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Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia

Aswin Usup[1], Yoshihiro Hashimoto[2], Hidenori Takahashi[1], and Hiroshi Hayasaka[3]

[1] Graduate School of Environmental Earth Science, Hokkaido University, N10 W5, Kita-ku, Sapporo 060-0810, Japan
[2] Fire Science Laboratory, Sapporo Fire Bureau, 3-1, 10 W13, Hachiken, Nishi-ku, Sapporo 063-0850, Japan
[3] Graduate School of Engineering, Hokkaido University, N13 W5, Kita-ku, Sapporo 060-8628, Japan

ABSTRACT Peat fire in tropical peatland not only releases a large amount of carbon into the atmosphere, but also causes significant damage to peatland ecology and the landscape. It is important to understand peat fire and to establish more effective methods to control peat fire. In this paper, the results of field and laboratory research elucidate the combustion and thermal characteristics of peat fire. Field studies were carried out at 9 study plots in actual peat fire areas along the Trans Kalimantan Highway of Central Kalimantan in 2002. Laboratory analyses using a bomb calorimeter and TG-DTA were carried out to obtain low and high ignition temperatures and calorific values of various peat fire fuels. Results of field studies on weather conditions, temperatures in peat layers during fire, patterns of peat fire fronts, peat fire spreading speeds, fuel composition, moisture contents and fuel losses during fires are described in this paper. This study clarified the nature of fire movement and the smoldering process in an actual peat fire in tropical peatland. Based on our results, a more effective method for controlling peat fire can be developed.

Key words: tropical peat, peat fire, peatland fire, thermal characteristics, Central Kalimantan.

INTRODUCTION

Tropical peatlands are important natural resources and have considerable effects on regional and global environments. Wetlands, including peatland, provide a wide range of products and services that are important for direct and indirect human uses, the welfare of wildlife, and the maintenance of environmental quality (Maltby and Immirzi, 1996). Tropical peatlands are one of the largest near-surface reserves of terrestrial organic carbon, and their stability therefore has important implications for climate change (Page *et al.,* 2002). However, the stability of tropical peatlands has been threatened since the early 1980s by human activities, such as converting forest to farmland, making transmigration settlements, excessive draining, and logging (Siegert *et al.,* 2001a). During El Niño years the peatlands have increased susceptibility to fire (Barber *et al.,* 2000).

In Indonesia, peatland fires are mostly anthropogenic (Goldammer and Seibert, 1990). Fires are used by local and immigrant farmers as part of small farmland activities such as land clearance (Siegert, 2001b) and to produce ash for fertilizer (Kanapathy, 1976). While doing these activities during droughts, some fires have spread out of control and become wildfires in peatland areas.

Fires in peatland not only burn the surface vegetation, but also the peat deposits up to 100 cm below the surface (Boemh *et al.,* 2001). However, peat fire occurs only in extreme drought conditions or after the ground water level has been lowered artificially (Wein, 1983; Takahashi *et al.,* 2001). Peat fires produce large amount of smoke and the deterioration in air quality, because of the dense haze causes health problems (Page *et al.,* 2002), seriously negatively effecting social activities, human health and the peatland ecosystem as a whole. Even low intensity burning peatland fires produce large emissions of particulate mater, CO and other gas compounds (Muraleedharan *et al.,* 2001; Page *et al.,* 2002; Wein, 1983). Therefore, studies on peat fire mechanisms are crucial for peatland fire management.

After large forest fire in Indonesia in 1997, many scientists began to study fire damage to biomass resources, biodiversity, natural ecosystems, social activities, human welfare and the global environment (Nugroho *et al.,* 1997; Chandrasekharan, 1998; Barber *et al.,* 2000; Siegert, 2001a; Saharjo *et al.,* 2003) but there have been no studies on peat fire mechanisms in tropical peatlands.

Wein (1993) examined peat fire behavior using a schematic cross section of the combustion zone of the surface peat layer with a preliminary model of energy, moisture and gas flux to and from the zone of combustion during burning.

Hungerford *et al.* (1995) also showed a comprehensive model of sustained smoldering and consumption processes of peat soil in Alaska. The smoldering front begins to burn downward and laterally, resulting in the creation of a bowl-shape depression. Miyanishi (2001) elucidated the processes of smoldering combustion and pyrolysis in a shallow duff layer with a numerical simulation model. The results of numerical simulation showed that both pyrolytic and oxidative degradation of duff occur down to a depth of about 1 cm and that only endothermic pyrolysis occurs below that depth due to a lack of oxygen.

The results of the studies mentioned above give an excellent overview of similar aspects of peat fire processes in tropical peatland. In spite of the very different climate, peat material and social economical conditions in which peat fires occur, there are some common physical factors that play major roles in determining the incidence and propagation of peat fires. These factors are the main subject of this paper.

The aim of this study is to clarify the physical aspects of peat fire characteristics in tropical peatland of Central Kalimantan, including the weather in the dry season, peat combustion properties and characteristics of fuel materials.

STUDY SITES AND METHODS

Study sites

As shown in Fig 1, the study sites are located in a secondary peatland forest along the Trans Kalimantan Highway between Palangka Raya and Pulang Pisau and in a secondary peatland forest near Fire Climatology Station University of Palangka Raya in Central Kalimantan-Indonesia. The peatland is a mixed farmland and wasteland in the fluvial plain of the Kahayan and Sebangau Rivers.

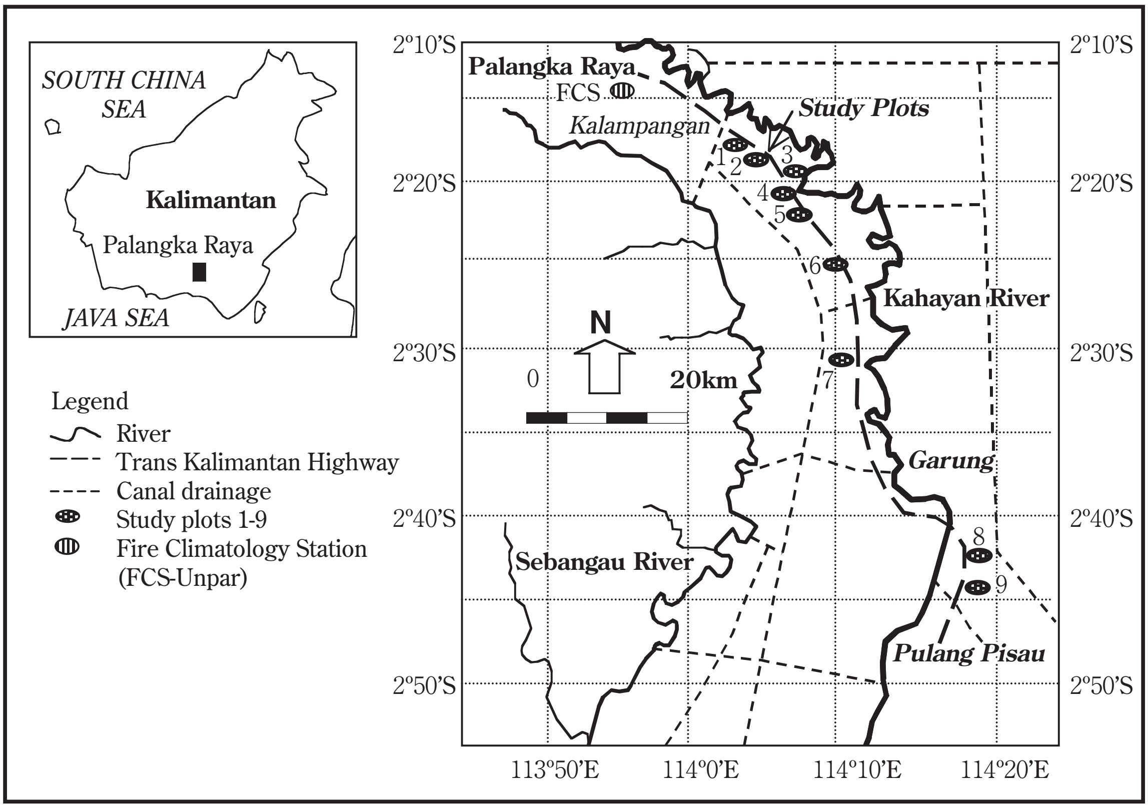

Fig. 1. Geographical map of the study area and location of the study plots along the Trans Kalimantan Highway, between Palangka Raya and Pulang Pisau.

