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Habitat evolution of a peat swamp forest and belowground carbon sequestration during the Holocene along the coastal lowland in Central Sumatra, Indonesia

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Abstract

Habitat evolution of a peat swamp forest and belowground carbon storage was examined in a coastal lowland along the eastern coast of Central Sumatra, Indonesia. Boring surveys using a hand-operated peat sampler for 32 sites and radiocarbon dating for 29 samples revealed that the peat swamp forest had begun formation by 6500 cal BP and expanded rapidly between 6500 and 5000 cal BP and between 4000 and 2000 cal BP to nearly the present distribution area. The thickness of the peat layer formed under the peat swamp forest reached approximately 4 m, even in the margin of the peat dome, and more than 9 m in the center. Stored carbon per unit volume of the peat layer was estimated to be between 30 and 44 kg C m⁻³ in the margin of the peat dome and approximately 26 kg C m⁻³ in the center, which was less than the general carbon values of the mangrove peat. The relatively higher amount of stored carbon per unit volume in the margin was possibly caused by an inflow of allochthonous carbon from flood deposits. Belowground carbon burial rate of the peat layer was calculated as between 31 and 105 g C m⁻² years⁻¹ in the peat dome margin and between 27 and 76 g C m⁻² years⁻¹ in the center, which were identical to mangrove peat. These data suggest that peat swamp forests have played a significant role as places for carbon sequestration belowground as well as mangrove forest with mangrove peat.

Keywords: Peat swamp forest, Habitat evolution, Belowground carbon sequestration, Holocene, Sumatra

Introduction

Tropical coastal swamp forests, such as mangrove forests, peat swamp forests, and freshwater swamp forests, are considered to be places of significant carbon sequestration during the Holocene (Fujimoto 2004; Dommain et al. 2011; Page et al. 2011; Alongi 2012). The coastal swamp forests have generally expanded with the evolution of coastal lowland after the postglacial transgression.

The habitat evolution of mangrove forests has been revealed geomorphologically (e.g., Woodroffe 1982; Fujimoto et al. 1996, 1999a), and concrete data on belowground carbon storage has been accumulating since the late 1990s (Fujimoto et al. 1999b; Fujimoto 2004; Alongi 2012). Fujimoto (2004) compiled the data

on belowground carbon storage and revealed that the *Rhizophora* community, which develops in the low sediment inflow area, can solely create mangrove peat (Mochida et al. 1999) and has the highest ability to accumulate belowground carbon in mangrove communities.

Freshwater swamp forests generally develop behind the mangrove forest on deltas with high sediment inflow, such as the Mekong and Chao Phraya deltas, and have no rich organic sediments except the delta margins away from the river channel (Nguyen et al. 2000; Tanabe et al. 2003; Fujimoto et al. 2011). On the other hand, lowland peat swamp forests develop on the coastal lowland with little sediment inflow on islands, such as Sumatra and Borneo, and they form peat domes that are over 10 m thick (Gastaldo 2010; Dommain et al. 2011).

Sediments and topography of coastal peat swamp forests were first reported by Polak (1933). Anderson (1964) was the first to discuss in literature the development of coastal

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peat swamps in the tropics using radiocarbon ages. Furukawa and Supiandi (1985) revealed the topography and stratigraphy using a 60-point boring survey along a 70 km transect on the Batang Hari Lowland in Sumatra. Neuzil et al. (1993) clarified the inorganic geochemistry of domed peat in the Siak River Lowland and Bengkalis Island. Supardi et al. (1993) revealed the geology of the same area as Neuzil et al. (1993) and reported the depositional ages of peat layer formed under peat swamp forests. Staub and Esterle (1994) and Staub and Gastaldo (2003) revealed the sedimentary structure and peat accumulation processes based on a large number of cores and radiocarbon ages on the Rajang River Delta in Sarawak. Neuzil (1997) compiled the radiocarbon ages obtained from the basal peat of four peat swamps in Sumatra and Kalimantan and discussed the initiation of peat formation and the peat accumulation rate. Palynological studies were also conducted for Holocene peat in Malaysia and Indonesia (e.g., Anderson and Muller 1975; Haseldonckx 1977; Morley 1981; Cole et al. 2015).

These studies revealed the outline of evolution for the coastal lowlands covered by peat swamp forests. However, there are few studies (Staub and Esterle 1994; Staub and Gastaldo 2003) on the spatial habitat evolution of tropical peat swamp forests in a specific coastal lowland based on intensive coring and dating. Most previous studies obtained depositional ages of the peat layer from a few boring cores (e.g., Anderson 1964; Furukawa and Supiandi 1985; Cameron et al. 1989; Staub and Esterle 1993; Supiandi 1988; Neuzil 1997).

In terms of carbon storage, Dommain et al. (2011) estimated peat dome initiation and peat and carbon accumulation rates using existing data (e.g., Neuzil 1997; Shimada et al. 2001; Page et al. 2004) obtained from Peninsular Malaysia, Kalimantan, and Sumatra. Dommain et al. (2014) calculated stored and released carbon from the peat swamps of Kalimantan and Sumatra using the data compiled by Dommain et al. (2011). Dommain et al. (2015) suggested that mechanisms of peat accumulation in tropical forests were possibly different from those of northern peatlands. Cobb et al. (2017) built a numerical model of waterlogging and peat accumulation to simulate peat dome geomorphogenesis and carbon fluxes.

However, there are few data (Cameron et al. 1989; Neuzil 1997; Dommain et al. 2015) on carbon concentrations together with bulk density of peat deposits for the coastal peat swamp forest, which are essential for calculating carbon storage.

The aims of this study are to clarify the spatial habitat evolution of a peat swamp forest on a coastal lowland along the eastern coast of Central Sumatra, to estimate carbon accumulation rates related to the geomorphological situation, and to discuss the differences with the values of mangrove peat.

Regional settings

This study was carried out on the coastal lowland in Riau Province, Central Sumatra (Fig. 1). The coastal lowland develops along the Siak, Kampar, and Indragir Rivers. Most areas of the coastal lowland of Sumatra, which are distributed along the eastern coast, were covered by peat swamp forests until recent years. However, the coverage area dropped from 75 to 28% peatlands between 1990 and 2010 (Miettinen et al. 2011) and to 19% in 2015 (Miettinen et al. 2016) due to development, mainly for plantation fields. The peat swamp forests in Riau Province decreased from 30,962 km² (80% peatlands) in 1990 to 13,879 km² (36%) in 2010 (Miettinen et al. 2011) and to 9812 km² (24%) in 2015 (Miettinen et al. 2016) for plantations, such as oil palm, acacia pulp, and coconut, and agricultural land. Small areas of mangrove forests are distributed along the coast. Though oilfields have been developed in the area between the Siak and Kampar Rivers, the peat swamp forest in the development area has been protected, except for roads and drill sites.

