Charcoal and organic geochemical properties as an evidence of Holocene fires in tropical peatland, Central Kalimantan, Indonesia

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ABSTRACT A fire-history study of the tropical peatland of Central Kalimantan has been conducted using charcoal and organic geochemical analyses. A-153 cm core was taken from Kalampangan. Charcoal analysis and 14C dating were used to understand the fire pattern, and organic geochemical analysis was used to identify environmental changes caused by fires. The peat formed from 9472 - 8981 to 7624 - 7424 cal. yr BP (calendar years before present) coeval with the development of the wet and warm climate of the Southeast Asia region. Fire frequently occurred in the study area during the peat formation. The fire intensity must have been low to have allowed continuous peat formation. The record indicated that two comparatively severe fires, or fire periods, occurred in the study area between ca. 7500 and ca. 7600 cal BP and between ca. 6400 and ca. 6500 cal. yr BP. In addition, several fires caused nitrogen loss from the peatland and destroyed the plant communities. Re-established plant communities gained nitrogen for photosynthesis from the atmosphere through bacterial fixation. As a consequence, low quality litters with more negative δ15N were produced.

Key words: charcoal, Central Kalimantan, fire, Holocene, organic geochemistry, peatland.

INTRODUCTION

Tropical peatland of Central Kalimantan, Indonesia, has been exposed to serious degradation due to peatland fires in the last decade (Page et al., 2002; Tacconi, 2003). Although peatlands are typically not susceptible to burning because of water saturation, they are mainly composed of organic matter, which is susceptible to fire under drought conditions. The severe peatland fires in 1997/1998 and 2002/2003 are examples of drought-induced fires due to human activities and climate change (Schimel & Baker, 2002).

However, fire might have frequently occurred in the peatlands of Central Kalimantan thousands years ago, as indicated by charcoal layers in the peat. Those charcoal layers are testimony to the fact that fires have occurred and that they play a significant role in the tropical peatland dynamics. However, until now there has been no report on the fire-history of tropical peatland of Central Kalimantan. Information about fire-history is important to understand the role of fire in tropical peatland dynamics.

To clarify the fire-history of tropical peatland in Central Kalimantan, evidence of fire in peat should be examined in fine resolution, while dating of the fire events should be done systematically. Charcoal is a fossil indicator of fire and charcoal analysis has been used widely to study fire-history. Furthermore, combustion of organic material is one of the most important impacts of fire on belowground systems and may alter physical and chemical properties of the material (Neary et al., 1999), perhaps leading to environmental changes. Analysis of organic geochemical properties of peat may reveal environmental changes caused by fires.

This study aims to reconstruct the fire-history of tropical peatland of Central Kalimantan based on charcoal analysis and to reveal changes in organic geochemical properties in peat with special reference to fire events. Based on the fire-history, the role of fire in tropical peatland dynamics will be discussed.

REGIONAL SETTING

Central Kalimantan has a wet tropical climate, with mean annual precipitation ranging between 2300 and 3000 mm, and the mean annual temperature between 25 and 27°C (Asdak, 1995; Takahashi & Yonetani, 1997). During the 5-6 months the precipitation exceeds 200 mm/month, whereas during the 2-3 month dry season the precipitation is less than 100 mm/month (MacKinnon et al., 1996).
Tropical peatland of Central Kalimantan is distributed in the lowland areas, about 5-35 m above sea-level, and stretches about 200 km inland from the coastal area (Fig. 1). Central Kalimantan peatland is approximately 27% of the total peatland area in Borneo (Shimada, 2001). Several large rivers, such as the Kapuas, Barito, and Katingan rivers, flow from the mountains north of the peatland area and dissect the peatland before entering the Java Sea. Peat thickness varies from about 0.5 to 9.7 m (Shimada et al., 2001).

Tropical peat swamp forests occupy most of Central Kalimantan area. Some of forests have been devastated from land conversion, forest/peat fire, and wood logging. The dominant species in Kalampangan forests are *Tetrameristra glabra*,
Calophyllum sp., Shorea sp., Combretocarpus rotundatus, palaquium sp., Buchanania sessifolia, Syzygium sp., Dacytlocladus stenostachys, Dyera costulata, Ilex cymosa, Tristaniopsis obovata, and Dyoppyros sp. (Tuah et al., 2003). In the pristine forests of the Sebangau River area, Palauquium leiocarpum, Syzygium densinervium, Xanthophyllum palembanicum, Hydnocarpus and Shorea guiso are dominant (Simbolon & Mirmanto, 2000).