Nine study plots along the highway were selected for field observations of wildfire in peatland during the dry season in 2002. The wildfires in each plot were caused independently. The distances between plots ranged from about 1 to 30 km. The depths of the peat layer at the nine plots were about 1-3 m (RePPProT, 1990). The principal types of vegetation in the study plots were cinnamon fern (*Osmunda cinnamomea,* pakis), vegetable fern (*Stenochlaena palustris,* kalakai) and bracken fern (*Pteridium,* Gleditsch, hawuk) with heights ranging from 1 to 3 m.

The poor tree vegetation in the study plots was caused by commercial logging, road clear-cutting, conversion of forests to farmlands and settlements since the 1980s, as well as by frequent fires. Because of the poor tree vegetation, the study sites were subjected to intense solar heat and strong winds.

Climate observatory

A climate observatory has been established in an open area of 30 square meters in a wildfire experimental station located about 2 km west of the main campus of the University of Palangka Raya and about 20 km northwest of plot 1. Air temperature and humidity were measured at a height of 1.5 m in a weather shelter using a platinum electronic resistance sensor and a capacitive thin-film polymer sensor (HMP-5D, Visala). Rainfall was measured at a height of 1.2 m using a trapping bucket type of rain gauge (34-T, OTA Keiki). Wind speed and direction were measured at a height of 4 m using a wind vane (WS-05103, Young). Global radiation was measured at a height of 1.5 m using a thermocouple sensor (PCM-01, Prede). Soil temperatures were measured at depths of 0 cm (surface), 10 cm, 20 cm and 40 cm using platinum electronic resistance sensors, and climate parameters were recorded by using a data logger (Kadec, KONA System) at one-hour intervals. Ground water levels were measured with a pressure sensor (Drug, DCM-100) in a well.

Peat combustion properties

Ignition temperature and calorific values of peat samples

Peat samples were taken from peat layers at depths of 0-20 cm, 20-40 cm and 40-60 cm in a secondary peat swamp forest near the University of Palangka Raya Climatology Station. Each peat sample was separated into fine and coarse peat materials using a 2.0 mm mesh sieve. Ignition temperatures were determined in the laboratory using a Thermogravimetry Different Thermal Analysis, TG-DTA Jasco A 6300. The heating rate used was 10°C min^{-1} from ambient temperature to 500°C. The samples used in this analysis were only 0.20 to 0.35 grams each, because the heating rate of a sample cannot be kept constant if the mass of the sample is too much (Ichihara *et al.,* 2000)

The peat calorific values were determined by a Bomb calorimeter, IKA C7000. The bomb capacity is 300 bars/210 ml with an energy input up to 30,000 joules under ambient temperature (ranging from 18 to 30°C). Peat samples were taken from three locations at depths of 0-5 cm and 5-10 cm from a secondary peat swamp forest near the fire climatology station, a farmland near plot 1 and from a pristine forest about 7 km west of plot 4. Samples were about 1.2 mg, oven-dried and powdered.

Fire temperature in the field

Chromel-alumel thermocouples 0.5 mm in diameter with a stainless steel sheath and a 6-channel data logger (KADEC-US, KONA System Co. Ltd, Japan) were used to measure fire temperatures in the field above and below the ground surface. Thermocouple sensors were set at depths of 0, 5, 10, 15 and 20 cm in the peat layer 5 cm ahead of the fire front in study plot 2 and at depths of 0, 10, 20, 30 and 40 cm in the peat layer 5 cm ahead of the fire front in plot 3. The reference soil temperatures were measured at depth of 40 cm, 4-5 m from the fire front. The data logger was buried at a depth of more than 30 cm to prevent damage by high temperature.

Peat fire spreading speed

Peat fire spreading speeds in peat soil were measured in three quadrates (each 3m by 3m) in study plots 3, 5 and 7. The quadrates were set up leeward of the fire front against the prevailing wind of these areas. Iron rods 75 cm in length and 6 mm in diameter were pleased in 50 cm intervals in each quadrate for fire observation. Typical fire front measurement is shown in Fig. 10. Since fire movement depends on both wind direction and peat properties, the fire fronts form complex shapes. Distance between an initial point and several points on the fire front were measured at one-day intervals. In this paper, the mean value of several measured distances is defined as the speed of peat fire spreading. The distance of fire line movement was measured using an iron ruler and observed once a day during the fire season in September 2002. Measurements at overhanging areas were carefully done using an iron stick and ruler.

Fuel materials in a secondary peat forest

Fuel properties

Fig. 2 shows the method to calculate the amount of grass, litter and peat before and after fires in study plot 5. The methods of Bessie and Johnson (1995) were followed. Line transects were established (1) near the burning site to calculate the amount of grass, litter and peat before burning and (2) in a scar burn to calculate the amount of grass, litter and peat after burning.

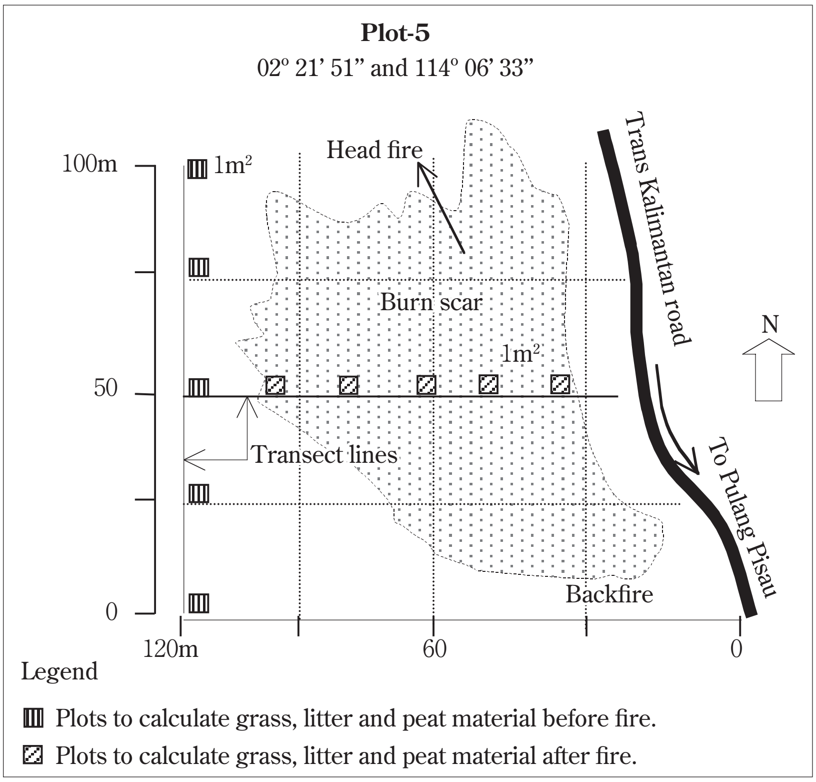

Fig. 2. Five, 1m² plots to calculate grasses, litter and peat before and after burning. This is an example of fuel measurements in plot 5.

Ratios of dead to fresh plant at $1m^2$ were determined by weighing the samples separately in the field and oven-drying them at 80°C for 24 hours.

Fuel materials below the ground surface were measured at plots 3, 4 and 5. Three quadrates, each of $1m^2$ in area were set in each plot. Materials in each quadrate were collected from layers at 0-15 cm, 15-30 cm and 30-50 cm in depth and separated into four categories: wood/root debris, grass root, and fine and coarse peat matrix sieved with a 2 mm mesh. The wood debris, wood root and grass root were classified according to size and weighed before and after oven drying. The peat matrix was classified into two sizes using a 2 mm mesh sieve after air-drying for 2-3 days.

