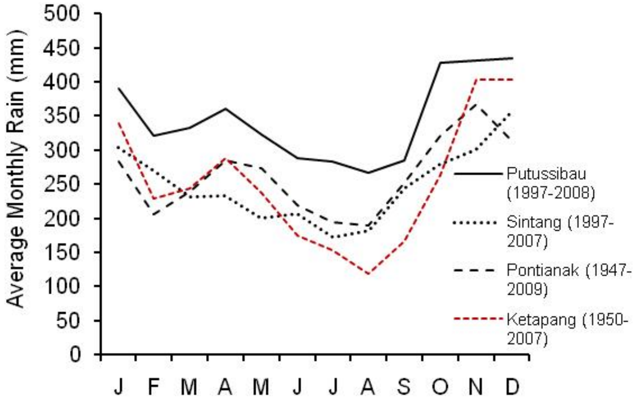

Fig. 1. The average monthly rain from selected climate stations in the West Kalimantan Province (Source: BMKG Supadio, unpublished, 2010).

rainfall variability in Borneo in the future would enhance the degradation of tropical peats (Li et al., 2007).

Peat degradation is characterized by a change of physical, biological and chemical properties leading to functional deterioration and ecological decline that harms environment and socio-economy development. Therefore, peat degradation is definitely a complex process associated with land uses and social perspectives. Unwise land uses drive significant changes of physical, biological and chemical properties towards peat degradation, and an increase of Carbon emission from land use change.

The underlying causes of peat degradation are commonly land use conversion from peat swamp forests into agriculture and other uses. As peat growth depends on inputs of fresh vegetation biomass, the removals of peat forming vegetation directly reduce the deposit of vegetation biomass into peat profile. Without consistent input of vegetation biomass, peats stop to grow (Moore, 1989; Clymo, 1984, 1991). In addition to vegetation removals, the peat forest conversion is usually associated with the construction of drainage canals that lower water table depths for creating favourable medium for growths of crops. A decomposition rate in drained peat with low water table depth is more rapid than in water-saturated peat with high water table depth. The decline of water table depths increases the thickness of oxidative layer (acrotelm), which is rich in oxygen (aerobic), fresh litter and moist. The acrotelm is active and more favourable for decays than the permanent water-logged layer (Catotelm).

2 Regional setting

West Kalimantan Province (±146 000 km^2) has predominantly lowlands, flat topography, swamps, and rivers. This region is rich in biodiversity living in both terrestrial and aquatic ecosystems.

Table 1. Peat Distribution and Associated Peatland Draining Rivers in West Kalimantan Province (Source: Modified from BPS Kalimantan Barat, 2007).

Region/Distirct	Peat Area (km^2)	River Catchments
Kapuas Hulu	3225	Upper Kapuas
Sintang	789	Upper Kapuas
Sekadau & Sanggau	967	Mid Kapuas
Landak	1142	Mid and Lower Kapuas
Pontianak, Kubu Raya & Pontianak Municipality	3845	Lower Kapuas
Subtotal	9968	
Ketapang	6275	Pawan
Bengkayang	347	Sambas
Sambas	706	Sambas
Mempawah	300	Mempawah
Total	17 597	

The climate of West Kalimantan is ever-wet all the year (see Fig. 1). The annual rain is highly abundant ranging from 3000 to 5000 mm, and the evaporation is around 1500 mm per year. This wet tropical climate supports the development of water surplus, humid, and water-saturated environment. Lowlands, flat topography and ever wet tropical climate favour peat formations. According to USDA soil taxonomy, peat belongs to Histosol that largely contains organic soil materials at least 40 cm depth (Soil Survey Staff, 2010).

Indonesia has approximately 183 176 km^2 of tropical peats (Agus and Subiksa, 2008), or almost 5% of the world peats. In tropical regions, Indonesia has the largest tropical peat deposits, which are mainly distributed in Kalimantan (Borneo), Sumatra and Papua. A total estimate of 17 500 km^2 of peats occurs in West Kalimantan Province (see Table 1).

The distribution of peats in this province greatly associates with rivers, lakes, and inundated depression region. The Kapuas River (1145 km) runs from Pontianak through the Kapuas Hulu Ranges, covering about 100 000 km^2 catchments area or equal to 68% of the total area of the province. Other major rivers are the Pawan (197 km), Sambas (233 km) and Mempawah (<100 km).

There are three types of peat genesis. These consist of coastal, basin and high peats. Coastal peats occurs near sea level (1–2 m a.s.l.), and are usually shallow (<3 m), with close association with mangroves, brackish water, and tidal influences. Further, inland along the river valleys with the altitudes between 5 and 20 m, basin peat domes occur. Podzolization in the mineral substratum supports the development of water-logged environment. Tides influence the periphery of basin peat dome, and the centre of dome is commonly flat, and seasonally flooded by rain water. Small hills and rivers may cut basin peat dome. High peats occur in

Table 2. ^{14}C and Calibrated Calendar Ages of coastal peats from the lower Kapuas River basin.

No	Lab Code	Depth (cm)	σ^{13}C (‰)	% Modern	Peat Age ± SD	Calibrated Date (Cal Yr BP)[1]	
					(^{14}C Yr BP)	Mean ± SD	Median
1	Wk26756	40	−29.9 ± 0.2	92.4 ± 0.4	631 ±33	607 ±34	599
2	Wk26758	440	−29.7 ± 0.2	62.4 ± 0.3	3175±39	3402±38	3401
3	Wk 26757	700	−28.2 ± 0.2	62.4 ± 0.3	3784±40	4164±73	4163
4		450*			3590±60	3896±90	3896
5		580*			3410±40	3665±63	3661
6		700*			3600±60	3911±90	3910
7		700*			3410±60	3668±86	3664

* The last four age is adopted from Diemont and Supardi (1987).
[1] The conversion of ^{14}C age into Calendar year age was done by Oxcal 4.1 program (Ramsey, 2010).

the depressions at altitude greater than 20 m a.s.l. Sometimes, high peats are marginally developed between hills or undulating terrains of the upper river basin. High peats may form small domes, with variability of depths. The formation of hard-pan in the mineral substratum maintain inundated environment.

Biomass deposit into peat profile suffers from decomposition, and it is only between 5 and 10% of the biomass are preserved into peat. Water-logged environment, poor nutrients and low pH inhibit the growth of decomposers. High lignin content in the peat forming vegetation species slows biological and chemical decomposition.

In coastal regions of the rivers, coastal peats commonly occur in a variety of dome shapes on former sea beds (Diemont and Supardi, 1987). In the upper Kapuas river basin, inland peat formation is very complex, occurring on former lake beds and several depression areas between small hills. It is common that distribution of inland peats in the upper Kapuas River is marginally scattered and these peats form a variety of small peat domes, which may range from 1 to 10 km^2 (Anshari, 2009).

The formation of peats is very complex processes of incomplete decays of organic matters under anaerobic environment. Peat accumulation occurs when the decay rate is lower than the preservation rate. Therefore, a consistent input of partially decayed organic matters should be maintained in order to favour peat accumulation. When the decay rate is rapid and high, peat does not grow but suffers from decomposition that turns the organic matters into gases and dissolved organic acids and substances.

Selected radio Carbon ages of tropical peats in Kalimantan and Peninsular Malaysia are so variable, spanning from 30 000 to hundreds of years (Anshari et al., 2001, 2004; Page et al., 2004; Wüst and Bustin, 2004; Wüst et al., 2008). The radio Carbon analysis indicates that coastal peat in the Kapuas River basin is formed around 3000–4000 years BP (see Table 2). The basal dates show that the formation of peats in this coastal region of West Kalimantan probably occurred at the same time (Diemont and Supardi, 1987).

In contrast, the peat age from the upper Kapuas River basin is very much older than peats from the lower Kapuas River basin. Anshari et al. (2004) reported that the age of peat from Danau Sentarum National Park in the upper Kapuas River is greater than 30 000 yrs BP (see Table 3). Further, a basal radio Carbon date of peat from Sebangau National Park is 20 000 yrs BP (Page et al., 2004). In Tasek Bera Basin, peat dates range from 3400 to 20 000 yrs BP (Wüst and Bustin, 2004). More radio Carbon dates are required in order to detect the initiation of peats in this region. Also, it is important to note that peat formations are intermittently in several phases of accumulations and decays of organic matters (Anshari et al., 2004). The rates of peat accumulation in Kalimantan and Tasek Bera of Peninsular Malaysia are estimated to occur from 0.1 to 2.5 mm yr^{-1} (Wüst and Bustin, 2004; Page et al., 2004; Hope et al., 2005).

3 Methods

3.1 Sample collection and research site

The study was conducted in West Kalimantan Province, Indonesia (see Fig. 2). We collected peat core samples using a Russian type auger by Eijkelkamp, Holland. The peat sample campaigns were done between 2007 and 2010. We retrieved the core sample every 50 cm increment until reclaiming mineral substrate beneath peat. Every 50 cm peat core was transferred into half-cut PVC pipe ($\Phi = 2$ inch), and carefully wrapped with home cling wrap. We took subsamples at a 50 cm interval up to 200 cm depths for laboratory analyses. Table 4 summarizes location and core sample categories.