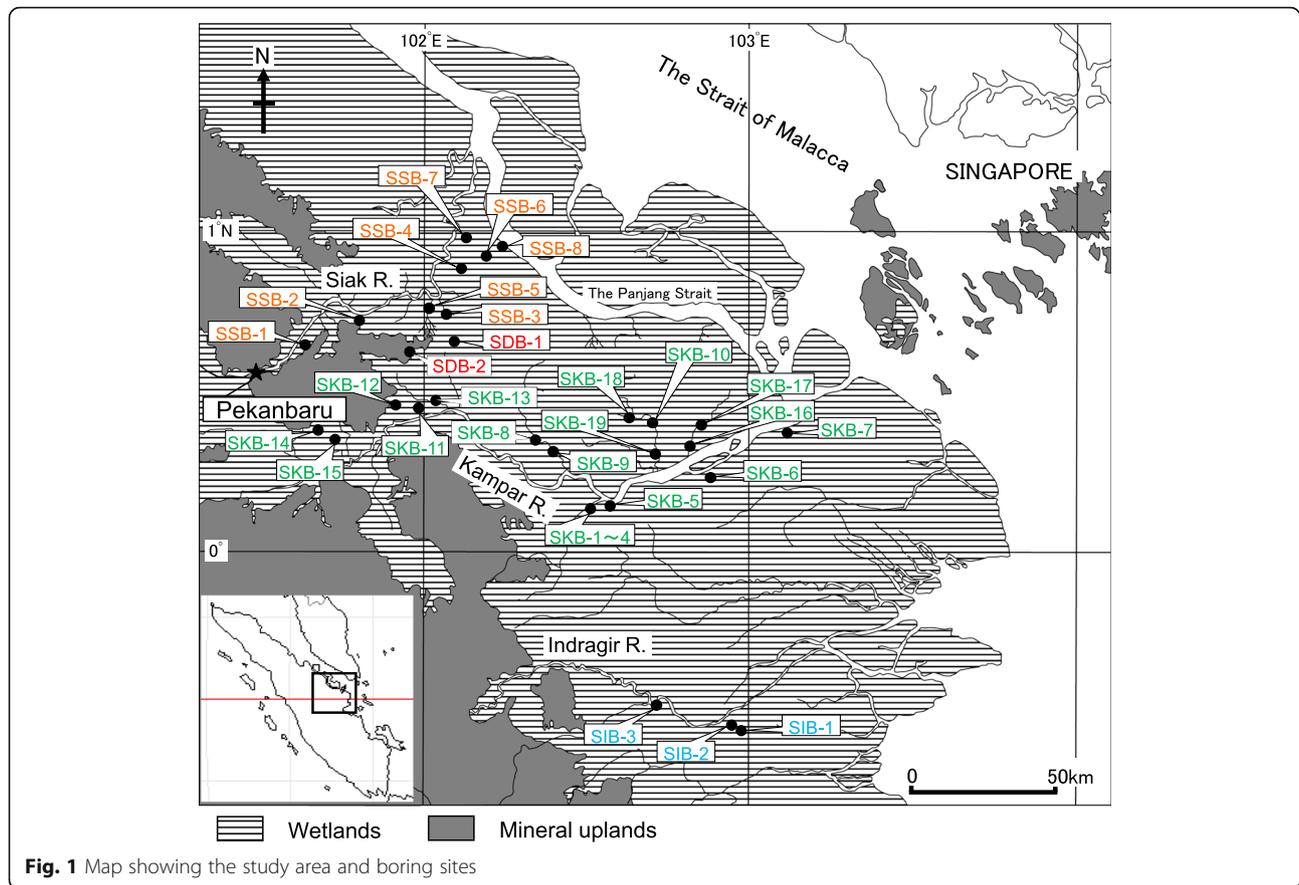
Methods

Boring survey and sampling

Boring surveys using a hand-operated peat sampler (DIK-105A, Daiki, Japan), which enabled the collection of undisturbed semicircular columnar cores 50 cm long and 5 cm diameter, excluding large woody debris, was conducted for 32 sites between 2005 and 2008 (Fig. 1 and Table 1). Eight sites were located along the Siak River (SSB-1 to 8), 19 sites were along the Kampar River (SKB-1 to 19), and 3 sites were along the Indragir River (SIB-1 to 3).

SDB-1 was located around the center of the peat dome between the Siak and Kampar Rivers, approximately 17 km from the Siak River mainstream. SDB-2 was situated beside an upland. Most sites were situated along the rivers because we had to use a boat for field research, except along limited roads. However, we conducted the boring survey not only along the mainstream but also along the tributaries to collect data from as many interior sites as possible. As SDB-1 was situated on the private land of PT. Bumi Siak Pusako, an oil development company, we carried out the research with the permission of the company.

Soil samples for bulk density measurement and carbon and nitrogen contents analyses were collected at four sites, three of them located beside the Kampar River (SKB-1, 5, and 6), and another one was located around the center of the peat dome between the Siak and Kampar Rivers (SDB-1). The soil samples were sequentially collected, except for the top 50 cm horizon of SKB-5 and the woody horizons of SKB-5 and SDB-1, which were impossible to collect as undisturbed cores



using the peat sampler. The sampled depth of cores for analysis at SKB-1, 5, and 6 are shown in Table 3. One sample for each core was collected for analysis at these sites. At SDB-1, each 50 cm long boring core was cut into 10 cm sections, and one or two cut cores were used for analysis for each layer, up to 188 cm deep, 12 cut cores were used for the analysis of the homogenous peat layer between 190 and 920 cm deep. The number of samples analyzed for each layer is shown in Table 4.

Soil analyses and radiocarbon dating

Dry weight measurements for bulk density calculations and carbon and nitrogen contents analyses were conducted at the Indonesian Soil Research Institute in Bogor. Dry weight was measured after 24 h drying at 80 °C, which is an optimal procedure for peat and highly organic soils (O'Kelly 2005). Carbon and nitrogen contents were analyzed by the Walkley-Black and Kjeldahl methods, respectively.

To estimate the sedimentary environment around the boundary between the peat layer and the underlying clay layer, electrical conductivity (EC), and total sulfur (TS) content analyses were conducted for soil samples obtained from 4 sites along the Kampar River (SKB-1, 3, 5 and 6). The samples were collected at 20 to 30 cm

intervals. EC was measured using a portable EC meter (WM-22EP, TOA DKK, Japan) according to the method by Yokoyama (1993), and TS analysis was conducted using an elemental analyzer (Flash EA1112, Thermo Electron Corporation, USA) at the University of Tokyo. Generally, freshwater, brackish-water, and marine sediments were indicated by EC values less than 0.4 mS/cm, 0.4 to 1.2 mS/cm, and 1.3 to 3.0 mS/cm, respectively (Yokoyama 1993). TS content was also useful in identifying marine sediments. Generally, freshwater sediments were indicated by a value of less than 0.3%, while marine sediments were indicated by values over 0.3% (Keith and Digenis 1959). We applied these values of combination to estimate sedimentary environments.