Peat moisture was measured at plot 1 and plot 2 on August 8, 2002. Peat samples of about 200 g were taken from six depths between the surfaces to 50 cm in depth at intervals of 10 cm, and stored in plastic bags. The samples were weighed before and after drying in an oven at 120°C for 24 hr.

Fuel loss by fire

Grass and litter in each quadrate and peat to a depth of 50 cm were collected and weigh. All unburned materials from the original surface to a depth of 50 cm in each quadrate were collected and weighed after the fire. Biomass loss of surface fuels and peat loss caused by fire was calculated in the five quadrates in the study plot Equation (1):

$\overline{M}_{loss}=\overline{M}_{b\,dry}-\overline{M}_{a\,dry}\ (kg\ m^{-2})$,

where $\overline{M}_{loss}$ is the mean mass loss caused by fire, $\overline{M}_{a\,dry}$ are $\overline{M}_{b\,dry}$ the mean masses of material after and before fire. A part of the collected fuel materials was used to measure moisture contents in an oven at 120°C for 24 hr. Total dry biomass weights in each quadrate before and after the fire were estimated using the material moisture measurement. The dry weights of surface materials used for $M_{a\,dry}$ Ma dry were measured without oven drying, because the materials were already very dry due to the fire.

RESULTS AND DISCUSSION

Weather in the dry season

Fig. 3 shows mean monthly rainfall during a period of 23 years from 1981 to 2003 and monthly rainfall in 1997 and 2002 in Palangka Raya, Central Kalimantan, Indonesia. The mean monthly rainfall ranged from 100 to 341 mm. The dry season in Central Kalimantan is normally two months per year, July and August, with a mean monthly rainfall of about 100 mm. According to Mackinnon *et al.,* (1996) mean monthly rainfall less than 100 mm is categorized as a ***dry month*** and mean monthly rainfall more than 200 mm month^{-1} is categorized as a ***wet month***. Occasionally, there is an abnormally long dry season lasting 4 to 5 months; usually this is due to the effect of El Niño, as in the case of 1982, 1987, 1991, 1994, 1997 and 2002. This weather phenomenon made large areas of tropical peatland susceptible to fire.

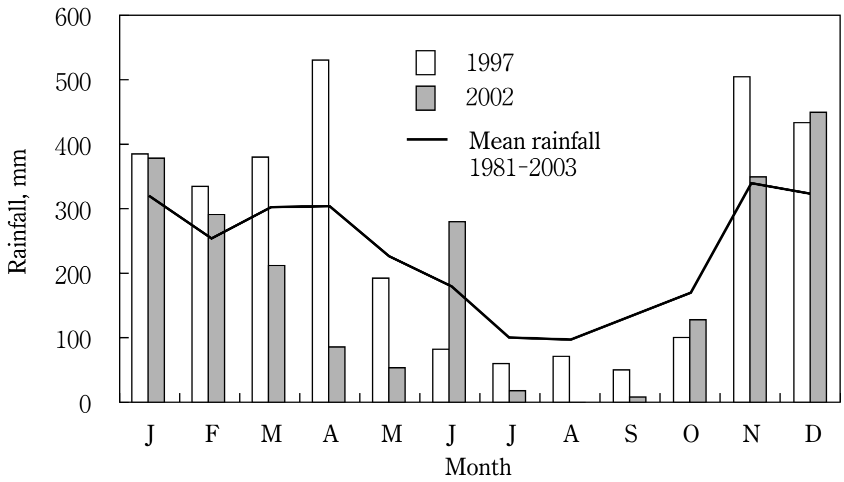

Fig. 3. Mean monthly rainfall from 1981 to 2003 in Palangka Raya, Central Kalimantan, and comparison with the monthly mean rainfall of 1997 and 2002.

Fig. 4 shows the mean monthly air temperatures in Palangka Raya from 1981 to 2001. The mean monthly air temperatures in 1997 were about 1.5°C higher than the monthly mean of the other 23 years. The increase in air temperature in this area may have been caused by the reduction of forest canopy as a result of extensive logging, conversion of forest to agriculture land, and frequent forest fires. According to Takahashi and Yonatani, (1997) the removal of forest canopy and peatland degradation alter the peatland's microclimates, producing a greater albedo effect and leading to an increase in temperature and decrease in relative humidity.

Fig. 5 shows mean monthly ground water levels (GWL) during the last 10 years in a pristine peat swamp forest in Central Kalimantan and the mean monthly ground water levels during the El Niño years of 1997 and 2002. The lowest GWL were in November 1997 (97.6 cm below the surface) and in September 2002 (94.1 cm below the surface). As a result, the peat soil in November 1997 and September 2002 was extremely dry and easy to ignite.

Ground water level is, in fact, a key factor determining fires in peatland areas. Lowering of the ground water level also affects the moisture content of grass, litter and the surface peat itself, and making conditions suitable for sustaining fires. In 1997 more than 1.4 Mha of tropical peat swamp forest was burned in Central Kalimantan (Siegert *et al.,* 2001b).

The climatic conditions in 2002, during our study, were as follows: rainfall in July and August was 2.0 and 0.0 mm

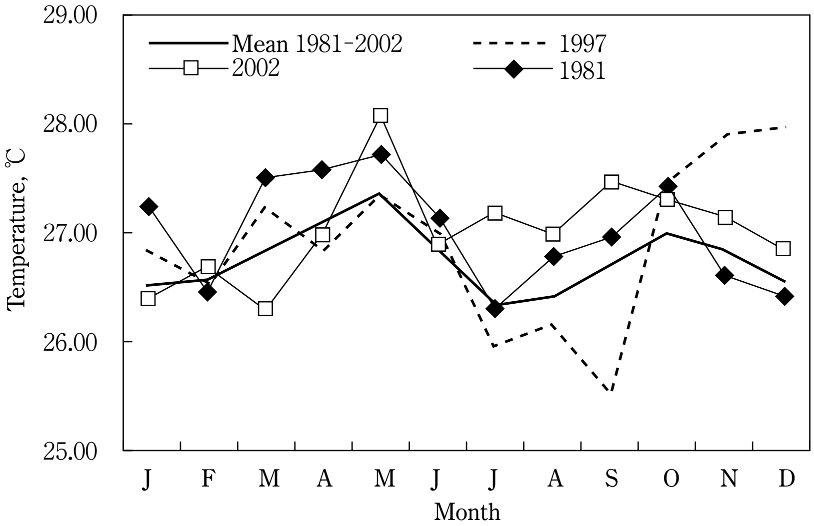

Fig. 4. Mean monthly air temperature from 1981 to 2001 in Palangka Raya of Central Kalimantan, and comparison with monthly mean air temperatures of 1981, 1997 and 2002.

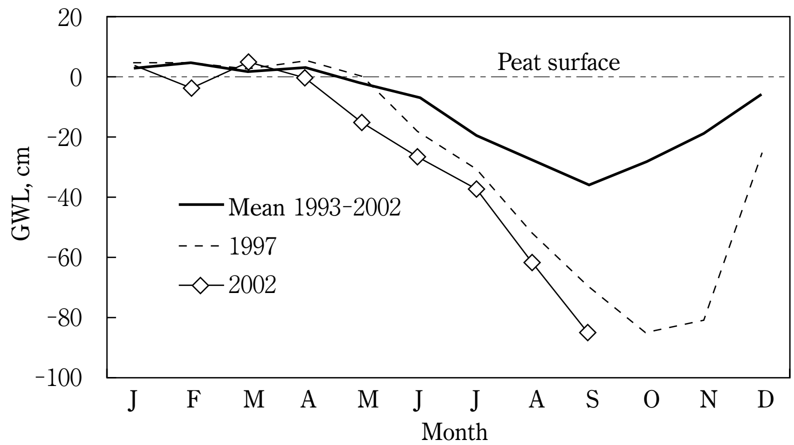

Fig. 5. Mean monthly ground water levels in a pristine peat swamp forest from 1993 to 2002 in Palangka Raya, Central Kalimantan, and comparison with the monthly mean of ground water levels of 1997 and 2002 (Takahashi, 2003).

respectively, maximum daily air temperature was 36°C for both months and minimum relative humidity was about 40% in July and 34% in August. The 10 minute average daily wind speed ranged from 2.2 to 4.0 m s^{-1}.