Core samples comprise of several land use groups, consisting of coastal and inland peat forests (PF1 and PF2), logged over peat forest (LF), industrial timber estate (EIT) of fast

Table 3. Selected Radio Carbon Dates of Peats from Kalimantan and Peninsular Malaysia.

Site	Core	Lab. No.	Depth (cm)	Peat Age ± SD (^{14}C Yr BP)	Source
Tasek Bera Basin (Peninsular Malaysia)	TB5	BIRM255	860	4500 ± 80	Wüst and Bustin (2004)
	B78	TO-8272	536	20 480 ± 190	
	B53	TO-7613	530	3410 ± 50	
	B7	TO-8269	644	3930 ± 70	
	B115	TO-8271	436	3730 ± 80	
Danau Sentarum National Park, West Kalimantan	A	OZE 137	10–11	12 440 ± 60	Anshari et al. (2004)
	A	OZE 138	27–28	28 900 ± 250	
	A	OZE 139	49–50	28 250 ± 150	
	A	OZE 140	102–103	24 250 ± 120	
	A	Wk 5777	120–150	23 570 ± 170	
	A	OZE 141	149–150	32 800 ± 300	
	B	OZE 133	14–15	265 ± 35	
	B	Wk 6278	41–42	1366 ± 72	
	B	OZE 134	60–61	2920 ± 50	
	B	Wk 6275	67–68	3117 ± 57	
	B	OZE 135	71–72	13 070 ± 70	
	B	Wk 6277	91.5–92.5	16 840 ± 120	
	B	OZE 136	94–95	28 600 ± 250	
	B	Wk 5779	104–124	28 780 ± 100	
Sebangau National Park Central Kalimantan	SA65		90–110	170 ± 60	Page et al. (2004)
	SA65		110–130	540 ± 60	
	SA65		190–210	4670 ± 80	
	SA65		330–350	7820 ± 50	
	SA65		570–590	8540 ± 100	
	SA65		650–670	10 320 ± 50	
	SA65		840–860	22 120 ± 320	
	SA65		940–960	20 350 ± 130	

growing species, community agriculture (CA), and oil palm plantations (see Fig. 2 and Table 4).

The inland peat forest is located in Danau Sentarum National Park in the upper Kapuas River basin, and is sufficiently intact and undrained. The coastal peat forest is located in Sungai Putri peat dome of Ketapang District, and it is also undrained. Both inland and coastal peat forests were selectively logged in the past. At present, no timber harvesting occurs in inland peats of Danau Sentarum National Park, and some illegal logging currently taking place in coastal peat forest of Sungai Putri peat dome.

Logged over peat forest is located in Antibar peat dome near Mempawah (about 70 km North of Pontianak). This coastal peat forest currently suffers from rapid rates of illegal logging activities, and slightly drained due to road construction.

The early industrial timber estate (EIT) is located in a small peat dome near Pontianak in the lower Kapuas River basin. The estate has just cleared the natural forest and replaced with a fast growing timber species (*Acacia* spp.) for one year. The timber plantation is slightly drained in order to lower water table depth.

The oil palm plantations consist of three age groups. One of the early oil palm (EOP2) is located in a scattered inland peat in the upper Kapuas River Basin. Other palm plantations are all located in coastal peat domes, and consist of early oil palm (<5 years), intermediate oil palm (5–10 years), and mature oil palm (15–20 years). All oil palm sites are heavily drained and regularly received fertilizers, particularly Nitrogen, Phosphorous, and Potassium.

The community agriculture (CA) is located in drained and open peat of Rasau Jaya peat dome. The forest of this peat dome was cleared and converted into agriculture by the government in 1972. Farmers usually plant maize and many kinds of vegetables in this peat. The use of chicken manures and limited amount of chemical fertilizers is common practice in this agriculture.

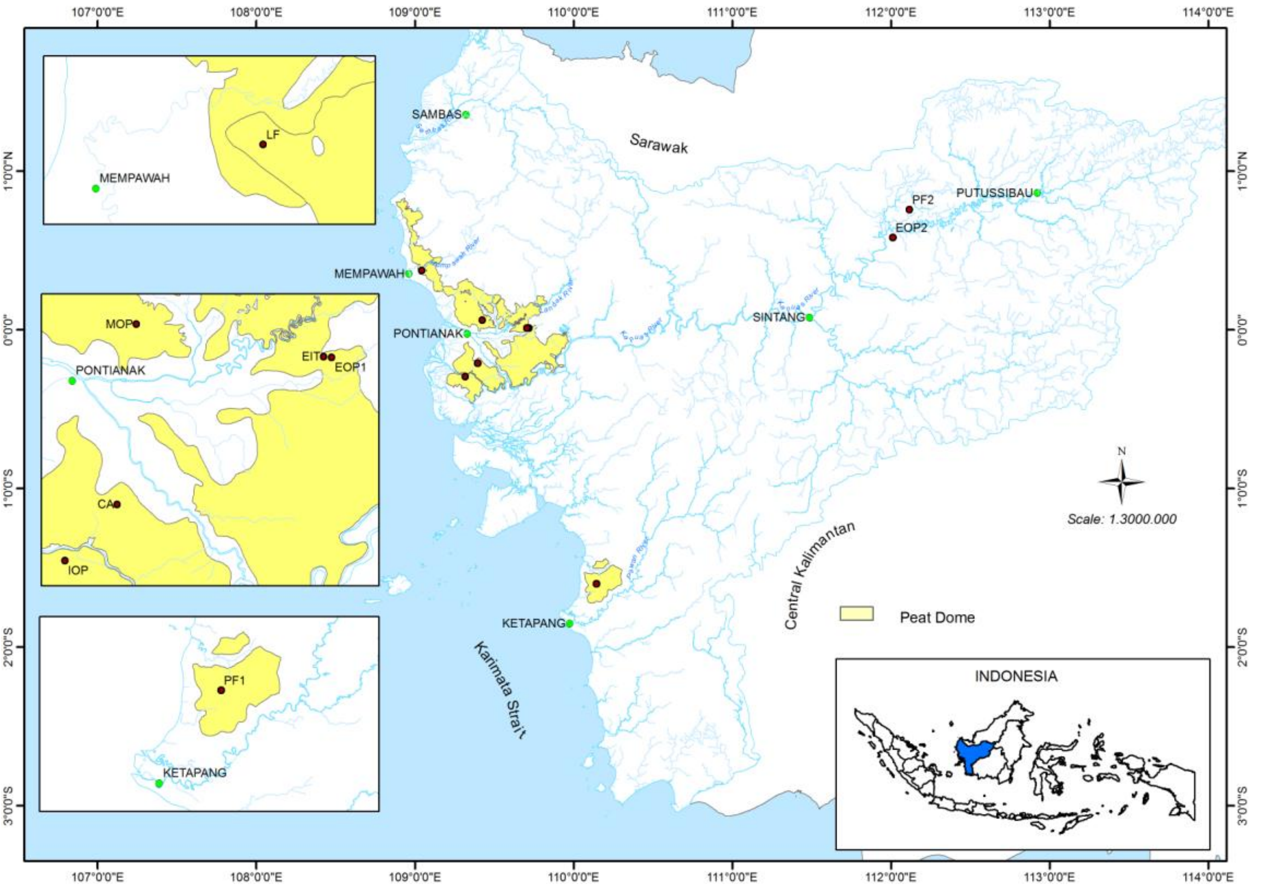

Fig. 2. West Kalimantan Province, showing study sites in selected coastal peat domes and two sites in inland peats.

Table 4. Land Use and Drainage Categories of Study Sites.

No	Code	Category		Location	Coordinates
		Land Use	Drainage/Disturbance		
1	CA	Community Agriculture	Drained Peat	Coastal Peat (the lower Kapuas River basin)	0°12.572′ S 109°23.743′ E
2	EOP1	Early Oil Palm (<5 yrs)	Drained Peat	Coastal Peat (the lower Kapuas River basin)	0°0.619′ N, 109°43.011′ E
3	EOP2	Early Oil Palm (<5 yrs)	Drained Peat	Inland Peat (the upper Kapuas River basin)	0°34.906′ N, 112°0.636′ E
4	IOP	Intermediate Oil Palm (5–10 yrs)	Drained Peat	Coastal Peat (the lower Kapuas River basin)	0°17.631′ S, 109°19.038′ E
5	MOP	Mature Oil Palm (15–20 yrs)	Drained Peat	Coastal Peat (the lower Kapuas River basin)	0°3.617′ N, 109°25.454′ E
6	EIT	Early Industrial Timber	Slightly Drained Peat	Coastal Peat (the lower Kapuas River basin)	0°0.707′ N, 109°42.299′ E
7	LF	Logged over Peat Forest	Slightly Drained Peat	Coastal Peat (the lower Mempawah River basin)	0°22.498′ N, 109°2.643′ E
8	PF1	Coastal Peat Forest	Undrained Peat	Coastal Peat (the lower Pawan River basin)	1°36.031′ S, 110°8.598′ E
9	PF2	Inland Peat Forest	Undrained Peat	Inland Peat (the upper Kapuas River basin)	0°45.463′ N 112°06.986′ E

Table 5. A list of research variables in this study.