Freshwater peat deposits formed under the peat swamp forest are occasionally underlain by mangrove peat (Cameron et al. 1989; Dommain et al. 2015). These two peats can be easily distinguished visually because the freshwater peat generally contains a large amount of woody debris (Cameron et al. 1989; Dommain et al. 2015), though the upper central portion of the peat dome (Cameron et al. 1989) and tip-up pool deposits formed after tree falls (Dommain et al. 2015) are more fibrous and less woody, whereas the mangrove peat mainly consists of roots (Fujimoto et al. 1999a) with

Table 1 Description of boring sites

Loc. no.	Latitude (N)/longitude (E)	Distance from river mouth (km)	Land use
SKB-1~4	N 0° 08' 39.3"/E 102° 31' 01.3"	101	Peat swamp forest
SKB-5	N 0° 09' 31.3"/E 102° 34' 07.5"	95	Private house
SKB-6	N 0° 15' 28.7"/E 102° 52' 45.4"	60	Coconut and pineapple plantation
SKB-7	N 0° 23' 00.5"/E 103° 06' 32.6"	30	Mangrove forest
SKB-8	N 0° 21' 13.5"/E 102° 20' 58.6"	112 (48)	Peat swamp forest
SKB-9	N 0° 19' 10.7"/E 102° 24' 15.0"	107 (49)	Peat swamp forest
SKB-10	N 0° 24' 44.6"/E 102° 42' 06.8"	73 (39)	Peat swamp forest
SKB-11	N 0° 27' 10.3"/E 102° 01' 30.7"	147 (59)	Coconut plantation
SKB-12	N 0° 27' 35.1"/E 101° 56' 01.7"	158 (66)	Private house
SKB-13	N 0° 27' 45.6"/E 102° 02' 09.9"	145 (57)	Private house
SKB-14	N 0° 23' 15.8"/E 101° 41' 49.1"	183	Private house
SKB-15	N 0° 21' 21.5"/E 101° 43' 58.2"	180	Oil palm plantation
SKB-16	N 0° 19' 36.5"/E 102° 49' 34.5"	62 (35)	Peat swamp forest
SKB-17	N 0° 23' 20.5"/E 102° 50' 39.7"	57 (28)	Peat swamp forest
SKB-18	N 0° 25' 36.2"/E 102° 38' 26.3"	79 (44)	Peat swamp forest
SKB-19	N 0° 18' 40.7"/E 102° 42' 49.6"	74 (44)	Peat swamp forest
SDB-1	N 0° 40' 23.7"/E 102° 06' 14.3"	(36)	Peat swamp forest
SDB-2	N 0° 38' 17.1"/E 101° 57' 44.2"	(49)	Private house
SIB-1	S 0° 33' 28.9"/E 102° 59' 11.3"	72	Private house
SIB-2	S 0° 32' 27.9"/E 102° 56' 47.5"	75	Private house
SIB-3	S 0° 28' 06.0"/E 102° 43' 32.3"	93	Private house
SSB-1	N 0° 39' 18.8"/E 101° 38' 19.4"	86	Secondary forest
SSB-2	N 0° 44' 21.4"/E 101° 49' 04.6"	67 (54)	Private house
SSB-3	N 0° 45' 31.9"/E 102° 03' 55.8"	53 (32)	Secondary forest
SSB-4	N 0° 53' 28.1"/E 102° 07' 32.0"	38 (16)	Pineapple farm
SSB-5	N 0° 46' 06.3"/E 102° 02' 27.1"	52 (31)	Grass land
SSB-6	N 0° 56' 34.3"/E 102° 12' 56.3"	(5)	Oil palm plantation
SSB-7	N 0° 59' 15.0"/E 102° 08' 09.0"	27 (10)	Oil palm plantation
SSB-8	N 0° 57' 22.1"/E 102° 14' 22.5"	(2)	Oil palm plantation

Number in parentheses indicates distance from the nearest coast of the Panjang Strait

black bark fragments. To reinforce the visual identification, EC and TS content analyses were applied for the basal peat at SKB-6.

Radiocarbon dating was conducted for 28 wood fragment samples and a peat sample at Institute of Accelerator Analysis Ltd. in Japan (Table 2) using the accelerator mass spectrometry (AMS) method; however, four samples (IAA-687, 689, 690, and 691) were analyzed by the radiometric method. The radiocarbon ages were calibrated to calendar year using CALIB 5.0. The calibrated ages in Table 2 show the minimum and maximum values of 1 σ standard deviation with median possibility in parentheses. Radiocarbon ages obtained from the basal horizon of peat swamp forest peat reported by Supardi et al. (1993) were also calibrated to the calendar year because the ages were indicated by ^{14}C age only. The calibrated ages were shown in Fig. 4.

Results

Distribution of peat layers and their formative ages

Figures 2 and 3 show the geologic columns of boring sites along the Kampar River and the Siak and Indragir Rivers, including the center of peat dome between the Siak and Kampar Rivers, and the results of radiocarbon dating using calibrated age. Figure 4 shows the spatial distribution of the calibrated ages obtained around the basal horizon of the peat layer, indicating the initiation age of peat swamp forest or mangrove forest consisting of *Rhizophora* sp., including the cores that were short of the base of the peat layer.

On the inland valley bottom lowlands, an age of approximately 7030 cal BP (IAAA-72998) was obtained from the clay layer with peat (3.20 to 3.23 m depth), which was just below the peaty clay layer overlain by the

Table 2 Results of radiocarbon dating and calibrated ages

Lab. code	Site no.	Depth (cm)	Sample	$\delta^{13}\text{C}$	Conventional age (^{14}C BP)	1 σ calibrated age (cal BP)	Moving average of calibration curve (years)
IAAA-42316	SKB-1	345–350	Wood frag	-39.90 ± 0.74	2850 ± 40	2880-(2960)-3010	20
IAA-687	SKB-2	320–330	Wood frag	-28.9	2300 ± 80	2150-(2310)-2430	50
IAAA-42317	SKB-3	370–380	Wood frag	-31.53 ± 0.88	2830 ± 40	2870-(2940)-2980	20
IAAA-42427	SKB-3	430–440	Wood frag	-26.91 ± 0.61	2750 ± 40	2790-(2840)-2870	20
IAA-689	SKB-5	367–397	Wood frag	-26.3	1670 ± 80	1440-(1580)-1700	20
IAA-690	SKB-5	443–470	Wood frag	-26.0	2160 ± 80	2060-(2160)-2310	50
IAA-691	SKB-6	330–337	Peat	-27.6	3690 ± 80	3920-(4030)-4140	50
IAAA-62241	SKB-8	125	Wood frag	-26.25 ± 0.69	1290 ± 30	1180-(1230)-1280	20
IAAA-62242	SKB-8	362	Wood frag	-25.56 ± 0.70	2160 ± 30	2120-(2170)-2300	20
IAAA-62243	SKB-9	165	Wood frag	-25.25 ± 0.82	1360 ± 30	1280-(1290)-1300	20
IAAA-62244	SKB-9	309	Wood frag	-26.67 ± 0.71	2440 ± 30	2360-(2480)-2680	20
IAAA-62245	SKB-10	130	Wood frag	-29.16 ± 0.72	2330 ± 30	2340-(2350)-2350	20
IAAA-62246	SKB-10	195	Wood frag	-20.11 ± 0.72	3520 ± 30	3720-(3790)-3840	20
IAAA-72997	SKB-11	260	Wood frag	-38.78 ± 0.60	5690 ± 40	6410-(6470)-6500	20
IAAA-73002	SKB-15	387	Wood frag	-34.00 ± 0.94	5560 ± 40	6310-(6350)-6390	20
IAAA-73003	SKB-17	315–320	Wood frag	-24.02 ± 0.87	2750 ± 30	2790-(2840)-2870	20
IAAA-73004	SKB-17	340–342	Wood frag	-29.41 ± 0.81	2860 ± 30	2930-(2980)-3050	20
IAAA-73005	SKB-18	314–315	Wood frag	-30.16 ± 0.70	3560 ± 30	3830-(3860)-3900	20
IAAA-73006	SKB-18	380–385	Wood frag	-25.59 ± 0.55	3870 ± 40	4240-(4300)-4400	20
IAAA-52500	SDB-1	180–190	Wood frag	-30.33 ± 0.93	560 ± 40	530-(590)-630	20
IAAA-52501	SDB-1	580–590	Wood frag	-27.61 ± 0.78	3990 ± 40	4420-(4470)-4520	20
IAAA-52502	SDB-1	915–920	Wood frag	-24.86 ± 0.74	5210 ± 40	5930-(5970)-5990	20
IAAA-52503	SIB-2	180–185	Wood frag	-29.21 ± 0.82	1500 ± 30	1350-(1380)-1410	20
IAAA-52504	SIB-2	197–205	Wood frag	-25.76 ± 0.88	1400 ± 40	1290-(1310)-1340	20
IAAA-52505	SIB-3	61–64	Wood frag	-20.64 ± 0.74	1180 ± 30	1060-(1110)-1160	20
IAAA-52506	SIB-3	146–150	Wood frag	-27.68 ± 0.96	1200 ± 40	1070-(1130)-1170	20
IAAA-72998	SSB-1	320–323	Wood frag	-29.07 ± 0.61	6130 ± 40	6950-(7030)-7150	20
IAAA-73000	SSB-4	395–400	Wood frag	-27.24 ± 0.64	3540 ± 30	3730-(3830)-3880	20
IAAA-73001	SSB-6	262–263	Wood frag	-21.46 ± 0.62	5720 ± 30	6460-(6510)-6550	20