Peat combustion and thermal properties

Ignition temperature

Fig. 6 shows the pyrolysis processes of peat samples obtained from a depth of 40-60 cm from a secondary peat swamp forest as measured by a thermogravimetry and differential thermal analysis (TG-DTA) in the laboratory. Pyrolysis is defined as the chemical breakdown of solid fuel under the influence of heat and usually in an oxygen-deficient environment (Miyanishi, 2001). In this paper, ignition temperature is defined as the transitional point from endothermic to exothermic processes (Frandsen, 1997).

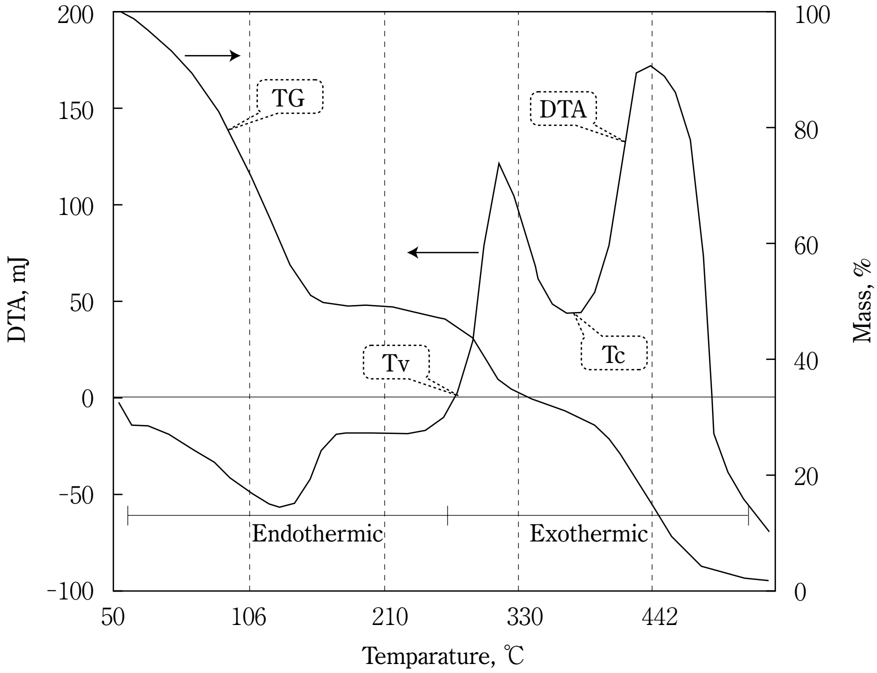

Fig. 6. TG-DTA curves of the peat material at 40-60 cm in depth from secondary peat swamp forest of Central Kalimantan.

There are two important curves of thermogravimetry (TG) and different thermal analysis (DTA). A TG curve shows the weight loss of a peat sample during a pyrolysis process, in which there are three major types of weight loss: (1) water evaporation, $\triangle W_d$ (2) combustion of volatile matters, $\triangle W_v$ and (3) combustion of charcoal matter, C_c. A DTA curve shows the rate of heat release from a peat sample during the pyrolysis process. An endothermic reaction occurs in the pre-ignition process, while an exothermic reaction occurs after the peat sample start to burn. The DTA curve is important for determining (1) the ignition temperature of volatile matters, T_v and (2) the ignition temperature of char, T_c. Results of peat pyrolysis for both fine and coarse peat materials obtained from depths of 0-20 cm, 20-40 cm and 40-60 cm are shown in Table 1.

Table 1. Combustion characteristics of peat from TG-DTA. Legend: T_v, ignition temperature of volatile matter; T_c , ignition temperature of char; $\triangle W_d$, weight loss at drying process; $\triangle W_v$, weight loss of volatile matter; C_c, carbon content of peat soil.

Peat Depth (cm)	T_v(℃)	T_c(℃)	$\triangle W_d$(%)	$\triangle W_v$(%)	C_c(%)
Fine peat material					
0-20	263	350	45.4	16.4	38.2
20-40	275	368	54.3	11.4	34.4
40-60	277	368	57.2	10.8	32.1
Coarse peat material					
0-20	256	340	20.7	47.6	31.7
20-40	268	369	54.1	11.6	34.3
40-60	260	363	50.0	13.4	36.7

Ignition temperatures of peat volatile matter, T_v, of tropical peat both, for fine and coarse materials, ranged from 256 to 277°C. These values correspond to ignition temperatures of boreal peat of 210 to 270°C as described in Ignition Handbook (Babraukas, 2003). T_v surface peat was lower than that of deeper peat layers. It has been reported that surface peat has a low moisture content, high carbon content, and low decomposition level (Yonebashi *et al.,* 1992). Ignition temperature of char, T_c of tropical peat, both for fine and coarse materials, ranged from 340 to 369°C. These values correspond to the reported ignition temperatures of lignin in the range of 280 to 500℃ (Roberts, 1970).

Simultaneous analysis of TG and DTA curves, show that the pyrolysis processes of peat materials can be divided into the following three phases:

(1). ***First phase.*** The first phase is an endothermic phase in which the soil moisture absorbed by the soil matrix evaporates while temperature increase to 150°C. The weight loss of peat were 20-45% at the a depth of 0-20 cm, about 54% at a depth of 20-60 cm and about 50-57% at a depth of 40-60 cm. In this phase, an endothermic peak appears on the DTA curve corresponding to the water content of the peat soil.

(2). ***Second phase.*** After the peat has been heated to 260°C heat continuous to gradually increase the pyrolysis speed, with hemicelluloses and celluloses decompose into gasses as CO_2, CO, CH_4, CH_3OH, CH_3COOH and laevoglucose. In this phase the weight loss of peat material ranges from 10-47% on the TG curves and involves dehydration leading to the formation of carbonaceous char that can lead to glowing combustion. The initial peak of the DTA curve and the weight loss amounts of the TG curve correspond to hemicelluloses and cellulose in the peat soil, because the hemicelluloses degrade at temperature of 200-260°C and 240-350 for celluloses (Roberts, 1970).

(3) ***Third phase.*** In this phase, self-combustion occurs and appears at the second peak of DTA curves and the TG curve changes with the rapid weight loss. The second peak of the DTA curve was higher than the initial peak. This means that peat charcoal burn was more violent than the burning of volatile matter in the peat soil. The violence peat charcoal burn is probably due to the presence large amount of lignin in the peat soil.

The amount of weight loss in this phase corresponds to the amount of carbon, Cc, in peat soil. The carbon content was calculated as the difference between residues at 340°C and 500°C, and these values are indicative of the true char values (Momoh *et al.,* 1996). Carbon yield from the surface peat ranged from 31 to 38% at a depth of 0-20 cm, and from 32 to 36% at deeper peat layers. These carbon values are lower than the carbon content of Industrial Finland peat at H1-2 of 48-50% (Andriesse, 1988) and also lower than those determined by Neuzil (1997) of 57% for global tropical peat.

Based on the results of analysis, shown in Table 1, the highest yields of carbon were found in surface peat, probably due to the minor components of chemical factors and inorganic compounds present. The rate of heating, particle size, presence of moisture and increase in inorganic content also affected the yield of char (Miyanishi, 2001).

Calorific values

The calorific value is defined as the total heat generated by the complete combustion of a unit mass of a sample at a constant volume in an oxygen atmosphere of a bomb calorimeter (Núñes Reguria, 1997). The calorific values of peat samples obtained at depths of 0-5 cm and 5-10 cm from pristine forests, secondary forests, and farmland are listed in Table 2.

Table 2. Calorific values of peat sampled from threes locations at 0-5cm and 5-10cm in depth.