No	Code	Variable	Unit	Method
1	pH (H_2O)	Soil Acidity		pH Meter
2	DBD ($g\,cm^{-3}$)	Dry Bulk Density	$g\,cm^{-3}$	Core Method and Oven Dry at 105 °C
3	LOI	Loss on Ignition	$g\,kg^{-1}$	Dry Combustion at 550 °C
4	GWC (ρ)	Gravimetric Water Content (ρ)	$g\,kg^{-1}$	Gravimetric, Oven at 105 °C
5	VWC (θ)	Volumteric Water Content (θ)	$g\,cm^{-3}$	By Calculation (DBD × GWC/1000)
6	TOC	Total Organic Carbon	%	High Temperature Combustion by Elemental Analyzer
7	TN	Total Nitrogen	%	High Temperature Combustion by Elemental Analyzer
8	Atomic C/N Ratio	Atomic C/N Ratio		By Calculation TOC/TN

3.2 Laboratory analysis

We studied selected physical and chemical property changes of peats due to different land uses and drainage disturbances. Research variables are peat pH (H_2O), Dry Bulk Density (DBD), Loss on Ignition (LOI), Gravimetric Water Content (GWC), Volumetric Water Content (VWC), Total Organic Carbon (TOC), Total Nitrogen (TN), and Atomic C/N Ratio (see Table 5). We took sub-samples for laboratory analysis at every 50 cm interval. The volumes of sub-samples for measurements are 50 cm^3 for pH, TOC, and TN, and 100 cm^3 for DBD, GWC, and LOI.

We used Inolab pH meter (type 720 Bench to pH meter) to measure peat acidity. Fresh subsamples were diluted into distilled water at 1:5 for pH (H_2O) measurements. GWC and DBD were determined after drying at 105 °C for 24 h. LOI values were calculated after combusting the oven dry samples at 550 °C for 5 h. LOI value represents the amount of organic matters. GWC, Ash Free DBD, and LOI were calculated using Eqs. (1), (2), (3), and (4).

$$\text{Water Content } (g\,kg^{-1}) = \frac{WS(g) - DOW_{110}(g)}{DOW_{110}(g)} \times 1000 \quad (1)$$

$$\text{DBD } (g\,cm^{-3}) = \frac{DOW_{110}(g)}{SV}(cm^3) \quad (2)$$

$$\text{LOI } (g\,kg^{-1}) = \frac{DOW_{110}(g) - AW_{550}(g)}{DOW_{110}(g)} \times 1000$$

(Heiri et al., 2001) (3)

$$\text{Ash Free DBD } (g\,cm^{-3}) = DBD \times LOI \quad (4)$$

Where: WS = wet sample weight, DOW_{110} = constant weight after drying at 110 °C for 24–48 h, SV = sample volume, LOI = Loss on Ignition, DBD = Dry Bulk Density AW_{550} = ash residue weight after combusting at 550 °C for 5 h.

The concentrations of TOC and TN were determined by dry combustion at high temperature with El Vario CHNS Analyzer. Samples were prepared by drying at 40 °C for at least 24 h until constant weights. About 20 mg of dry samples were oxidized and the evolved gases were measured.

3.3 Statistical analysis

We used SPSS version 17 for independent t-tests and Oneway ANOVA (SPSS, 2008). We compared average values of research variables according to contrasted locations (i.e. coastal and inland peats), and peat layers (i.e. acrotelm and catotelm). We assume that averages of acrotelm and catotelm depths are up to 100 cm, and greater than 100 cm, respectively. We realize that depths of acrotelm seasonally fluctuate following rainfall, and may be either less or greater than 100 cm. The determination of the acrotelm depth between 0–100 cm in this study is a conservative estimate. Takahashi (1999) reported that the water table depth of peat swamp forest in Central Kalimantan in a severe drought associated with El Niño of 1997 was 98 cm below the peat surface.

We used oneway ANOVA to analyze differences of peat properties according to the defined land use and drainage categories. As the numbers of samples collected from these groups are not equal, data distribution is not normal, and has unequal variances. To overcome this concern, we used Welch and Brown-Forsythe statistics in order to detect significant differences of the research variables with unequal variances (Field, 2005). If mean differences of research variables are statistically significant, we used Games-Howell (GH) procedure to detect specific differences in drainage and land use categories.

Table 6. Means of Research Variables according to Acrotelm versus Catotelm, and Inland and Coastal Peats.

Variable	Peat Stratum and Location	N	Mean	Std. Deviation	Variable	Peat Stratum and Location	N	Mean	Std. Deviation
pH (H_2O)	Acrotelm	123	3.59	0.20	VWC ($g\,cm^{-3}$)	Acrotelm	148	0.92	0.24
	Catotelm	95	3.69	0.18		Catotelm	99	1.01	0.19
	Inland peat	47	3.61	0.21		Inland peat	23	0.74	0.17
	Coastal peat	171	3.64	0.19		Coastal peat	224	0.98	0.22
DBD ($g\,cm^{-3}$)	Acrotelm	163	0.12	0.04	TOC (%)	Acrotelm	225	51.82	3.47
	Catotelm	107	0.10	0.04		Catotelm	111	52.41	4.43
	Inland peat	46	0.09	0.04		Inland peat	47	51.78	4.18
	Coastal peat	224	0.12	0.04		Coastal peat	289	52.05	3.77
LOI ($g\,kg^{-1}$)	Acrotelm	163	958.22	62.95	TN (%)	Acrotelm	225	2.40	1.12
	Catotelm	107	964.57	55.18		Catotelm	111	2.00	1.21
	Inland peat	46	965.02	56.37		Inland peat	47	1.85	1.19
	Coastal peat	224	959.86	60.76		Coastal peat	289	2.33	1.15
GWC ($g\,kg^{-1}$)	Acrotelm	148	8645.82	3201.61	Atomic C/N Ratio	Acrotelm	225	30.55	22.22
	Catotelm	99	11 076.47	3568.68		Catotelm	111	39.49	24.53
	Inland peat	23	12 111.43	4278.68		Inland peat	47	45.96	33.11
	Coastal peat	224	9364.24	3378.36		Coastal peat	289	31.48	20.73

Table 7a. Results of Independent t-tests for Acrotelm versus Catotelm (a) and Inland versus Coastal Peats (b).

Variable	Acrotelm versus Catotelm	Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig.	*t*	df	Sig. (2-tailed)	Mean Difference
pH (H_2O)	Equal variances assumed	1.84	0.18	−3.77	216.00	0.00	−0.10***
DBD ($g\,cm^{-3}$)	Equal variances assumed	0.16	0.69	2.72	268.00	0.01	0.01**
LOI ($g\,kg^{-1}$)	Equal variances assumed	0.63	0.43	−0.85	268.00	0.40	−6.35
GWC ($g\,kg^{-1}$)	Equal variances assumed	4.25	0.04	−5.58	245.00	0.00	−2430.65***
	Equal variances not assumed			−5.46	194.37	0.00	−2430.65***
VWC ($g\,cm^{-3}$)	Equal variances assumed	5.23	0.02	−3.33	245.00	0.00	−0.10***
	Equal variances not assumed			−3.49	237.83	0.00	−0.10***
TOC (%)	Equal variances assumed	1.01	0.31	−1.35	334.00	0.18	−0.60
TN (%)	Equal variances assumed	3.07	0.08	3.00	334.00	0.00	0.40***
Atomic C/N Ratio	Equal variances assumed	9.25	0.00	−3.35	334.00	0.00	−8.94***
	Equal variances not assumed			−3.24	200.91	0.00	−8.94***

*** $p < 0.00$; ** $p < 0.01$; * $p < 0.05$

Table 7b. Continued.

Variable	Inland versus Coastal Peats	Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig.	*t*	df	Sig. (2-tailed)	Mean Difference
pH (H_2O)	Equal variances assumed	1.10	0.30	−0.82	216.00	0.41	−0.03
DBD (g cm^{-3})	Equal variances assumed	0.01	0.94	−4.47	268.00	0.00	−0.03***
LOI (g kg^{-1})	Equal variances assumed	0.88	0.35	0.53	268.00	0.60	5.16
	Equal variances not assumed			0.56	68.25	0.58	5.16
GWC (g kg^{-1})	Equal variances assumed	5.40	0.02	3.62	245.00	0.00	2747.19***
	Equal variances not assumed			2.99	24.90	0.01	2747.19**
VWC (g cm^{-3})	Equal variances assumed	2.66	0.10	−4.85	245.00	0.00	−0.23***
TOC (%)	Equal variances assumed	2.21	0.14	−0.44	334.00	0.66	−0.27
TN (%)	Equal variances assumed	0.17	0.68	−2.67	334.00	0.01	−0.48**
Atomic C/N Ratio	Equal variances assumed	30.43	0.00	4.03	334.00	0.00	14.48***
	Equal variances not assumed			2.91	52.02	0.01	14.48**

*** $p < 0.00$; ** $p < 0.01$; * $p < 0.05$

4 Results

4.1 Independent t-tests

Table 6 presents means of research variables as classified into acrotelm-catotelm, and inland-coastal peats. We summarized results of independent t-tests for acrotelm (0–100 cm) versus catotelm (>100 cm), and inland versus coastal peats in Table 7a and b.