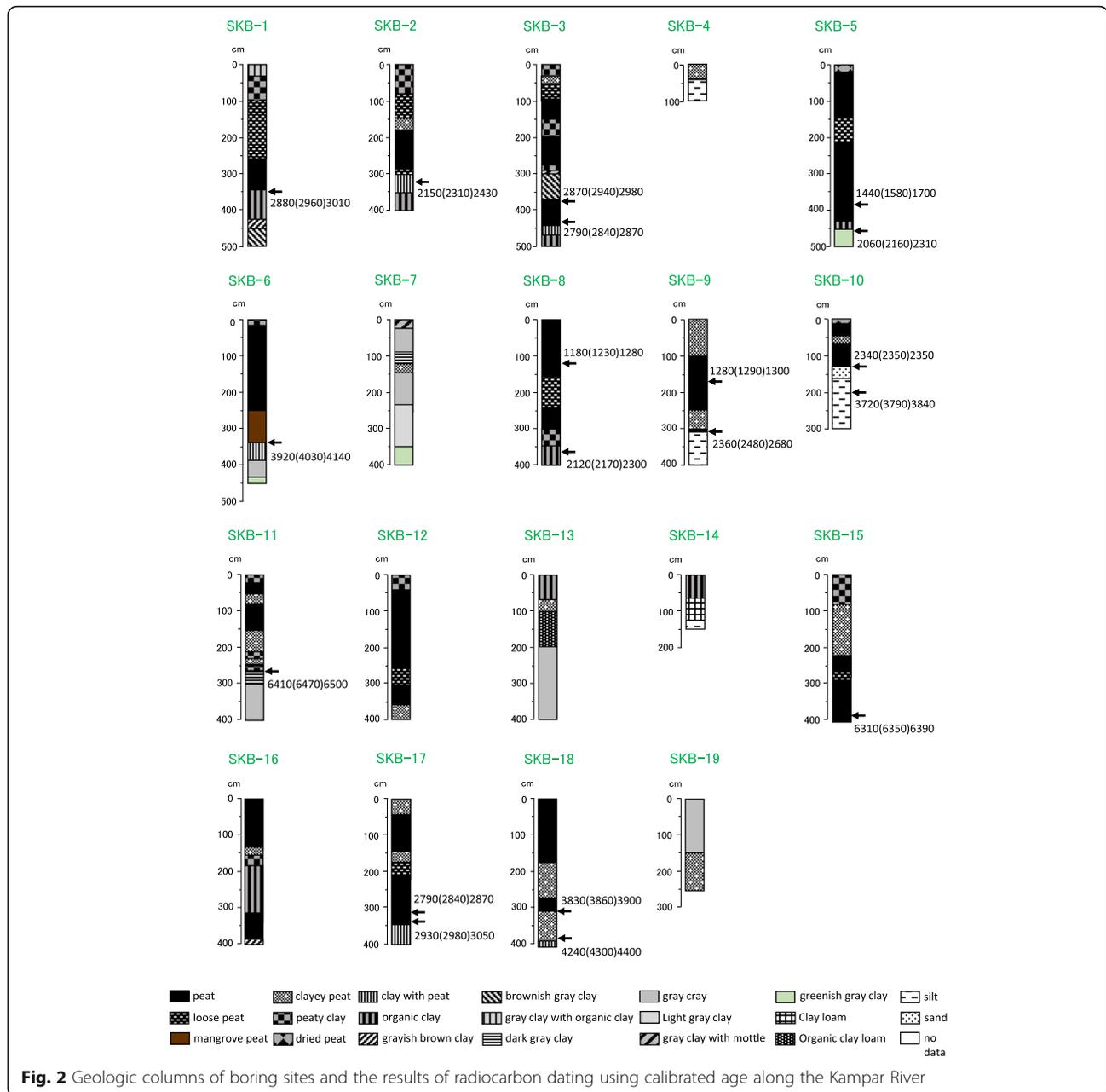
peat layer at SSB-1 in the Siak River basin, and an age of approximately 6350 cal BP (IAAA-73002) was obtained from the middle horizon of the peat layer (3.87 m depth) at SKB-15 in the Kampar River basin. At SKB-11, which is located near the mouth of the valley bottom lowland of the Kampar River, an age of approximately 6470 cal BP (IAAA-72997) was obtained from the basal horizon of peat layer (2.60 m depth).

Near the center of landward peat dome on the coastal lowland between the Siak and Kampar Rivers, peat layer over 9.2 m thick was confirmed at SDB-1, and an age of approximately 5970 cal BP (IAAA-52502) was obtained from the deepest horizon of the core (9.15 to 9.20 m depth).

On the coastal lowland of the Siak River basin, a peat layer over 4 m thick was formed 38 km inland from the river mouth (SSB-4), and an age of approximately 3830

cal BP (IAAA-73000) was obtained from the deepest horizon (3.95 to 4.00 m depth). At the site located approximately 11 km seaward from SSB-4, an age of approximately 6510 cal BP (SSB-6 IAAA-73001) was obtained from the clay layer overlain by the peat layer (2.62 to 2.63 m depth).

On the coastal lowland of the Kampar River basin, a peat layer less than 4.5 m thick was distributed along the river, and ages between approximately 2170 and 2980 cal BP were obtained from the basal horizon of the peat layer (SKB-1: IAAA-42316, SKB-3: IAAA-42427, SKB-5: IAA-690, SKB-9: IAAA-62244, SKB-10: IAAA-62245, and SKB-17: IAAA-73004), though distinctly older ages, approximately 4030 (IAA-691) and 4300 cal BP (IAAA-73006), were obtained from the basal horizon of the peat layer at SKB-6 and clayey peat layer at SKB-18,



respectively. Sampling depths for the coring sites are shown in Table 2.