Location	Depth (cm)	Material	Calorific value (kJ g^{-1})		Average (kJ g^{-1})	Moisture (%)
			1	2		
Pristine peat forest	0-5	Root & wood	21.21	21.10	21.15	49
		Peat Soil	20.50	20.61	20.56	32
	5-10	Root & wood	21.86	21.14	21.50	37
		Peat Soil	20.97	20.98	20.97	26
Secondary peat forest	0-5	Root & wood	18.85	18.85	18.85	45
		Peat Soil	19.63	19.58	19.60	43
	5-10	Root & wood	18.34	18.38	18.36	67
		Peat Soil	19.53	19.45	19.49	31
Agriculture / Bare peat	0-5	Peat Soil	23.07	23.89	23.48	19
	5-10	Peat Soil	19.92	21.27	20.59	23

The calorific values of peat ranged from 19 to 23 kJ g^{-1}. These values are larger than those of boreal peat which range from 8.0 to 18.0 kJ g^{-1} (Tokyo Astronomical Observatory, 1998) and than those of typical trees (i.e., *Combretucarpus rotundatus,* 17.5 kJ g^{-1}) in a peat swamp forest. Tropical peat is usually formed from wood, whereas boreal peat is formed from sphagnum and grasses. Due to their higher calorific values, tropical peat materials are more flammable than are other fuels, especially when they are dry.

Calorific values of peat materials at a depth of 0-5 cm were not different from those of peat materials at depth of 5-10 cm, both in pristine and secondary forests, but there was small difference between peat soil and root/wood.

In the secondary peat forest, calorific values of peat were slightly lower than those of the other peat, because peat materials in the secondary forest contain residues of former fires such as ash and unburned materials.

The calorific values of agriculture farmland at a depth of 0-5 cm depth were higher than those of the secondary and pristine forests. The high calorific values of the farmland might have been caused by the decomposition of surface peat and accumulation of char by burning surface peat for fertilizer.

Temperatures in peat layers during a fire event

Some typical peat fire temperatures were observed at plot 3 during a fire event from August 21 to 26 in 2002 and are shown in Fig. 7. The peak temperature of 275°C was measured on August 22 and kept a constant temperature for at least for 4-5 hours (Fig. 7a). Fig 7c clearly shows that the peat fire started at 7 a.m. and moved away at 12 a.m. of 22 August. The rapid temperature rise at 7 a.m. was due to heat from the peat fire front as part of the pre-heating process. The slow temperature rise around 90°C was caused by the evaporation of peat moisture. After this the temperature rose rapidly again.

The second temperature peak on August

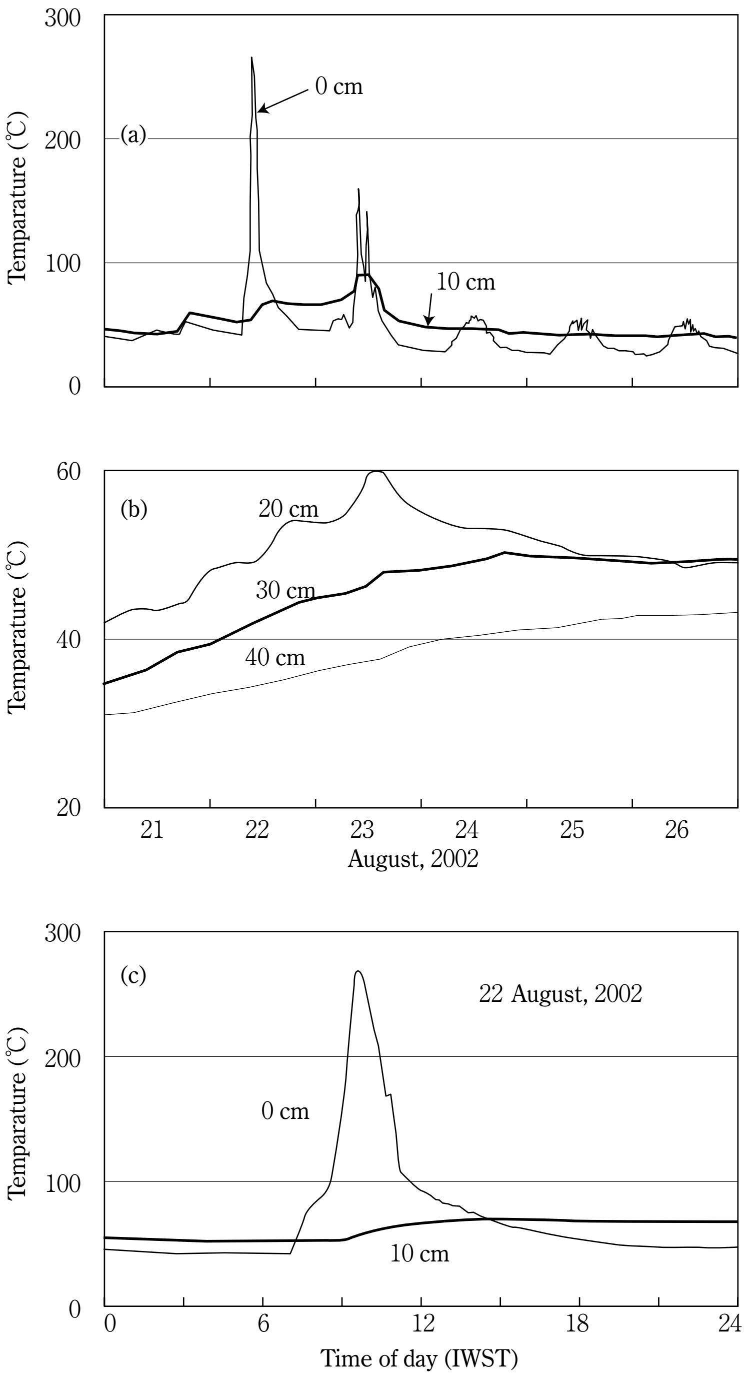

Fig. 7. The temperatures in peat layers during a fire event from August 21 to 26, 2002 in plot 3 of Kalampangan. (a) at ground surface and 10 cm depth from surface, (b) at 20, 30, 40 cm depth, (c) diurnal temperature changes of ground surface and 10 cm depth on the first day of the fire event, August 22, 2002.

23, in Fig 7a, was due to the continuation of the surface peat fire mentioned above. A temperature of around 75°C at 10 cm depth in Fig 7c may indicate smoldering combustion which still continued in the burned peat hole. Tendencies for temperatures to rise at depths of 20, 30 and 40 cm permit smoldering. This smoldering combustion became very active during the daytime when solar radiation was strongest on August 23. The lower temperature of the surface layer on August 23 was caused by the exposed fires-sensors on air after surface peat fire done of one day before.

Fig. 8 shows the relationship between burning time and the pattern of high temperature penetration into deeper peat layers, as affected by the burning of dry wood. Initially, the surface temperature of the peat layer rose slightly to 50℃ after burning for five minutes, and there was no effect on deeper peat layers. After thirty minutes, the surface peat temperature increased to 400℃ and the temperature of peat at a depth of 5 cm also increased to 100°C. An increasing fire temperature of surface peat corresponded with growing fire at the wood fuel locations. After 40 minutes, the surface temperature had decreased to 350°C and peat layer at a depth of 5 cm had started to burn. From this case it was noted that if the surface peat is heated (200-400°C) for 40 minutes, the peat at a depth of 5 cm will burn, while peat at deeper layers will not burn.