Table 6 shows that pH and DBD values are relatively low. Peat pH is slightly higher in catotelm than acrotelm, and pH in inland and coastal peats is very much similar to each other. DBD in acrotelm is slightly higher than catotelm, and DBD in inland peats is lower than in coastal peats. LOI values are generally lower in acrotelm than catotelm, and are higher in inland peats than in coastal peats. As expected, water contents in catotelm and inland peats are higher than acrotelm and coastal peats. The average TOC value is 52% in all categories. TN values are more concentrated in acrotelm and coastal peat. Accordingly, atomic C/N ratios in acrotelm and coastal peats are lower than catotelm and inland peats.

The t-tests for acrotelm-catotelm and inland-coastal peat show that LOI and TOC are indifferent. Significant differences between acrotelm and catotelm are found in pH, DBD, GWC, VWC, TN, and Atomic C/N Ratio. Peat pH, LOI and TOC between inland and coastal peats are statistically indifferent. Other variables (DBD, GWC, VWC, TN, and atomic C/N ratio) between coastal and inland peats are significantly different.

4.2 Oneway ANOVA

4.2.1 Drainage groups

Table 8 presents a summary of peat properties according to drainage categories. Values of peat pH, DBD, and TN increase following drainage disturbance. TOC values seem to decrease due to drainage influences. Therefore, atomic C/N ratios substantially decrease in drained peats. LOI seems unaffected by drainage.

Peat drainage influences pH, DBD, VWC and TN, showing some increasing trends towards drained peat. LOI and GWC do not indicate either an increasing or decreasing trend. TOC is slightly higher in undrained peat than in drained peat. It is obvious that atomic C/N ratio show a decreasing trend from undrained peat to drained peat (see Table 8).

Table 8. Means of Research Variables in Drainage Groups.

Variable	Drainage	N	Mean	SD	Variable	Drainage	N	Mean	SD
pH (H_2O)	Undrained Peat Forest	40	3.53	0.25	VWC (g cm^{-3})	Undrained Peat Forest	16	0.69	0.12
	Slightly Drained Peat	63	3.63	0.21		Slightly Drained Peat	72	0.95	0.22
	Drained Peat	115	3.67	0.16		Drained Peat	159	0.98	0.22
	Total	218	3.63	0.20		Total	247	0.95	0.23
DBD (g cm^{-3})	Undrained Peat Forest	39	0.09	0.03	TOC (%)	Undrained Peat Forest	40	53.38	3.16
	Slightly Drained Peat	72	0.11	0.04		Slightly Drained Peat	72	50.77	3.04
	Drained Peat	159	0.12	0.04		Drained Peat	224	52.17	4.05
	Total	270	0.11	0.04		Total	336	52.01	3.82
LOI (g kg^{-1})	Undrained Peat Forest	39	958.95	91.77	TN (%)	Undrained Peat Forest	40	0.96	0.33
	Slightly Drained Peat	72	967.97	39.05		Slightly Drained Peat	72	1.10	0.29
	Drained Peat	159	957.90	58.13		Drained Peat	224	2.87	0.93
	Total	270	960.74	59.97		Total	336	2.26	1.16
GWC (g kg^{-1})	Undrained Peat Forest	16	9754.42	2501.87	Atomic C/N Ratio	Undrained Peat Forest	40	62.86	24.58
	Slightly Drained Peat	72	10 249.69	3839.70		Slightly Drained Peat	72	50.22	16.42
	Drained Peat	159	9321.41	3487.46		Drained Peat	224	22.89	16.43
	Total	247	9620.05	3552.93		Total	336	33.51	23.36

Table 9. Test of Homogeneity of Variances in Drainage Groups.

Variable	Levene Statistic	df1	df2	Sig.
pH (H_2O)	10.740	2	215.00	0.00
DBD (g cm^{-3})	4.510	2	267.00	0.01
LOI (g kg^{-1})	3.566	2	267.00	0.03
GWC (g kg^{-1})	2.966	2	244.00	0.05
VWC (g cm^{-3})	3.373	2	244.00	0.04
TOC (%)	2.264	2	333.00	0.11
TN (%)	29.136	2	333.00	0.00
Atomic C/N Ratio	4.379	2	333.00	0.01

Table 9 presents a test result of homogeneity of variances in drainage groups. All variables, except TOC, have unequal variances. Table 10 depicts results of robust tests of equality of means of the variables. The robust tests of equality of means show that LOI and GWC are indifferent and other variables are significantly different.

Table 11 presents Games-Howell (GH) multiple comparisons. Highly significant differences between undrained peat forest and drained peats are found in pH, DBD, VWC, TN and atomic C/N ratio. As shown, DBD in slightly drained peats (i.e. logged over peat forest (LF) and industrial timber plantation (EIT)) shows significant different from drained peats used for oil palm and agriculture. Significant different in TOC is shown between slightly drained peat and both drained and undrained peats. TN in drained peat is significantly different from undrained peat forest and slightly drained peat. Atomic C/N ratios show significantly different in all drainage groups.

Table 10. Robust Tests of Equality of Means of Research Variables in Drainage Groups.

Variable		Statistic[a]	df1	df2	Sig.
pH (H_2O)	Welch	5.69	2.00	84.20	0.00
	Brown-Forsythe	6.05	2.00	107.63	0.00
DBD (g cm^{-3})	Welch	16.01	2.00	119.16	0.00
	Brown-Forsythe	12.47	2.00	201.91	0.00
LOI (g kg^{-1})	Welch	1.22	2.00	90.41	0.30
	Brown-Forsythe	0.53	2.00	67.57	0.59
GWC (g kg^{-1})	Welch	1.55	2.00	44.37	0.22
	Brown-Forsythe	2.08	2.00	108.04	0.13
VWC (g cm^{-3})	Welch	38.12	2.00	51.03	0.00
	Brown-Forsythe	19.66	2.00	140.80	0.00
TOC (%)	Welch	9.83	2.00	102.71	0.00
	Brown-Forsythe	8.95	2.00	161.94	0.00
TN (%)	Welch	351.33	2.00	132.33	0.00
	Brown-Forsythe	548.31	2.00	301.17	0.00
Atomic C/N Ratio	Welch	109.19	2.00	84.58	0.00
	Brown-Forsythe	95.69	2.00	87.73	0.00

[a] Asymptotically *F* distributed

4.2.2 Land use groups

We present means of research variables in land use groups in Table 12. Peat pH shows inconsistent variability in these groups. We believe that the variability of organic substances has a greater role in determining pH values. Without chemical fractionation of these organic matters, it is difficult to explain why peat pH has small variability in these land use groups.

DBD show an increasing trend from peat forests to disturbed and converted peats used for logging, oil palms, and industrial timber. A small sample number in CA influences low DBD values in this research.

Table 11. Games-Howell (GH) Multilple Comparisons of Drainage Groups.

Dependent Variable	(I) Disturbance	(J) Disturbance	Mean Difference (I–J)	Std. error	Sig.
pH (H_2O)	Undrained Peat Forest	Drained Peat	-0.14^{***}	0.04	0.00
	Undrained Peat Forest	Slightly Drained Peat	−0.10	0.05	0.10
	Slightly Drained Peat	Drained Peat	−0.04	0.03	0.39
DBD ($g\,cm^{-3}$)	Undrained Peat Forest	Drained Peat	-0.03^{***}	0.01	0.00
	Undrained Peat Forest	Slightly Drained Peat	-0.02^{**}	0.01	0.01
	Slightly Drained Peat	Drained Peat	−0.01	0.01	0.09
VWC ($g\,cm^{-3}$)	Undrained Peat Forest	Drained Peat	-0.30^{***}	0.03	0.00
	Undrained Peat Forest	Slightly Drained Peat	-0.27^{***}	0.04	0.00
	Slightly Drained Peat	Drained Peat	−0.03	0.03	0.61
TOC (%)	Slightly Drained Peat	Drained Peat	-1.40^{**}	0.45	0.01
	Undrained Peat Forest	Drained Peat	1.21	0.57	0.09
	Undrained Peat Forest	Slightly Drained Peat	2.62^{***}	0.61	0.00
TN (%)	Undrained Peat Forest	Drained Peat	-1.91^{***}	0.08	0.00
	Slightly Drained Peat	Drained Peat	-1.78^{***}	0.07	0.00
	Undrained Peat Forest	Slightly Drained Peat	−0.14	0.06	0.08
Atomic C/N Ratio	Undrained Peat Forest	Slightly Drained Peat	12.64^{**}	4.34	0.01
	Slightly Drained Peat	Drained Peat	27.32^{***}	2.23	0.00
	Undrained Peat Forest	Drained Peat	39.97^{***}	4.04	0.00

*** $p<0.00$; ** $p<0.01$; * $p<0.05$

TOC values are relatively constant in the peat forests than the disturbed and converted peats used for logging, oil palms, and industrial timber. In general, TOC values range from 49 to 54%. The quality of organic matters must have a greater influence in the variability of TOC.