MATERIALS AND METHODS

The field study was at a channel connecting the Sebangau and Kahayan Rivers. Outcrop observation was done to identify visible charcoal layers (macro-charcoal) prior to coring. A-153 m core was taken from the wall of the channel using a half cylinder type Eijkelkamp peat core sampler (cf. Neuzil et al., 1997). Charcoal samples were taken from 12 charcoal layers in the outcrop for radiocarbon dating. Samples for micro-charcoal and pollen analyses were taken from the core at 2 cm intervals. There was no sample available from 27 to 41 cm and at 129 cm, because of the presence of wood.

Radiocarbon dates were obtained using the $^{14}$C AMS method. These dates were calibrated to calendar years using the program CALIB rev.4.3 (Stuiver & Reimer, 2000). For the samples between the dated points, ages were estimated by linear interpolation.

Micro-charcoal analysis was conducted using the pollen-slide method. In this method, the number of charcoal particles is counted on slides prepared for pollen analysis. All particles black, opaque, angular and $>10 \mu m$ in size were counted as charcoal. The results of micro-charcoal analysis are presented as charcoal/pollen ratios (C/P ratio). The C/P ratio is defined as the percentage of charcoal particles to pollen grains. Fluctuation in C/P ratio reflects relative fire intensity (the amount of fuel consumed) and severity (temperature).

LOI values were measured following Heiri et al. (2001). Carbon, nitrogen, $\delta^{13}$C and $\delta^{15}$N were determined using a Fisons NA 1500 CHN analyzer.

RESULTS

Chronology

Radiocarbon dating shows that the core covers a period from ca. 9472 - 8981 cal. yr BP to ca. 7624 - 7424 cal. yr BP (Table 1). Two dates do not conform to the stratigraphic sequence (radiocarbon age inversion): IN-2 (7864 - 7654 cal. yr BP) and IN-9 (9296 - 8640 cal. yr BP). These inversions are not significant for the interpretation of the sequence, because they show overlapping radiocarbon ages with the underlying dates (Fig. 2), indicating that samples of IN-2 and IN-9 belong to the same period with IN-3 (7844 - 7474 cal. yr BP) and IN-10 (8785 - 8385 cal. yr BP), respectively. The age/depth relationship (Fig. 2) indicates a coherent sequence of increasing age with depth and relatively constant sedimentation rates of ca. 0.08 cm/yr throughout the sequence.

Table 1. Radiocarbon dates from Kalampangan peat core. Calibrated ages were calculated using CALIB 4.3 (Stuiver and Reimer, 2000), calibrated age in years B.P. and 2$\sigma$ range are given.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample</th>
<th>Laboratory ID</th>
<th>Depth (cm)</th>
<th>Radiocarbon age (years B.P.)</th>
<th>Calendar age range (cal. yr B.P.)</th>
<th>2$\sigma$ (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN- 1</td>
<td>JNC 4596</td>
<td>19</td>
<td>6650 ± 81</td>
<td>7624 - 7424</td>
<td>-26.93</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN- 2</td>
<td>JNC 4597</td>
<td>26</td>
<td>6972 ± 101</td>
<td>7964 - 7654</td>
<td>-31.41</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN- 3</td>
<td>JNC 4598</td>
<td>29</td>
<td>6814 ± 107</td>
<td>7844 - 7474</td>
<td>-30.99</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN- 4</td>
<td>JNC 4599</td>
<td>56</td>
<td>6979 ± 103</td>
<td>7970 - 7613</td>
<td>-29.59</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN- 5</td>
<td>JNC 4600</td>
<td>67</td>
<td>7256 ± 109</td>
<td>8221 - 7917</td>
<td>-30.65</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN- 6</td>
<td>JNC 4601</td>
<td>85</td>
<td>7320 ± 104</td>
<td>8344 - 7943</td>
<td>-31.90</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN- 7</td>
<td>JNC 4602</td>
<td>94</td>
<td>7364 ± 101</td>
<td>8364 - 7998</td>
<td>-28.79</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN- 8</td>
<td>JNC 4603</td>
<td>101</td>
<td>7608 ± 102</td>
<td>8563 - 8274</td>
<td>-29.85</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN- 9</td>
<td>JNC 4604</td>
<td>116</td>
<td>8090 ± 103</td>
<td>9296 - 8640</td>
<td>-29.88</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN-10</td>
<td>JNC 4605</td>
<td>121</td>
<td>7777 ± 102</td>
<td>8785 - 8385</td>
<td>-32.03</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN-11</td>
<td>JNC 4606</td>
<td>131</td>
<td>8059 ± 104</td>
<td>9159 - 8627</td>
<td>-31.29</td>
<td>AMS date</td>
<td></td>
</tr>
<tr>
<td>IN-12</td>
<td>JNC 4607</td>
<td>150</td>
<td>8203 ± 103</td>
<td>9472 - 8981</td>
<td>-30.68</td>
<td>AMS date</td>
<td></td>
</tr>
</tbody>
</table>
**Charcoal Stratigraphy**