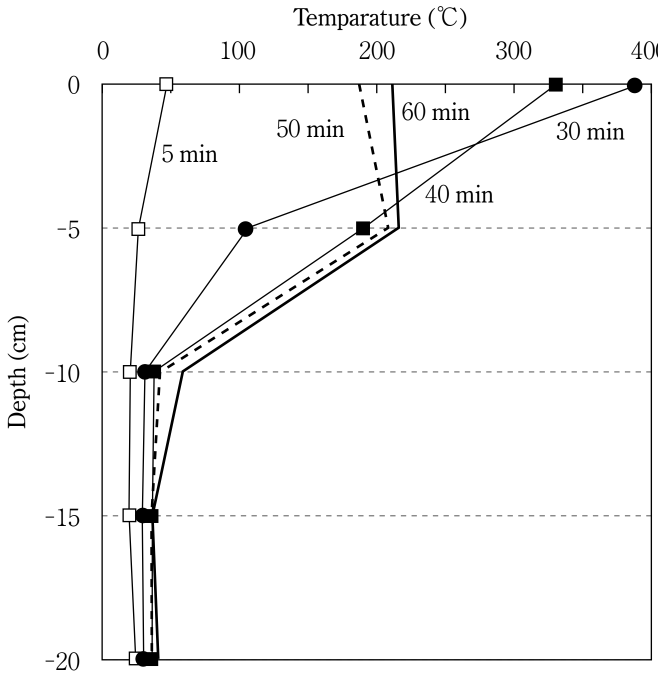

Fig. 8. Dry wood burning and pattern of temperature penetration into deeper peat layers on August 6, 2002 in Kalampangan.

High temperature penetration from a surface fire or surface peat fire into deeper peat layers is governed by many factors such as temperature level, duration of burning, peat moisture content, and quality of the peat matrix. According to Babrauskas (2003), if the peat layer is heated for more than two hours, the ignition temperature drops to 150-160°C.

Characteristics of the peat fire front

Patterns of peat fire fronts

Peat fire includes surface peat fire and deep peat fire. A surface peat fire is a peat fire that burns at a depth of 0-20 cm with the main fuel materials being grass-roots, humus and small woody fragments. A deep peat fire is a peat fire that burn at a depth of 20-50 cm with the main fuel materials being large woody fragments and peat matrix. In this paper, "***surface fire***", is defined as fire on the surface caused by surface fuels and is distinguished from "***surface peat fire***".

Fig. 9 shows the results of field observations of peat fire development in tropical peat of Central Kalimantan. Initially, the surface fires occurred in surface peat, starting from the slashed area and then spreading out of control to bush vegetation or to secondary peat forest between the village and forest areas. Activities of the villagers in this area, such as land clearing by the use of fire, were the main causes of surface fires. In the field surface fires were observed at 20 point during this study

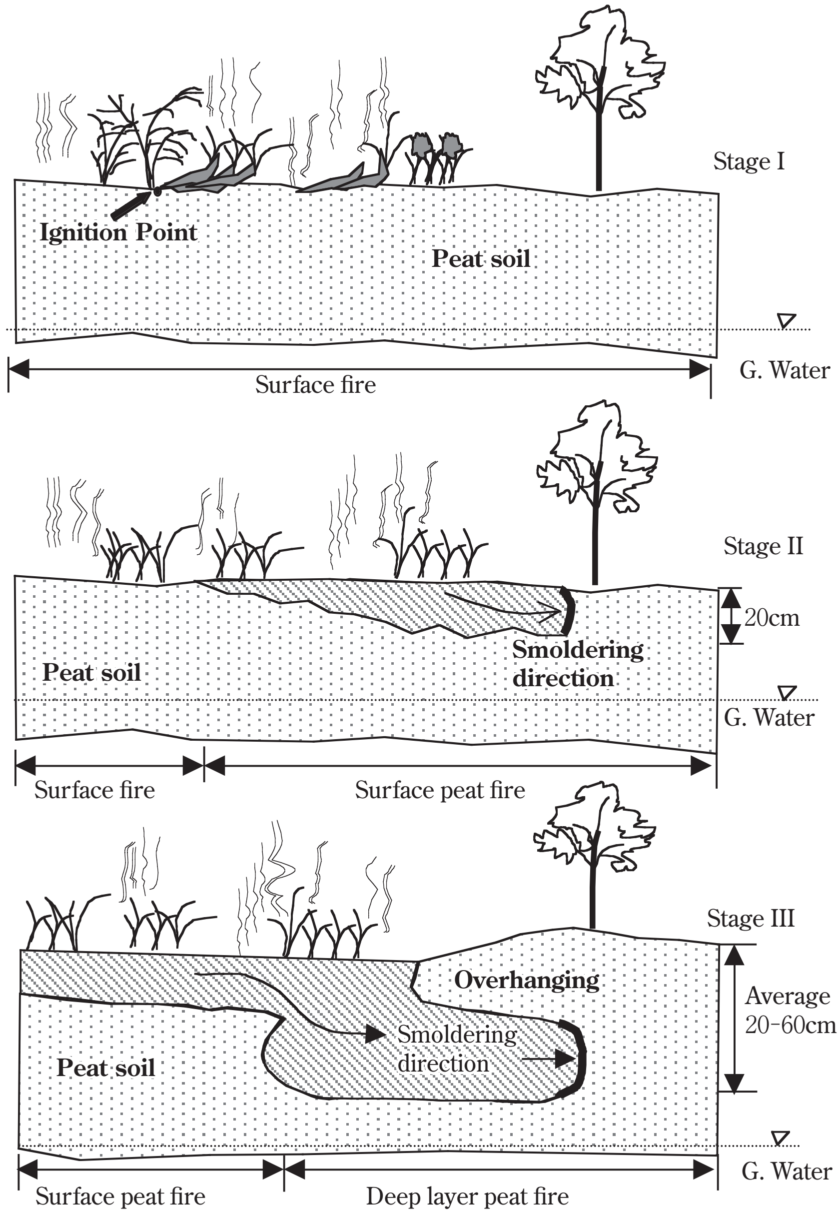

Fig. 9. Peat fire development in a tropical peatland of Central Kalimantan.Stage I: a spot of peat surface is ignited during the surface fire event. Stage II: surface peat fire burns at <20cm depth, Stage III: deep peat fire burns at >20cm depth.

and most surface fires were ignited from burning a slashed area. An interesting phenomenon is that even though fires in slashed areas were high intensity peat fires did not occur there, rather most peat fire were found in the surrounding, or adjacent un-slashed area, about 20-30 m ahead of the slashed area. The reason for this might be that the speed of fire spread in slashed areas was faster than in the un-slashed areas. In slashed areas the duration of burning is very short and to expand into deeper peat layers the fire requires not only high intensity surface fire, but also a long duration.

The surface fire ignited surface peat through cracks or woody materials, or assemblages of litter in small cavities that extend into the peat soil (Fig. 9a). A number of spot were clearly visible the after surface fire passed 1-2 hours later. These spots will extend into the peat soil if the fuel materials are sufficient enough to maintain a high fire temperature for at least 1-2 hours, otherwise these spots gradually disappear. The ignition point occurred in a location sheltered from the wind.

After surface peat had been ignited, a smoldering front started to burn laterally and downward into the surface peat to a depth of 0-20 cm (Fig. 9b) and then extended into deeper peat layers (20-50 cm) (Fig. 9c).

The processes of peat fires are not well understood. However, some characteristics of surface peat fires (at a depth of 0-20 cm) are know.

(1) Surface peat fires occur in “shallow peat” or “peaty soil” or in “karangas peat”. According to Shimada (2001), the depth of peat soil in floodplains and marginal peat of Central Kalimantan is 50 to 70 cm. Since the mean peat layer is thin, surface peat fires do not frequently penetrate into the deeper peat layers (down to 50 cm in depth). Moreover, soil materials at deeper layers, such as sand, granites and mineral soils, are noncombustible. This phenomenon was found in our study sites

8 and 9 where mineral soil constituted the bottom peat layer. According to Frandsen 1997 an inorganic content of 81.5% is the upper limit for peat soil ignition.

(2) Surface peat fires also occur widely in areas with deep peat soil, before the fire encounters conditions suitable for downward burning into deeper layers. Ground water level, moisture content, and fuel arrangement appear to be the main factors preventing a smoldering front burning into deeper layers of peat soil.

(3) Surface peat fires move quickly in zigzag lines of several fire fronts searching for favorable conditions to burn into a deeper peat layers. The width of the fire front is about 10-50 cm (Fig. 10). Surface peat fires ignite deep peat fires and serving as kindling charcoal for subsequent fires.