TN concentrations tend to be slightly higher in peats used for oil palms and agriculture due to fertilizer application. In general, TN values in peat forest range from 0.8 to 1.5%. In peats used for oil palms and agriculture, TN concentrations range from 2.4 to 3.4%. In consequence, atomic C/N ratios in peats used for oil palms and agriculture are lower than in peat forests.

Tables 13 and 14 present results of test homogeneity of variances, and robust tests of equality of means of research variables. We found that variances in land use classes are significantly unequal, and all research variables are significantly different. Results of GH multiple comparisons are presented in Table 15.

Based on GH multiple comparisons, DBD in inland peat forest are significantly different from DBD in selected peats used for agriculture, intermediate and mature oil palm plantations, the timber estate, and logged over peat forest. It is important to note that DBD in inland peat forest is not different from DBD in coastal peat forest. DBD in logged over peat forest is significantly different from DBD in EIT, PF1, EOP2, and CA. DBD in Coastal peat forest is notably different from most DBD in peats used for oil palms in coastal region. Further DBD in community agriculture is significantly different from DBD in PF2, LF, EOP1, IOP, and MOP. DBD in all oil palms of coastal peat is significantly different from DBD in early oil palm in inland peat.

LOI in intermediate oil palm plantations (IOP) significantly differs from PF2, EIT, LF, EOP1, MOP, and CA. TOC concentrations are not very much different in the land use categories. TOC in inland peat forest is only significantly different from TOC in EIT, which is also significantly different from TOC in IOP, CA and PF1. TOC in coastal peat forest (PF1) is significantly different from TOC in LF and MOP. TOC values in oil palms are all indifferent.

TN concentration in inland peat forest (PF2) is significantly different from other land uses in coastal peats and early oil palm in inland peat. TN in early industrial timber (EIT) in coastal peat is indifferent from TN in coastal peat forest, but is significantly different from other land use types. TN in coastal peat forest (PF1) is not significantly different from TN in logged over forest (LF), and is significantly different from other land uses. In peats used for oil palms and agriculture, TN concentrations in early oil palm of coastal peat (EOP1) and intermediate oil palm of coastal peat (IOP) are highly significantly different. In coastal area, peats used for oil palms show significant different between TN in IOP and MOP, and between TN in MOP and EOP2. TN in community agriculture (CA) is significantly different from TN is IOP and MOP.

As TN concentrations significantly increase in peats used for oil palms and agriculture, atomic C/N ratios between the peat forest and converted peats are mostly different. The C/N ratio in inland peat forest (PF2) is also different from the

Table 12. Means of Research Variables according to Land Use Groups.

Category	pH (H_2O)	DBD ($g\,cm^{-3}$)	LOI ($g\,kg^{-1}$)	GWC ($g\,kg^{-1}$)	VWC ($g\,cm^{-3}$)	TOC (%)	TN (%)	Atomic C/N Ratio
Coastal Peat Forest (PF1)	3.591	0.081	936.728	9385.125	0.719	54.386	1.568	41.896
SD	0.345	0.028	120.458	2426.795	0.201	2.272	0.779	17.372
N	16	20	20	20	20	20	20	20
Inland Peat Forest (PF2)	3.488	0.097	982.865	N/A	N/A	53.043	0.784	73.078
SD	0.143	0.026	33.326	N/A	N/A	3.663	0.199	24.778
N	24	23	23	N/A	N/A	24	24	24
Early Industrial Timber (EIT)	3.823	0.071	974.250	13112.138	0.894	50.211	1.243	42.413
SD	0.123	0.017	29.166	3631.144	0.206	1.929	0.252	10.598
N	28	32	32	32	32	32	32	32
Logged over Peat Forest (LF)	3.469	0.134	962.940	7959.738	0.999	51.210	0.981	56.458
SD	0.106	0.031	45.186	2063.609	0.225	3.668	0.270	17.656
N	35	40	40	40	40	40	40	40
Early Oil Palm 1 (<5 Yr) (EOP1)	3.686	0.119	976.189	9784.039	1.053	51.433	3.278	16.181
SD	0.141	0.040	44.932	3129.855	0.149	5.381	0.620	3.264
N	34	38	38	38	38	38	38	38
Early Oil Palm 2 (<5 yr) (EOP2)	3.717	0.076	944.728	11456.994	0.719	49.255	2.789	18.280
SD	0.226	0.047	68.867	4132.435	0.177	6.393	0.630	3.547
N	18	18	18	18	18	18	18	18
Intermediate Oil Palm (5–10 yr) (IOP)	3.571	0.136	917.056	8757.394	1.071	52.654	2.377	32.848
SD	0.066	0.047	69.524	3340.385	0.207	2.924	1.199	23.082
N	28	48	48	48	48	86	86	86
Mature Oil Palm (15–20 yr) (MOP)	3.698	0.132	986.933	7435.390	0.947	51.698	3.398	15.402
SD	0.158	0.024	9.601	2229.008	0.202	1.998	0.385	1.810
N	35	40	40	40	40	40	40	40
Community Agriculture (CA)		0.069	978.936	14061.973	0.953	53.248	3.071	17.514
SD		0.017	31.581	2015.596	0.201	4.287	0.335	2.204
N		11	11	11	11	38	38	38

Table 13. Test of Homogeneity of Variances.

Variable	Levene Statistic	df1	df2	Sig.
DBD ($g\,cm^{-3}$)	4.238	8	261	0.00
LOI (g kg?$^{-1}$)	10.270	8	261	0.00
TOC (%)	2.947	8	327	0.00
TN (%)	48.215	8	327	0.00
Atomic C/N Ratio	28.890	8	327	0.00
pH (H_2O)	12.841	6	187	0.00
GWC ($g\,kg^{-1}$)	3.482	6	187	0.00
VWC ($g\,cm^{-3}$)	2.453	6	187	0.03

Table 14. Robust Tests of Equality of Means of DBD, LOI, TOC, TN, Atomic C/N Ratio, pH, GWC and VWC.

Variable		Statistic[a]	df1	df2	Sig.
DBD ($g\,cm^{-3}$)	Welch	35.913	8	84.348	0.00
	Brown-Forsythe	22.250	8	156.630	0.00
LOI ($g\,kg^{-1}$)	Welch	8.274	8	76.732	0.00
	Brown-Forsythe	5.876	8	69.903	0.00
TOC (%)	Welch	7.827	8	105.036	0.00
	Brown-Forsythe	4.182	8	120.433	0.00
TN (%)	Welch	316.454	8	108.433	0.00
	Brown-Forsythe	102.987	8	175.225	0.00
Atomic C/N Ratio	Welch	74.902	8	103.795	0.00
	Brown-Forsythe	61.051	8	121.768	0.00
pH (H_2O)	Welch	28.708	6	70.010	0.00
	Brown-Forsythe	11.070	6	50.179	0.00
GWC ($g\,kg^{-1}$)	Welch	11.783	6	71.722	0.00
	Brown-Forsythe	12.155	6	124.197	0.00
VWC ($g\,cm^{-3}$)	Welch	30.249	6	74.885	0.00
	Brown-Forsythe	18.785	6	165.141	0.00

[a] Asymptotically *F* Distributed

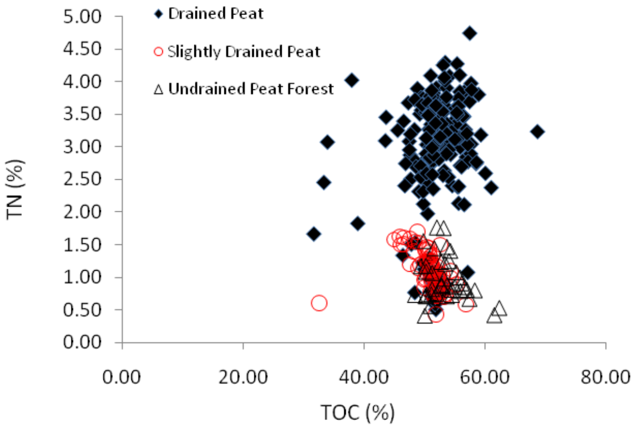

Fig. 3. A scatter plot TN versus TOC according to Drainage Groups.

C/N ratio in coastal peat forest (PF1), and the C/N ratios in PF1 and PF1 are significantly different from the C/N ratios in converted peats used for oil palms and agriculture.

Values of pH between coastal and inland peat forests are not significantly different according to GH multiple comparisons. Logged over forest shows significant different in pH from all peats used for oil palms, and early industrial timber (EIT). Means of pH in EIT is significantly different in all oil palms, except in EOP2. Further, pH value in IOP is significantly different from MOP and EOP1. It is important to note that pH in CA was not recorded in this analysis.

GWC values show significant differences between GWC values in EIT and EOP1, IOP and MOP. In oil palm land uses, GWC in MOP is significantly different from GWC in EOP1, EOP2, and IOP. GWC in PF1 was not recorded, and therefore was not compared.