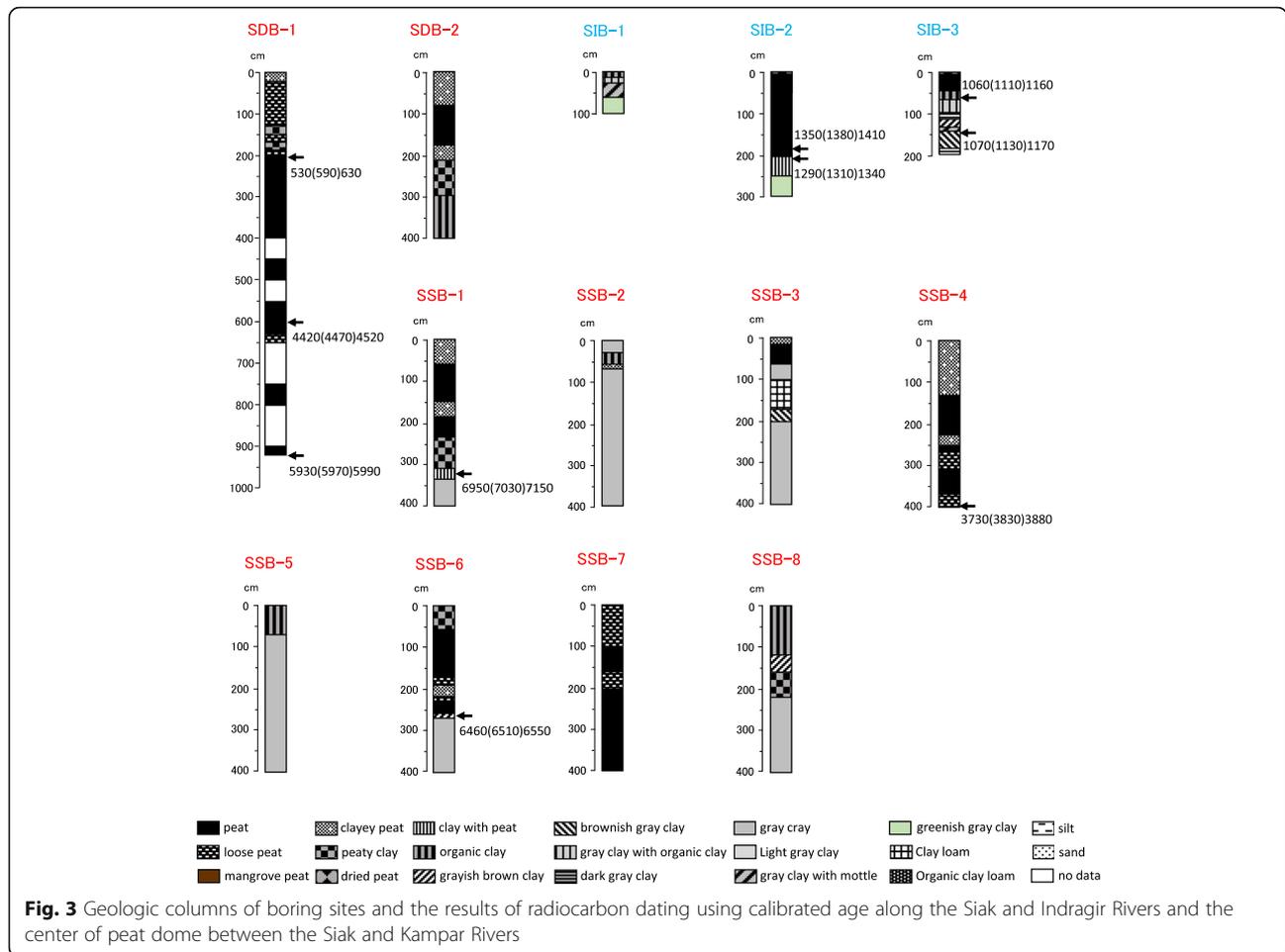
The basal peat between 2.5 and 3.4 m depth at SKB-6 was identified as mangrove peat from the main materials, i.e., fibric fine roots with distinctive black bark fragments. The wood sample for IAA-690, which was a black bark fragment, obtained from SKB-5 is presumed to be of mangrove origin because of this feature.

Along the Indragir River, relatively younger ages, between approximately 1130 and 1380 cal BP (SIB-2: IAAA-52504 and IAAA-52503, and SIB-3: IAAA-52505),

were obtained from the basal horizon of the peat layers, their thicknesses were less than 2 m.

EC and TS analyses

Figure 5 shows the results of EC and TS content analyses. High values of EC and TS content, indicating brackish to marine environments, were measured for the clay layers overlain by peat layers at SKB-1, 5, and 6. At SKB-1, over 0.5 mS/cm of EC and over 1% of TS content were obtained from the organic clay layer below 4.0 m depth. At SKB-5, over 0.4 mS/cm of EC was obtained



from the organic clay layer between 4.3 and 4.4 m depth, and over 1% of TS content was obtained from the greenish gray clay layer between 4.5 and 4.8 m depth. At SKB-6, over 0.5 mS/cm of EC was obtained from the clay layer below 3.5 m depth, and over 0.8% of TS content was obtained from the peat layer below 2.8 m depth, which was identified as mangrove peat from the main materials, with the clay layers overlain by the peat layer.

Low values of both EC and TS content, indicating freshwater environments, were obtained from the peat layer and upper horizon of the organic clay layer at SKB-1 and 3, less than 0.4 mS/cm and less than 0.3%, respectively, with the peat layer overlaying the clay layer at SKB-5 and the peat layer overlaying mangrove peat at SKB-6.