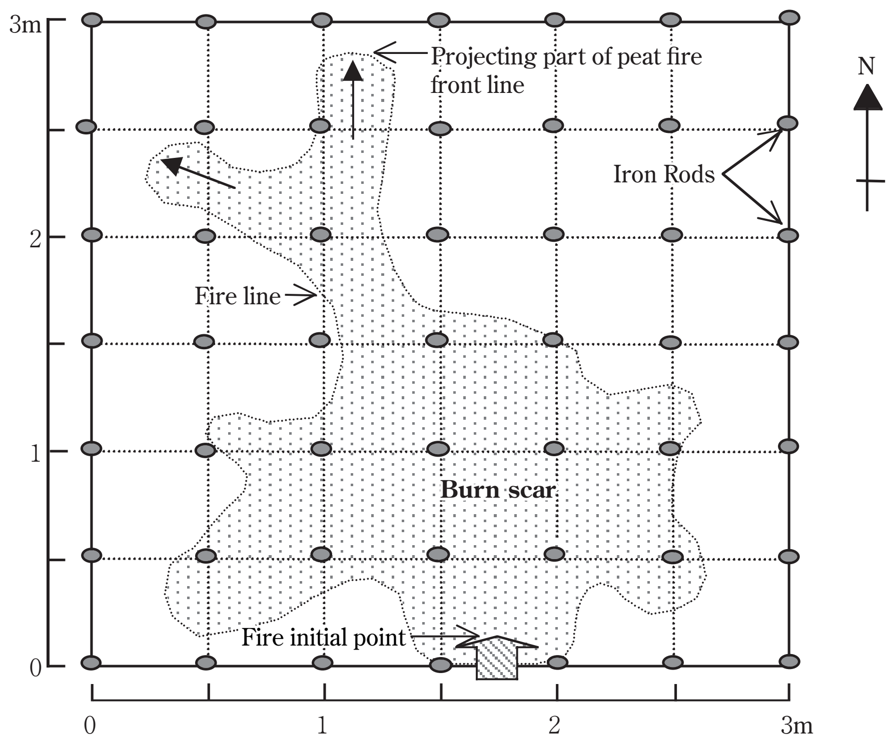

Fig. 10. A typical horizontal distribution of a burned surface peat layer with several projections of the fire front line at Plot-2 on August 10, 2002.

Deep peat fires (burning at a depth of 20-50 cm) are ignited by surface peat fire fronts. A deep peat fire is the final stage of the peat fire process. Deep peat fires spread into the peat dome, hummock, and areas surrounding tree roots. It also burned the peat stockpiles on both sides of the highway and the canal. Deep peat fires are hazardous, giving rise to black smoke and releasing pollutants into the atmosphere. Once a deep peat fire is ignited, it is difficult to extinguish, even under heavy rainfall. Cristjakov *et al.* (1983) reported that the concentration of bitumen per unit weight of peat soil increased after the peat had dried and that particles of dry peat responded to water with resin, and even if rain water penetrated into the peat through cracks, it was not absorbed by peat materials.

Deep peat fires frequently occur in the tropical peatland of Central Kalimantan. Favorable conditions for deep peat fires included: (1) lower water table, (2) low soil moisture, and (3) available fuel wood in the peat matrix. Physically, the deeper peat layers (20-50 cm) contain more wood debris than the surface layers. The wood debris appears in a chaotic arrangement and form many chinks or gaps (see woody materials in peat soil, Table 5). Moreover, the bulk density of peat soil at deeper layers (40-80 cm) was less than that of surface peat. This is also true of Malaysian tropical peat where the bulk density of a deep peat layer was 0.09-0.10 g ml^{-1}, while that of surface peat soil was 0.11-0.13 g ml^{-1} (Okazaki *et al.,* 2001). The high wood content and low bulk density of deeper peat layers enables oxygen to be supplied to the deeper peat layers when smoldering combustion occurs.

The peat fire processes in tropical peatland are not essentially different from the processes of peat fires in boreal forests, in which the smoldering progress dominants the lateral spread of the fire (Hungerford *et al.,* 1996). Horizontally, fire often burns peat soil below the surface leaving unburned material above (50-100 cm) that can cave in under a person's weight. Although the unburned overhanging collapses, the lateral spread of the fire continues and some fires resurface to promote new surface peat fires. The lateral spread of deep peat fire stops when the ground water level rises, at the end of the dry season.

Peat fire spreading speed

Table 3 shows the spreading speed of fire fronts measured at depths of 0-20 cm and 20-50 cm at study plots 3, 5, and 7. The average speed of surface peat fire (at a depth of 0-20 cm) was 3.83 cm h^{-1}, or about 92 cm day^{-1}. The maximum speed surface peat fire was 6.49 cm h^{-1}, or 155 cm day^{-1}, and the minimum speed was 1.73 cm h^{-1}, or 42 cm day^{-1}. The average speed of fire spread in deep peat (at a depth of 20-50 cm) was 1.29 cm h^{-1}, or about 29 cm day^{-1}. The maximum speed of deep peat fire was 2.50 cm h^{-1}, or 60 cm day^{-1} and the minimum speed was 0.50 cm h^{-1}, or 12 cm day^{-1}. The speed of spread of deep peat fire was half to one third of that of the surface peat fire.

Table 3. Speed of fire spread in tropical peatland, with standard deviation (SD), and number of fire samples (N).

Peat Fire type	Average (cm h^{-1})	Maximum (cm h^{-1})	Minimum (cm h^{-1})	SD (cm h^{-1})	N
Surface peat fire	3.83	6.49	1.73	1.41	20
Deep peat fire	1.29	2.5	0.5	0.64	20

The reported speeds of fire spread in tropical peatland are not greatly different than those reported for different types of peat and different regions. In a Russian peat fire, the speed of fire in stockpiled peat was reported to be 0.5-10 cm h^{-1} (Chistjakov *at al.,* 1983). The speed of fire in Australian peat was reported to be 4.2 cm h^{-1}, and that in Canadian peat, is 3-12 cm h^{-1} (Wein, 1983). Unfortunately, these reported speeds do not include depth measurements. The speed of fire spread has been shown to have a linear relationship with wind speed (Fernandes, 2001), but the relationships between the speed of fire spread in a tropical peatland and soil moisture and wind speed are still not clear.

Fuel materials in the secondary peat forest

Fuel composition

Table 4 shows the amount of fuel materials above ground in the 9 study plots. The amounts of surface fuels ranged from 15.4 to 39.6 tons ha^{-1} and the dry weight ratios of dead materials in the study plots were about 34-62%.

Table 4. Characteristics of fuel vegetation in study plots

Characteristics	Study plot								
	1	2	3	4	5	6	7	8	9
Vegetation type	……………………Bush……………………								
Maximum Vegetation height, including trees (m)	5	6	5	5	2	4	5	5	8
Ratio of dead (%) to fresh plants	34	40	59	53	39	62	45	47	52
Surface fuels (t ha^{-1})	34.2	39.6	20.1	34.4	23.9	20.5	20.5	15.4	19.6

The fuel materials in peat layers in plots 3, 4 and 5, from the surface to depths of 15 cm, 15-30 cm, and 30-50 cm were classified into four components: (1) fine peat material (2) coarse peat material, (3) wood/root debris, and (4) grass roots, Fig 11. The percentage of wood/root debris in the deeper peat layer was 19%, which is much larger than that of other layers, while the percentage of grass roots in the surface layer was 20%, which is larger than that of other layers.