VWC in coastal peat forest (PF1) is significantly different from VWC in peats used for MOP, IOP, and EOP1; and peats used for EIT and LF. In oil palms, there is significantly different between VWC in EOP 1 and EOP2; between IOP and MOP; between IOP and EOP2; between MOP and EOP2.

Figure 3 presents a scatter plot TOC versus TN according to drainage groups, and Fig. 4 presents scatter plots DBD versus TN according to land use groups. We recorded high TN concentration in drained peats used for oil palms and agriculture.

DBD in peat forests is generally lower than 0.1 g cm^{-3}. Rieley et al. (2008) recorded an average DBD value of 0.08 g cm^{-3} in peats from Central Kalimantan. Other authors commonly report the average DBD value of 0.1 g cm^{-3} for fibrist peats (Andriesse, 1988; Satrio et al., 2009; Soil Survey Staff, 2010).

Increases in TN in peats used for oil palms are mostly associated with application of fertilizers (see Figs. 3 and 4). All oil palms need regular and heavy inputs of fertilizers, particularly Nitrogen (N), Phosphorous (P) and Potassium (K). The direct impact of Nitrogen is to reduce C/N ratio as TOC values are relatively constant in all land use groups, and are not greatly affected by drainage. We believe that the reduction of C/N ratio greatly influences a rate of peat decomposition. The availability of N would enhance decomposers to oxidize peats into dissolved organic Carbon, dissolved organic acids, and CO_2 gas.

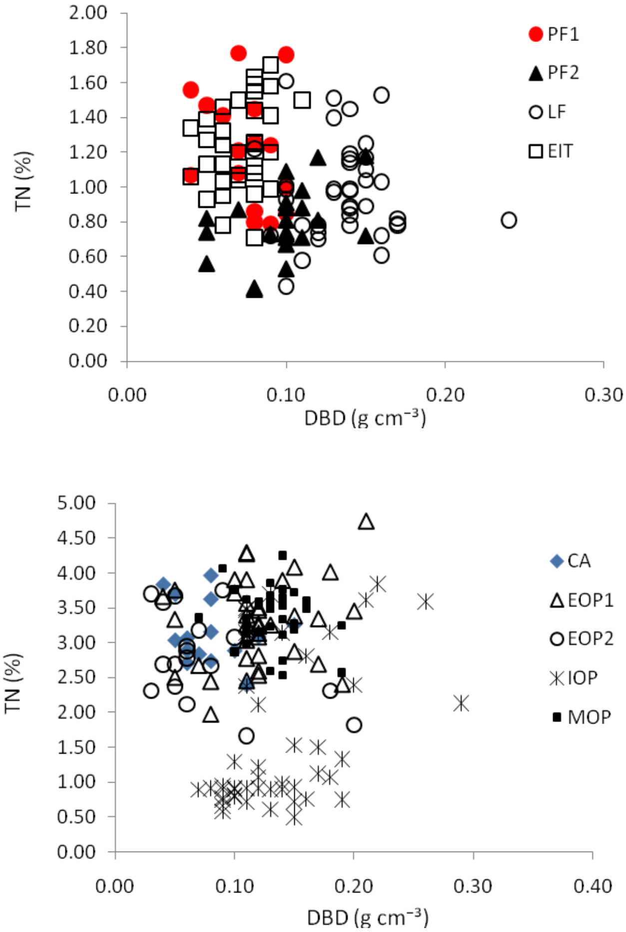

Fig. 4. Scatter plots DBD vs. TN according to Land Use Groups (PF1 = coastal peat forest; PF2 = inland peat forest; LF = logged over peat forest; EIT = industrial timber plantation; CA = community agriculture; EOP1 = Early Oil Palm (<5 yrs) in coastal peat; EOP2 = Early Oil Palm (<5 yrs) in inland peat; IOP = Intermiediate Oil Palm (5–10 yrs); MOP = Mature Oil Palm (15–20 yrs).

Figure 5 depicts scatter plots of LOI versus C/N ratio in land use groups, and Fig. 6 presents scatter plots LOI versus TOC, and LOI versus TN. These figures show that LOI values in both peat forest and converted peats for oil palms and agricture are consistently high, and values of C/N ratios in converted peats are substantially lower than in peat forest. Values of C/N ratio in IOP are comparably as high as in peat forest. This occurs because regular inundation in IOP causes rapid loss of Nitrogen, and retards the decomposition rate in this oil palm site.

Table 15. Games-Howell Multiple Comparisons of DBD, LOI TOC, TN, and Atomic C/N Ratio according to Land Use Groups.

Dependent Variable	(I) LandUse	(J) LandUse	Mean Difference (I–J)	Sig.
DBD (g cm^{-3})	Early Industrial Timber (EIT)	Intermediate Oil Palm (5–10 yr) (IOP)	−0.07***	0.00
	Early Industrial Timber (EIT)	Logged over Peat Forest (LF)	−0.06***	0.00
	Early Industrial Timber (EIT)	Mature Oil Palm (15–20 yr) (MOP)	−0.06***	0.00
	Early Industrial Timber (EIT)	Early Oil Palm 1 (<5 Yr) (EOP1)	−0.05***	0.00
	Inland Peat Forest (PF2)	Intermediate Oil Palm (5–10 yr) (IOP)	−0.04***	0.00
	Inland Peat Forest (PF2)	Logged over Peat Forest (LF)	−0.04***	0.00
	Inland Peat Forest (PF2)	Mature Oil Palm (15–20 yr) (MOP)	−0.03***	0.00
	Inland Peat Forest (PF2)	Early Industrial Timber (EIT)	0.03***	0.00
	Inland Peat Forest (PF2)	Community Agriculture (CA)	0.03**	0.02
	Early Oil Palm 1 (<5 Yr) (EOP1)	Coastal Peat Forest (PF1)	0.04***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Early Oil Palm 2 (<5 yr) (EOP2)	0.04*	0.05
	Early Oil Palm 1 (<5 Yr) (EOP1)	Community Agriculture (CA)	0.05***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Coastal Peat Forest (PF1)	0.05***	0.00
	Logged over Peat Forest (LF)	Coastal Peat Forest (PF1)	0.05***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Coastal Peat Forest (PF1)	0.06***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Early Oil Palm 2 (<5 yr) (EOP2)	0.06***	0.00
	Logged over Peat Forest (LF)	Early Oil Palm 2 (<5 yr) (EOP2)	0.06***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Early Oil Palm 2 (<5 yr) (EOP2)	0.06***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Community Agriculture (CA)	0.06***	0.00
	Logged over Peat Forest (LF)	Community Agriculture (CA)	0.07***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Community Agriculture (CA)	0.07***	0.00
LOI (g kg^{-1})	Intermediate Oil Palm (5–10 yr) (IOP)	Mature Oil Palm (15–20 yr) (MOP)	−69.88***	0.00
	Logged over Peat Forest (LF)	Mature Oil Palm (15–20 yr) (MOP)	−23.99*	0.05
	Logged over Peat Forest (LF)	Intermediate Oil Palm (5–10 yr) (IOP)	45.88**	0.01
	Early Industrial Timber (EIT)	Intermediate Oil Palm (5–10 yr) (IOP)	57.19***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Intermediate Oil Palm (5–10 yr) (IOP)	59.13***	0.00
	Community Agriculture (CA)	Intermediate Oil Palm (5–10 yr) (IOP)	61.88***	0.00
	Inland Peat Forest (PF2)	Intermediate Oil Palm (5–10 yr) (IOP)	65.81***	0.00
TOC (%)	Early Industrial Timber (EIT)	Coastal Peat Forest (PF1)	−4.17***	0.00
	Logged over Peat Forest (LF)	Coastal Peat Forest (PF1)	−3.18***	0.00
	Early Industrial Timber (EIT)	Community Agriculture (CA)	−3.04**	0.01
	Mature Oil Palm (15–20 yr) (MOP)	Coastal Peat Forest (PF1)	−2.69***	0.00
	Early Industrial Timber (EIT)	Intermediate Oil Palm (5–10 yr) (IOP)	−2.44***	0.00
	Inland Peat Forest (PF2)	Early Industrial Timber (EIT)	2.83*	0.04
TN (%)	Inland Peat Forest (PF2)	Mature Oil Palm (15–20 yr) (MOP)	−2.61***	0.00
	Inland Peat Forest (PF2)	Early Oil Palm 1 (<5 Yr) (EOP1)	−2.49***	0.00
	Logged over Peat Forest (LF)	Mature Oil Palm (15–20 yr) (MOP)	−2.42***	0.00
	Logged over Peat Forest (LF)	Early Oil Palm 1 (<5 Yr) (EOP1)	−2.30***	0.00
	Inland Peat Forest (PF2)	Community Agriculture (CA)	−2.29***	0.00
	Early Industrial Timber (EIT)	Mature Oil Palm (15–20 yr) (MOP)	−2.16***	0.00
	Logged over Peat Forest (LF)	Community Agriculture (CA)	−2.09***	0.00
	Early Industrial Timber (EIT)	Early Oil Palm 1 (<5 Yr) (EOP1)	−2.03***	0.00
	Inland Peat Forest (PF2)	Early Oil Palm 2 (<5 yr) (EOP2)	−2.01***	0.00
	Early Industrial Timber (EIT)	Community Agriculture (CA)	−1.83***	0.00
	Logged over Peat Forest (LF)	Early Oil Palm 2 (<5 yr) (EOP2)	−1.81***	0.00
	Inland Peat Forest (PF2)	Intermediate Oil Palm (5–10 yr) (IOP)	−1.59***	0.00
	Early Industrial Timber (EIT)	Early Oil Palm 2 (<5 yr) (EOP2)	−1.55***	0.00
	Logged over Peat Forest (LF)	Intermediate Oil Palm (5–10 yr) (IOP)	−1.40***	0.00
	Coastal Peat Forest (PF1)	Early Oil Palm 2 (<5 yr) (EOP2)	−1.22***	0.00
	Early Industrial Timber (EIT)	Intermediate Oil Palm (5–10 yr) (IOP)	−1.13***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Mature Oil Palm (15–20 yr) (MOP)	−1.02***	0.00
	Inland Peat Forest (PF2)	Coastal Peat Forest (PF1)	−0.78**	0.01
	Intermediate Oil Palm (5–10 yr) (IOP)	Community Agriculture (CA)	−0.69***	0.00
	Inland Peat Forest (PF2)	Early Industrial Timber (EIT)	−0.46***	0.00
	Inland Peat Forest (PF2)	Logged over Peat Forest (LF)	−0.20*	0.04
	Early Industrial Timber (EIT)	Logged over Peat Forest (LF)	0.26***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Community Agriculture (CA)	0.33***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Early Oil Palm 2 (<5 yr) (EOP2)	0.61*	0.02
	Intermediate Oil Palm (5–10 yr) (IOP)	Coastal Peat Forest (PF1)	0.81**	0.01
	Early Oil Palm 1 (<5 Yr) (EOP1)	Intermediate Oil Palm (5–10 yr) (IOP)	0.90***	0.00
	Community Agriculture (CA)	Coastal Peat Forest (PF1)	1.50***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Coastal Peat Forest (PF1)	1.71***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Coastal Peat Forest (PF1)	1.83***	0.00