Belowground carbon storage and its burial rate

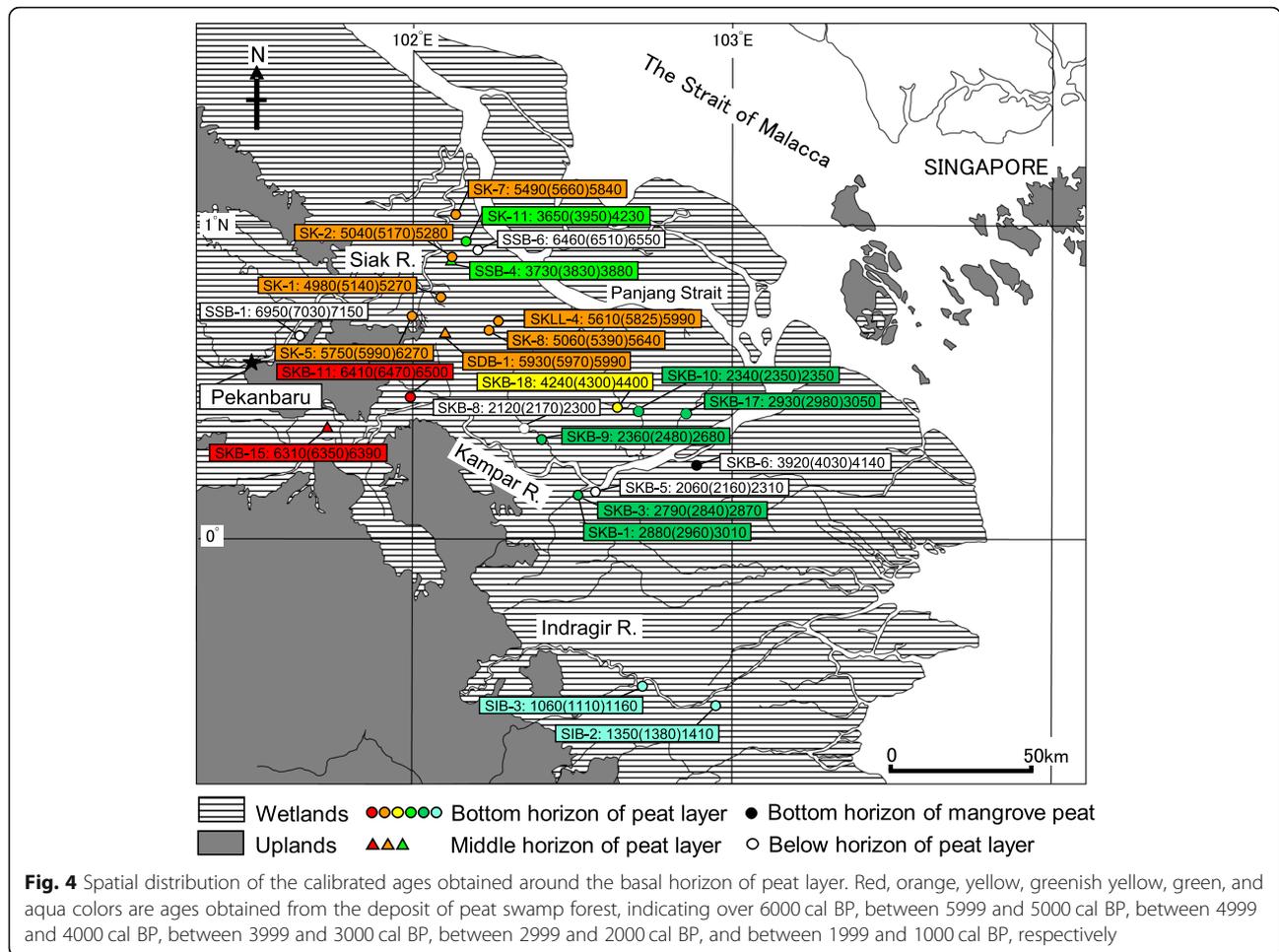
Tables 3 and 4 show the bulk density, carbon, and nitrogen concentrations and their masses per square meter at the boring sites in the margin and center of the peat dome, respectively.

Carbon concentrations of peaty layers at SKB-1, 5, and 6 located in the margin of peat dome were between 18 and 43%, which was lower than those at SDB-1 located in the center, except for the top 40 cm, those were approximately 55%.

At SKB-1 situated in the margin of peat dome, a 3.45-m-thick peat layer underlain by clay layer was deposited. The amount of stored carbon in the 3.45 m deep peat layer was 102.9 kg C m⁻², whereas the entire 5-m-thick deposit, which included a basal clay layer contained 158 kg C m⁻².

SKB-5, situated in the margin of peat dome, was located in a private garden, with a 4.29-m-thick peat layer, whose top 0.2 m was dried peat and was underlain by a clay layer. Samples for analyses were collected at up to 5.0 m depth, except for the top 0.5 m because non-disturbed samples for bulk density measurement could not be collected. Stored carbon was calculated at 165.2 kg C m⁻² in the peat layer between 0.5 and 4.29 m depth and 184.1 kg C m⁻² at up to 5.0 m depth.

SKB-6 that was situated in the margin of the peat dome was located in a coconut and pineapple field with



a peaty layer deposit of up to 3.37 m depth, though the top 0.17 m was peaty clay, and between 2.5 and 3.37 m was mangrove peat. Stored carbon was calculated at 97.0 kg C m⁻² at up to 2.5 m depth, 127.8 kg C m⁻² at up to 3.37 m depth, including the mangrove peat layer, and 175.9 kg C m⁻² at up to 4.33 m depth, including the underlying clay layer.

At SDB-1 located in a peat swamp forest near the center of peat dome, a peat layer over 9.2 m deep accumulated. Stored carbon was calculated at 239.5 kg C m⁻² at up to 9.2 m depth.

Belowground carbon burial rates of the peat layers were calculated to be between 31 and 105 g m⁻² years⁻¹ for the sites located in the peat dome margin and between 27 and 76 g m⁻² years⁻¹ for the site near the center of peat dome (Table 5).

Discussion

Habitat evolution of peat swamp forest

The calibrated ages indicating approximately 6350 cal BP and approximately 6470 cal BP obtained from the middle and bottom horizons of peat layers, which were inferred

to be peat swamp forest peat from the features, were in the valley bottom lowland of the Kampar River basin and its mouth (Figs. 2 and 4, SKB-15 and 11 located 180 km and 147 km inland from the mouth of the Kampar River, respectively); they show that the peat swamp forest in the valley bottom lowland began to be formed by 6350 cal BP.

The calibrated age indicating approximately 7030 cal BP obtained from the clay layer with peat just below the peaty clay layer overlain by peat swamp forest peat at SSB-1 located approximately 86 km inland from the mouth of the Siak River (Figs. 2 and 4) has two possible interpretations, i.e., there was either a period of mangrove forest or freshwater swamp forest because the clay layer overlain by the peat swamp forest peat was deposited under blackish or freshwater environments. The calibrated age indicating approximately 5970 cal BP obtained from the middle horizon of the peat swamp forest peat located approximately 36 km inland from the coastline of the Panjang Strait (Figs. 2 and 4, SDB-1) shows that the peat swamp forest expanded to near the center of present peat dome between the Siak and Kampar Rivers by 6000 cal BP.