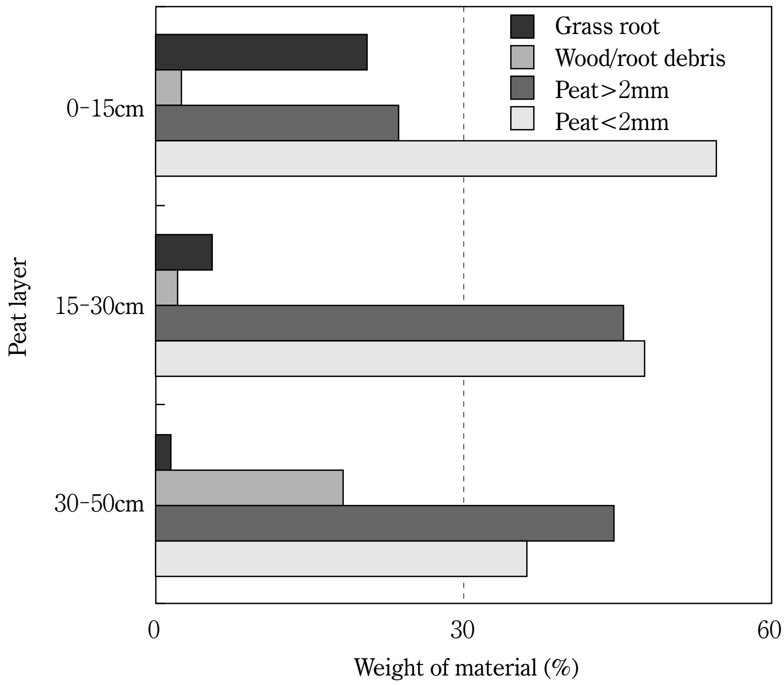

Fig. 11. The composition of fuel materials in peat layers from surface to 50 cm in depth in a one meter square quadrate.

Both grass roots in the surface layer and woody peat in deeper layers are very flammable when they are dry and are the main material for fire propagation into deeper peat layers. In addition, wood/root debris might form many chinks and gaps in the peat soil, through which fresh air can be supplied to the fire front.

Table 5. Amount of woody peat from surface to 50cm in depth at one meter square quadrates in tropical peat of Kalampangan and Tumbang Nusa.

Size diameter (cm)	Peat layers (cm) amount of woody peat					
	0-15 cm		15-30 cm		30-50 cm	
	Amount (pcs)	(%)	Amount (pcs)	(%)	Amount (pcs)	(%)
0.1-0.9	139	60	98	53	142	72
1.0-1.9	70	30	42	23	24	12
2.0-2.9	16	7	17	9	12	4
3.0-3.9	8	3	11	6	0	0
4.0-4.9	0	0	0	0	0	0
5.0-5.9	0	0	9	5	0	0
6.0-6.9	0	0	8	4	10	4
7.0-7.9	0	0	0	0	0	0
8.0-8.9	0	0	0	0	8	4
Total	233	100	185	100	196	100

Wood debris in each layer of each quadrate was counted and sorted according to diameter as shown in Table 5. There were no wood debris larger than 4 cm in diameter in the surface peat layer. Larger wood debris, 4.0-6.9 cm in diameter, were found in the peat layer at a depth of 15-30 cm , and much larger wood debris, 8.0-8.9 cm in diameter, were found in the layer at 30-50 cm in depth. This pattern is similar to that of tropical peatlands in Bacho Thailand and Mukah Malaysia, in which large woody debris were found in deeper peat layers (Okazaki *et al.,* 1994).

Peat moisture content

Fig. 12 shows the vertical profiles of peat moisture in various peat layers in study plots 1 and 2 measured on August 8, 2002. The moisture content of peat soil increased with depth. In both plots, the moisture of surface peat was about 100% in gravimetric moisture content. The peat moisture increased to about 120% at a depth of 10 cm, and was almost constant down to a depth of 40 cm. Lower than 40 cm, water content increased sharply to about 220%.

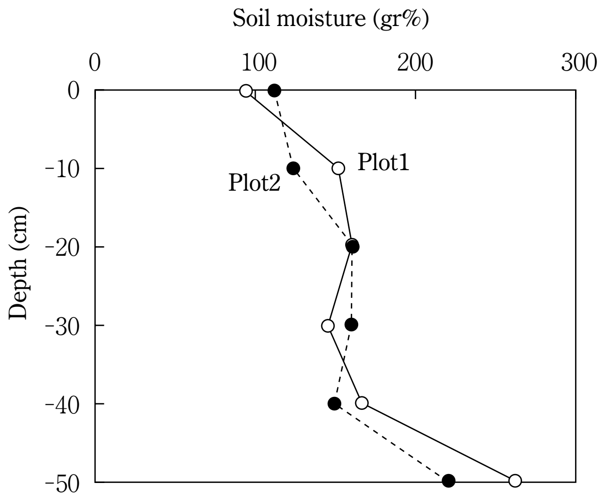

Fig. 12. The peat moisture content at study plot 1 and plot 2 sampled on August 8, 2002.

According to Frandsen (1987), peat soil is ignited at a moisture content below 110%. He also noted that the surface of a peat swamp forest can be ignited at a moisture content less than 130%. The low moisture content of the peat surface in both study plots indicated that the surface peat in these plots was dry enough possibly to burn in the middle of August.

Fuel loss by fire

Table 6 shows the mean values of biomass and peat in the five quadrates before fire and weight loss after fire in the nine study plots. The mean peat weight was approximately 34 kg m^{-2} and mean peat weight loss was approximately 8.3 kg m^{-2}, about 24% of the peat weight before fire. The mean weight of grass before burning was 3.3 kg m^{-2}, and loss by fire was 1.6 kg m^{-2}, about 48% of the initial grass. The mean weight of litter before burning was 2.2 kg m^{-2}, and loss by fire was 1.1 kg m^{-2}, or about 50% of the initial litter.

The amount of fuel material lost by fire in the study plots was larger than that of our previous study (artificial fire) on slashing and burning a secondary peat forest near a fire climatology station (Usup *et al,* 2002). At the time the surface fuel lost to fire was about 36% and peat soil was not burned at all. This was because the surface fuel in the present study was sufficiently dry and more suitable for surface fire propagation. In addition, there was abundant wood debris on the peat surface, which remained on the ground and unburned in a 1997 fire. The sparse rainfall from May to September in 2002 made the fuels on the peatland very dry, thus providing good fuel for combustion in this area.

The loss of surface fuel material in a fire depends on fuel type, moisture content, and fuel bed. According to Pyne *et al.* (1996), loss of surface fuel material in a fire never reaches 100%; it ranges from 50 to 95% in all wildfires. Loss was only about 27.4% in a forest subjected to slashing and burning for conversion into pasture land (Fernside, 1993), and loss was about 90% of trunks and large branches above ground (Seiler and Crutzen, 1980) and about 42-57% in a slashed area of a

Table 6. The mean amount of fuel material at 1m², grasses, litter and peat, in each study plot, before and after fire.

Plot	Initial fuel at 1m² (kg m⁻²)			Total (kg m⁻²)	Fuel loss at 1m² (kg m⁻²)			Total (kg m⁻²)
	Grass	Litter	Peat		Grass	Litter	Peat	
1	2.70	2.02	34.86	39.58	1.62	1.21	5.26	8.10
2	3.44	2.54	34.48	40.46	1.74	1.30	6.98	10.02
3	3.34	2.32	32.80	38.46	1.33	0.93	6.60	8.86
4	3.16	2.70	32.38	38.24	1.89	1.31	8.48	11.68
5	2.82	2.10	34.40	39.32	1.28	0.94	10.30	12.52
6	3.92	2.34	34.58	40.84	1.57	0.93	10.08	12.59
7	3.16	1.84	35.50	40.50	1.72	1.03	10.70	13.45
8	2.78	2.04	36.70	41.52	1.27	0.93	9.20	11.40
9	4.12	2.14	34.10	40.36	1.70	0.89	6.80	9.39
Mean	3.27	2.23	34.42	39.92	1.57	1.05	8.27	10.89
%	8.19	5.58	86.23	100.00	14.42	9.66	75.92	100.00

primary tropical forest in the Brazilian Amazon (Kauffman *et al.,* 1995). Loss was estimated to be about 25.1% in the Manuas region (Carvalho *et al.,* 1995).

According to Van Wagner (1972), the maximum amount of duff that could be consumed by fires in a Pinus resinosa, Pinus strobes and Pinus banksiana boreal forest was predicted to be 7.55 kg m^{-2}. The Standard Duff Moisture Code Layer in the Canadian Fire Weather Behavior System is 7 cm in depth and 5 kg m^{-2} in weight, assuming a duff bulk density of 0.071 g m^{-3} (Miyanishi, 2001).

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