Table 15. Continued.

Dependent Variable	(I) LandUse	(J) LandUse	Mean Difference (I–J)	Sig.
Atomic C/N Ratio	Mature Oil Palm (15–20 yr) (MOP)	Logged over Peat Forest (LF)	−41.06***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Early Industrial Timber (EIT)	−27.01***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Coastal Peat Forest (PF1)	−26.49***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Early Industrial Timber (EIT)	−26.23***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Coastal Peat Forest (PF1)	−25.72***	0.00
	Community Agriculture (CA)	Coastal Peat Forest (PF1)	−24.38***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Logged over Peat Forest (LF)	−23.61***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Intermediate Oil Palm (5–10 yr) (IOP)	−16.67***	0.00
	Early Industrial Timber (EIT)	Logged over Peat Forest (LF)	−14.04***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Community Agriculture (CA)	−2.11***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Early Oil Palm 2 (<5 yr) (EOP2)	14.57***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Community Agriculture (CA)	15.33***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Mature Oil Palm (15–20 yr) (MOP)	17.45***	0.00
	Coastal Peat Forest (PF1)	Early Oil Palm 2 (<5 yr) (EOP2)	23.62***	0.00
	Early Industrial Timber (EIT)	Early Oil Palm 2 (<5 yr) (EOP2)	24.13***	0.00
	Early Industrial Timber (EIT)	Community Agriculture (CA)	24.90***	0.00
	Inland Peat Forest (PF2)	Early Industrial Timber (EIT)	30.67***	0.00
	Inland Peat Forest (PF2)	Coastal Peat Forest (PF1)	31.18***	0.00
	Logged over Peat Forest (LF)	Early Oil Palm 2 (<5 yr) (EOP2)	38.18***	0.00
	Logged over Peat Forest (LF)	Community Agriculture (CA)	38.94***	0.00
	Inland Peat Forest (PF2)	Intermediate Oil Palm (5–10 yr) (IOP)	40.23***	0.00
	Logged over Peat Forest (LF)	Early Oil Palm 1 (<5 Yr) (EOP1)	40.28***	0.00
	Inland Peat Forest (PF2)	Early Oil Palm 2 (<5 yr) (EOP2)	54.80***	0.00
	Inland Peat Forest (PF2)	Community Agriculture (CA)	55.56***	0.00
	Inland Peat Forest (PF2)	Early Oil Palm 1 (<5 Yr) (EOP1)	56.90***	0.00
	Inland Peat Forest (PF2)	Mature Oil Palm (15–20 yr) (MOP)	57.68***	0.00
pH (H_2O)	Logged over Peat Forest (LF)	Early Oil Palm 2 (<5 yr) (EOP2)	−0.25***	0.00
	Logged over Peat Forest (LF)	Mature Oil Palm (15–20 yr) (MOP)	−0.23***	0.00
	Logged over Peat Forest (LF)	Early Oil Palm 1 (<5 Yr) (EOP1)	−0.22***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Mature Oil Palm (15–20 yr) (MOP)	−0.13***	0.00
	Logged over Peat Forest (LF)	Intermediate Oil Palm (5–10 yr) (IOP)	−0.10***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Intermediate Oil Palm (5–10 yr) (IOP)	0.11***	0.00
	Early Industrial Timber (EIT)	Mature Oil Palm (15–20 yr) (MOP)	0.13**	0.01
	Early Industrial Timber (EIT)	Early Oil Palm 1 (<5 Yr) (EOP1)	0.14***	0.00
	Early Industrial Timber (EIT)	Intermediate Oil Palm (5–10 yr) (IOP)	0.25***	0.00
	Early Industrial Timber (EIT)	Logged over Peat Forest (LF)	0.35***	0.00
GWC ($g\,kg^{-1}$)	Mature Oil Palm (15–20 yr) (MOP)	Early Oil Palm 2 (<5 yr) (EOP2)	−3840.15*	0.02
	Logged over Peat Forest (LF)	Early Oil Palm 2 (<5 yr) (EOP2)	−3436.11*	0.04
	Logged over Peat Forest (LF)	Intermediate Oil Palm (5–10 yr) (IOP)	−2101.16*	0.05
	Early Oil Palm 1 (<5 Yr) (EOP1)	Mature Oil Palm (15–20 yr) (MOP)	2188.69*	0.04
	Intermediate Oil Palm (5–10 yr) (IOP)	Mature Oil Palm (15–20 yr) (MOP)	2505.20**	0.01
	Early Industrial Timber (EIT)	Intermediate Oil Palm (5–10 yr) (IOP)	3331.45**	0.01
	Early Industrial Timber (EIT)	Early Oil Palm 1 (<5 Yr) (EOP1)	3647.97***	0.00
	Early Industrial Timber (EIT)	Coastal Peat Forest (PF1)	3699.08**	0.01
	Early Industrial Timber (EIT)	Logged over Peat Forest (LF)	5432.61***	0.00
	Early Industrial Timber (EIT)	Mature Oil Palm (15–20 yr) (MOP)	5836.65***	0.00
VWC ($g\,cm^{-3}$)	Early Industrial Timber (EIT)	Intermediate Oil Palm (5–10 yr) (IOP)	−0.26***	0.00
	Early Industrial Timber (EIT)	Early Oil Palm 1 (<5 Yr) (EOP1)	−0.16*	0.02
	Logged over Peat Forest (LF)	Intermediate Oil Palm (5–10 yr) (IOP)	−0.15*	0.03
	Intermediate Oil Palm (5–10 yr) (IOP)	Mature Oil Palm (15–20 yr) (MOP)	0.18***	0.00
	Early Industrial Timber (EIT)	Coastal Peat Forest (PF1)	0.20***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Early Oil Palm 2 (<5 yr) (EOP2)	0.25***	0.00
	Logged over Peat Forest (LF)	Early Oil Palm 2 (<5 yr) (EOP2)	0.27***	0.00
	Mature Oil Palm (15–20 yr) (MOP)	Coastal Peat Forest (PF1)	0.28***	0.00
	Logged over Peat Forest (LF)	Coastal Peat Forest (PF1)	0.31***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Early Oil Palm 2 (<5 yr) (EOP2)	0.33***	0.00
	Early Oil Palm 1 (<5 Yr) (EOP1)	Coastal Peat Forest (PF1)	0.36***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Early Oil Palm 2 (<5 yr) (EOP2)	0.43***	0.00
	Intermediate Oil Palm (5–10 yr) (IOP)	Coastal Peat Forest (PF1)	0.46***	0.00