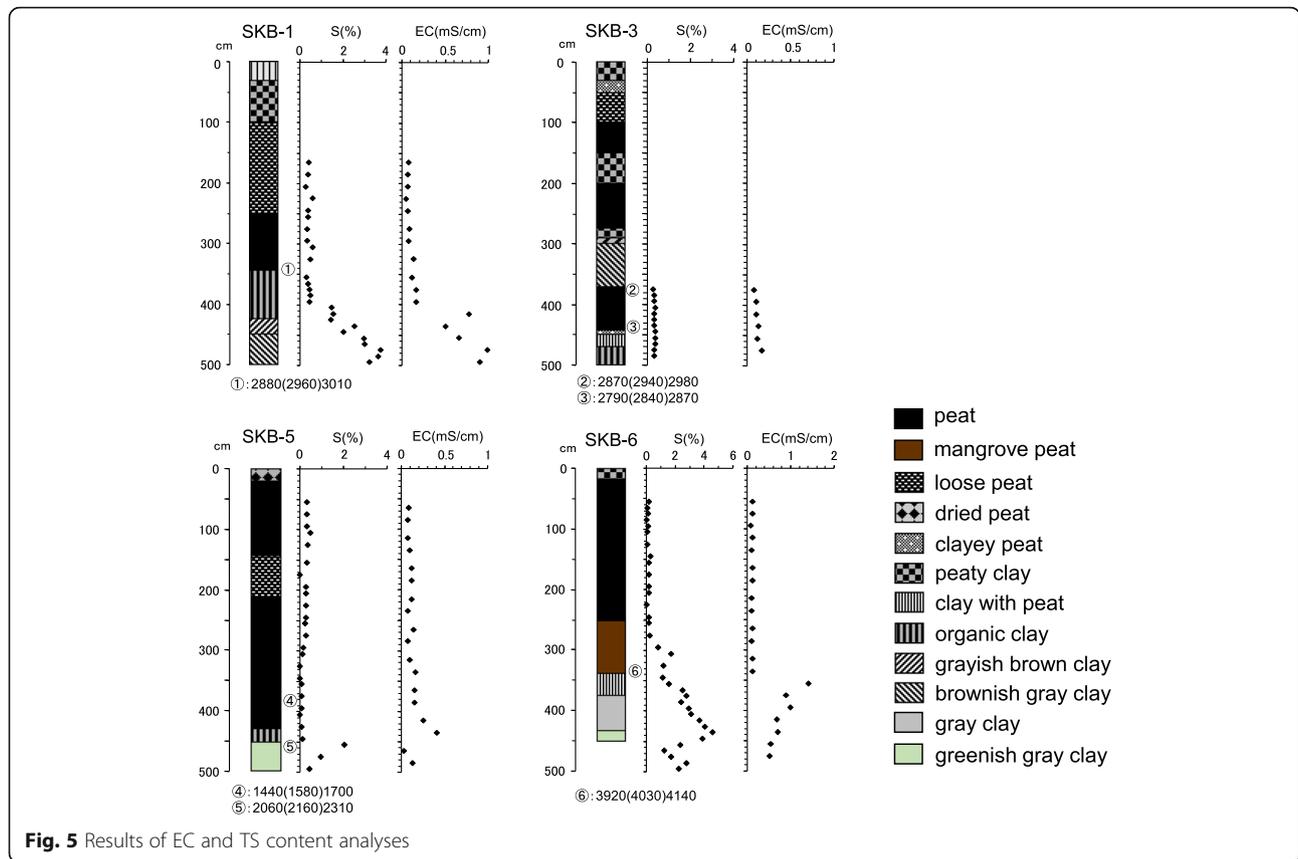


Fig. 5 Results of EC and TS content analyses

The age, approximately 6510 cal BP, obtained from SSB-6 located near the present coastline of the Panjang Strait possibly does not indicate the initiation age of the peat swamp forest but it does show the distribution of mangrove forest because the age was obtained from the clay layer overlain by the peat swamp forest peat and the site is situated in a geomorphological environment with low flooding impact because due to its distance from the rivers.

Supardi et al. (1993) reported 26 radiocarbon ages obtained from the peat swamp forest peat along the Siak River including 7 samples obtained from the basal horizon. SK-1, 2, 5, 7, 8, 11, and SKLL-4 in Fig. 4 are sites obtained the basal ages, which were indicated the ages between 3950 and 5990 cal BP.

The calibrated ages obtained from the Siak River Lowland in this study and Supardi et al. (1993) indicated that the peat swamp forest along the Siak River expanded between 6000 and 5000 cal BP.

On the other hand, the calibrated ages obtained from the bottom horizon of peat layers in the Kampar River basin suggest that the peat swamp forest on the coastal lowland expanded to the present area between 4300 and 2000 cal BP (Fig. 4, SKB-1, 3, 8, 9, 10, 17, and 18).

Approximately 4000 cal BP, a *Rhizophora* dominant mangrove forest was distributed around SKB-6 and was

located approximately 60 km inland from the present river mouth of the Kampar River. The calibrated age of IAA-690 obtained from SKB-5 and the EC and TS content values of the sampling horizon (Fig. 5) suggest that mangrove forests were distributed along the river up to 100 km inland approximately 2160 cal BP.

The calibrated ages obtained from the coastal lowland of the Indragir River (Fig. 4, SIB-2 and 3) strongly indicate that the formation of this coastal lowland occurred later than those in the Siak and Kampar River basins. The ages obtained from the basal horizons of peat layers in this study area suggested that the peat swamp forests expanded from the north to south, i.e., from the Siak River Lowland to the Indragir River lowland.

In the Asia-Pacific region, relatively high sea levels approximately 6500 cal BP and 4000 cal BP and relatively low sea levels approximately 5000 cal BP and 2000 cal BP were reported (Tjia 1996; Sinsakul et al. 1985; Sinsakul 1992; Fujimoto et al. 1996, 1999a). In the Sunda Shelf, a relatively high sea level approximately 4200 cal BP was recognized (Geyh et al. 1979; Hanebuth et al. 2011), though the high level approximately 6500 cal BP has not been determined.

The peat swamp forest initiated habitat formation by 6500 cal BP in the inland valley bottom lowlands. They developed first in the Siak River Lowland between 6000

Table 3 Bulk density, carbon, and nitrogen concentrations and their masses per square meter at the boring sites in the margin of peat dome

Loc. no.	Depth (cm)	Sedimentary facis	Sampled depth of cores for analyzing (cm)	Bulk density (kg m ⁻³)	Organic C (%)	Organic N (%)	C/N	Thickness for calculation (cm)	Stored C (kg C m ⁻²)	Stored N (kg N m ⁻²)
SKB-1	0–32	BOC	0–32	168.0	28.2	1.6	18.2	32	15.1	0.8
	32–150	PC	32–50	215.8	39.6	1.1	35.4	18	15.4	0.4
			50–100	121.4	18.2	0.4	44.3	100	22.1	0.5
			150–250	65.7	25.7	0.5	47.5	50	8.4	0.2
	250–345	P	200–250	188.0	18.8	0.4	50.8	50	17.6	0.3
			250–300	86.2	25.1	0.5	50.2	50	10.8	0.2
	345–424	OC	300–345	85.4	35.0	0.6	54.7	45	13.5	0.2
			345–350	236.3	24.7	0.5	48.4	5	2.9	0.1
			350–400	124.9	16.8	0.4	47.9	50	10.5	0.2
	424–450	GBC	400–424	376.6	15.3	0.3	49.2	24	13.8	0.3
424–450			204.3	11.6	0.3	41.4	26	6.2	0.1	
450–500			360.8	12.1	0.3	41.6	50	21.7	0.5	
							0–500	158.0	4.0	
SKB-5	0–20	DP	0–20	–	–	–	–	–		
	20–50	P	20–50	–	–	–	–	–		
	50–75	DBP	50–75	160.8	34.1	0.6	58.8	25	13.7	0.2
	75–140	P	75–100	123.6	36.7	0.8	44.2	25	11.3	0.3
			100–140	160.0	35.2	0.6	55.8	40	22.5	0.4
	140–208	LP	140–150	123.4	37.3	0.6	59.2	10	4.6	0.1
			150–200	88.8	42.4	0.7	57.3	58	21.8	0.4
	208–429	P	208–250	93.7	35.8	0.7	49.7	42	14.1	0.3
			250–300	135.4	36.7	0.7	51.0	50	24.9	0.5
			300–350	131.6	23.4	0.4	58.4	50	15.4	0.3
	429–450	DBOC	350–367	145.3	32.8	0.6	56.6	50	23.8	0.4
			400–429	137.9	32.5	0.6	59.1	29	13.0	0.2
			429–450	162.6	38.3	0.8	46.1	21	13.1	0.3
450–500	GGC	450–500	607.1	1.9	0.1	14.8	50	5.8	0.4	
							50–500	184.1	3.7	
SKB-6	0–17	PC	0–17	207.5	36.9	1.0	37.2	17	13.0	0.3
	17–100	P	17–50	129.2	33.9	0.8	42.8	33	14.4	0.3
			50–100	74.7	32.5	0.6	55.1	50	12.1	0.2
	100–180	FP	110–150	137.2	40.0	0.7	58.8	50	27.4	0.5
			150–180	109.2	42.7	0.8	52.7	30	14.0	0.3
	180–250	P	180–200	83.3	34.7	0.7	53.4	20	5.8	0.1
			200–250	98.7	20.9	0.4	49.7	50	10.3	0.2
	250–337	MP	250–300	88.7	43.9	0.8	57.8	50	19.5	0.3
			300–330	84.1	36.3	0.8	44.3	37	11.3	0.3
	337–375	GCwP	337–350	185.1	26.2	0.5	51.3	13	6.3	0.1
			350–375	243.8	28.4	0.5	52.6	25	17.3	0.3
	375–433	GC	375–400	347.4	12.6	0.3	48.4	25	10.9	0.2
			400–433	370.8	11.1	0.2	46.1	33	13.5	0.3
433–500	GGC	433–450	647.3	–	–	–	–			
		450–500	449.4	–	–	–	–			
							0–433	175.9	3.5	