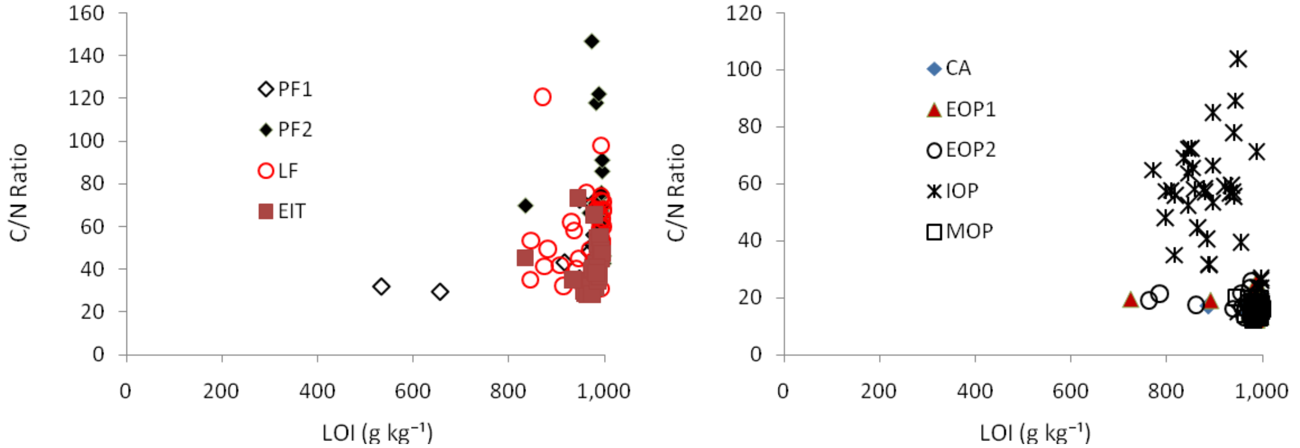

Fig. 5. Scatter plots of LOI versus C/N Ratio according to Land Use Groups (PF1 = coastal peat forest; PF2 = inland peat forest; LF = logged over peat forest; EIT = industrial timber plantation; CA = community agriculture; EOP1 = Early Oil Palm (<5 yrs) in coastal peat; EOP2 = Early Oil Palm (<5 yrs) in inland peat; IOP = Intermiediate Oil Palm (5–10 yrs); MOP = Mature Oil Palm (15–20 yrs).

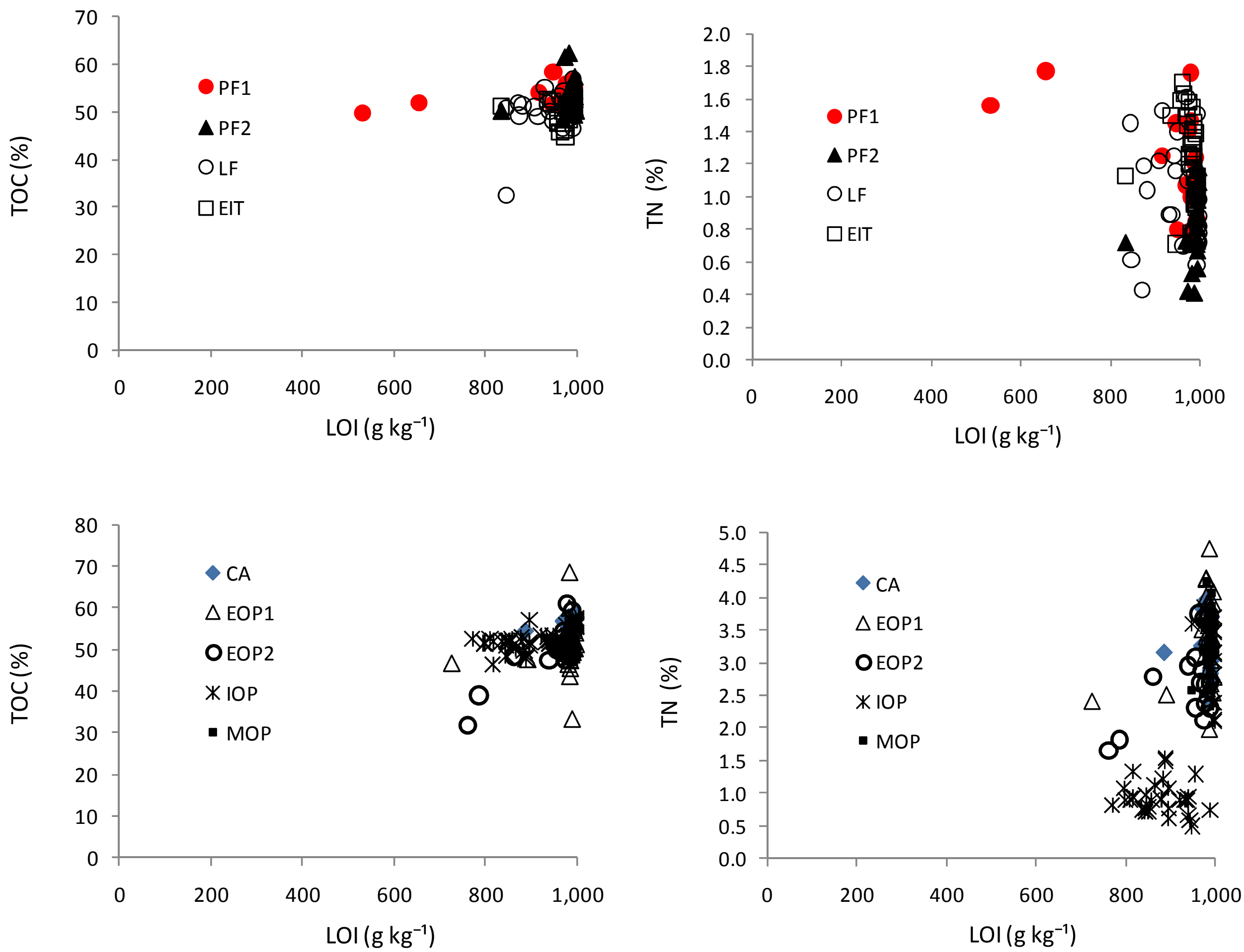

Fig. 6. Scatter plots LOI versus TOC and LOI versus TN according to Land Use Groups (PF1 = coastal peat forest; PF2 = inland peat forest; LF = logged over peat forest; EIT = industrial timber plantation; CA = community agriculture; EOP1 = Early Oil Palm (<5 yrs) in coastal peat; EOP2 = Early Oil Palm (<5 yrs) in inland peat; IOP = Intermiediate Oil Palm (5–10 yrs); MOP = Mature Oil Palm (15–20 yrs).

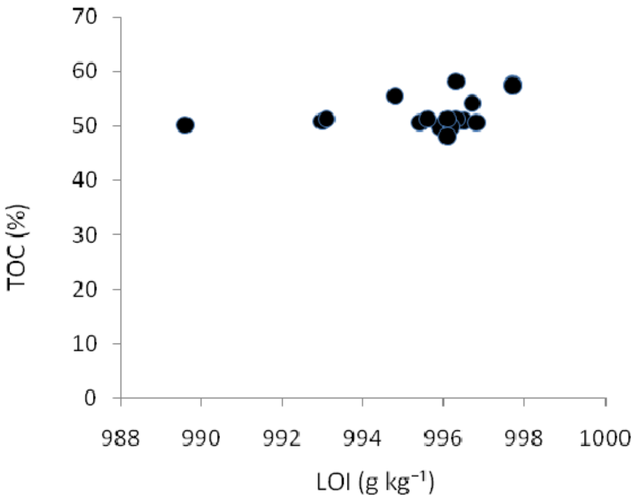

Fig. 7. A scatted plot LOI vs. TOC in the upper 200 cm depth from Sebangau Peat Forest, Central Kalimantan (Modified from Page et al., 2004).

Page et al. (2004) reported high LOI and TOC values in the upper 200 cm depth of peat from Sebangau peat forest in Central Kalimantan (see Fig. 7). The average values of TOC and LOI from 0–200 cm depth in this peat forest are 52% and 996 $g\,kg^{-1}$, which are comparably close to TOC and LOI values in this study.

5 Conclusions

We found that drainage and the conversion of peat forests into agriculture, oil palm and industrial timber plantation causes major changes of selected peat properties. In general, LOI and TOC values are constant in both peat forests and converted peats. Peat pH, DBD, and TN sufficiently tend to increase. Consequently, C/N ratio in the converted peats is significantly lower than in the peat forest. We believe that drainage largely influences an adequate increase of DBD and peat pH. Peat compaction is a direct consequence of drainage, and the removals of organic acids may substantially increase peat pH. An increase of TN concentrations in peats used for oil palms and agriculture is a direct impact of fertilizer uses, and subsequently leads to significant reduction of C/N ratio. We believe that increases in peat pH, DBD and TN concentration, and low C/N ratio (<20) in the drained and converted peats in this study are important indicators that indicate some processes of peat degradation.

Further studies are required in order to fully assess tropical peat degradation. We suggest to measure and develop models of decomposition rates under various land uses covering peat forests and drained peats used for agricultures, oil palms, and industrial timber plantations. Direct measurements of Carbon flux from these different land uses may improve our understanding on Carbon balance in tropical peats. Eddy covariance and closed gas chamber techniques for measuring CO_2 emissions from these peats are urgently required.

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