P peat, FP fibric peat, LP loose peat, MP mangrove peat, DP dried peat, DBP dark brown peat, PC peaty clay, BOC brown organic clay, DBOC dark brown organic clay, OC organic clay, GBC grayish brown clay, BGC brownish gray clay, GC gray clay, GGC greenish gray clay, wP with peat

Table 4 Bulk density, carbon, and nitrogen concentrations and masses per square meter at SDB-1 near the center of peat dome

Depth (cm)	Sedimentary facies	Number of samples	Bulk density (kg m ⁻³)	Organic C (%)	Organic N (%)	C/N	Thickness for calculation (cm)	Stored C (kg C m ⁻²)	Stored N (kg N m ⁻²)
0–40	DP	2	45.9 (3.0)	35.9 (0.6)	1.4 (0.1)	26.6 (1.7)	40	3.3	0.1
40–130	LP	2	33.0 (9.6)	53.2 (1.7)	1.0 (0.2)	56.3 (9.1)	90	19.3	0.4
130–150	DeP	2	112.8 (47.0)	56.8 (2.9)	1.0 (0.1)	56.8 (7.2)	20	12.8	0.2
150–170	LP	1	42.8	56.5	0.8	71.5	20	4.8	0.1
170–188	DeP	1	105.8	54.7	1.9	28.2	18	10.4	0.4
188–920	P	12	46.1 (22.7)	55.9 (6.2)	0.8 (0.1)	68.7 (5.4)	732	188.8	2.8
							0–920	239.5	3.9

P peat, DP dried peat, LP loose peat, DeP decomposed peat. Values for the layers with plural samples are mean (standard deviation)

and 5000 cal BP and expanded after 4000 cal BP in the Kampar River and the Indragir River Lowlands (Fig. 4). Namely, the peat swamp forests in the study area seem to have formed their habitat with the sea-level changes; the sea-level falls between 6500 and 5000 cal BP and between 4000 and 2000 cal BP seems to have especially affected the habitat expansion on the coastal lowlands because of decrease of tidally affected area, though the sea-level fall between 6500 and 5000 cal BP has not been recognized in this area.

Carbon sequestration ability of coastal peat swamp forest

Stored carbon per unit volume of the peat layer at SKB-1, 5, and 6 situated in the margin of the peat dome were calculated at 29.8, 43.6, and 38.8 kg C m⁻³, respectively, while at SDB-1 situated in the center, it was 26.0 kg C m⁻³. These results indicated that stored carbon per unit volume of the peat layer in the center was possibly less than that of the margin.

Carbon concentrations at SKB-1, 5, and 6 were distinctly lower than those of SDB-1; the bulk densities of the former sites were higher than those of later site (Tables 3 and 4), suggesting that the deposits in the peat dome margin contained a clay fraction deposited by flooding. Some parts of the accumulated carbon in the margin were possibly originated by allochthonous organic matter brought with flood deposits.

Belowground carbon burial rates of the peat layers of peat swamp forests were calculated to be between 31 and 105 g m⁻² years⁻¹ in the peat dome margin and between 27 and 76 g m⁻² years⁻¹ near the center of peat dome. These values were equivalent to the data from previous studies conducted for coastal peat swamps in the tropics (e.g., Neuzil 1997; Page et al. 2004).

Stored carbon per unit volume and long-term carbon burial rate of the mangrove peat were estimated to be between 50 and 65 kg C m⁻³ and between 24 and 92 g C m⁻² years⁻¹, respectively (Fujimoto 2004); though the short-term burial rate was occasionally calculated to be higher, for example 300 g C m⁻² years⁻¹ by Dommain et al. (2015). Though the belowground stored carbon per unit volume in peat swamp forest was possibly lower than that of *Rhizophora* forest, which is the sole mangrove genus that can create mangrove peat, the long-term carbon burial rate was almost identical. The results suggested that peat swamp forests have played an equally significant role as places for belowground carbon sequestration as *Rhizophora* forests during the late Holocene.

Conclusions

The peat swamp forest initiated its formation by 6500 cal BP in the inland valley bottom lowlands and expanded rapidly between 6000 and 5000 cal BP and

Table 5 Belowground carbon burial rates of peat layers

Loc. no.	Depth (cm)	Span of accumulation		Stored C (kg C m ⁻²)	C burial rate (g m ⁻² years ⁻¹)
		From-to	Years		
SKB-1	0–345	BC1010–AD2005	3015	103	34
SKB-5	50–382	AD370 ¹⁾ –AD1740	1370	144	105
	382–456.5	BC210–AD370	580	35	61
SKB-6	0–333.5	BC2080–AD2005	4085	127	31
SDB-1	0–185	AD1360–AD2006	646	49	76
	185–585	BC2520–AD1360	3880	104	27
	585–917.5	BC4020–BC2520	1500	86	57

¹The age of the horizon at 50 cm deep at SKB-5 was estimated under assumption that the peat accumulation rate was constant since AD1740

between 4000 and 2000 cal BP to nearly the present distribution area. The thickness of the peat layer formed under the peat swamp forest reached approximately 4 m, even in the margin of the peat dome, and more than 9 m at the center. Stored carbon per unit volume of the peat layer was estimated to be between 30 and 44 kg C m⁻³ in the margin of the peat dome and approximately 26 kg C m⁻³ in the center, which was less than the general amount for mangrove peat. Belowground carbon burial rate of the peat layer was calculated to be between 31 and 105 g m⁻² years⁻¹ in the peat dome margin and between 27 and 76 g m⁻² years⁻¹ in the center, which were identical to rates of the mangrove peat; however, the accumulated carbon in the margin possibly contained some allochthonous carbon brought in by flooding. These data suggest that peat swamp forests have played a significant role as places for belowground carbon sequestration similar to mangrove forests with mangrove peat.

Abbreviations

AMS: Accelerator mass spectrometry; EC: Electrical conductivity; TS: Total sulfur

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Availability of data and materials

All data generated and analyzed during this study are included in this published article.

Authors' contributions

KF designed the methods of field research and analyses and wrote the manuscript. MM carried out EC and TS content analyses and drew the drafts of figures. SK planned the outline of the project and proposed it to the research fund. HS arranged the research permission and soil analyses in Indonesia. All authors joined in the field research. MM and SK read and approved the final manuscript.

Authors' information

Dr. Herwint Simbolon, who was a core member of our research team, suddenly passed away in 2011. We offer him our sincerest condolences and this paper.

Competing interests

The authors declare that they have no competing interests.

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