Figure 3 shows the distribution of charcoal layers and the C/P ratios. Fifteen charcoal layers, ranging from 1 to 5 cm, could be identified in the outcrop. Macro-charcoals were found in every layer.

![Diagram showing age/depth relationship of macro charcoal layers. The straight lines are the regression lines.](image1)

![Diagram showing the distribution of C/P peaks along with intraplated-ages(cal. yr BP). The gray curves are exaggeration of the black curves with low C/P peaks.](image2)

**Fig. 2.** Age/depth relationship of macro charcoal layers. The straight lines are the regression lines.

**Fig. 3.** The distribution of C/P peaks along with intraplated-ages(cal. yr BP). The gray curves are exaggeration of the black curves with low C/P peaks.
On the other hand, the C/P diagram shows 21 peaks with a trend of high peaks (C/P > 900%) occurring in the middle of the core at 53, 61 and, in the top, at 1 and 9 cm. These C/P peaks mask the other, lower, peaks. Low peaks (C/P ratio < 140%) were identified in an exaggerated diagram.

**LOI, C/N Ratio, δ¹³C and δ¹⁵N**

The LOI, TC, TN, C/N, δ¹³C and δ¹⁵N values are plotted versus depth along with radiocarbon time scale (Fig. 4). The lost on ignition (LOI) remains high along the core with an average value of 99.66%. The TC values range from 54.6 to 66.9% with an average of 60.32%. The TN values range from 0.46 to 0.89% with an average value of 0.67%. The C/N ratios are high along the core, ranging from 67.7 to 125.9, with an average of 92.64. The δ¹³C values fluctuate narrowly between -31.1 and -29.8%, with an average of -30.36%. The δ¹⁵N values range from -2.68 to 0.38%, with an average value of -0.83%.

![Fig. 4](image_url)  
**Fig. 4.** Vertical distributions of charcoal layers, C/P ratios, LOI, TC, TN, C/N, δ¹³C and δ¹⁵N with radiocarbon age. Shaded areas indicate when fire events (C/P peaks) correlated with organic geochemical properties, indicating fire.

Figure 4 also displays the correlations among charcoal layers, C/P peaks and organic geochemical properties, along with radiocarbon ages. The LOI, TC and δ¹³C show no significant correlations, while the TN, C/N and δ¹⁵N demonstrate significant correlations to charcoal layers and charcoal peaks, as shown in the intervals between 90 and 102, 114 and 118, 132 and 142, 156 and 162 cm depths. In these intervals, TN and δ¹⁵N decrease while C/N increases. In the 12-16, 22-26, 36-38, 54-58, 64-68, 74-78, and 88-96 cm intervals, significant decreases of TN and increases of C/N without significant decreases of δ¹⁵N are apparent.

**DISCUSSION**

**Fire History**

The distribution of charcoal layers and C/P ratio peaks along the core describes the fire-history of Central Kalimantan. Fire
has occurred frequently from ca. 7624 - 7424 cal. yr BP to 9472 - 8981 cal. yr BP. Macro-charcoal fragments observed in the
charcoal layers indicate local fires, because macro-charcoal is theoretically and empirically never transported far from the fire
(Patterson et al., 1987; Clark, 1988; Whitlock & Millspaugh, 1996; Ohlson & Tryterud, 2000). Also, the fires might have
produced micro-charcoal particles preserved in the core.

Charcoal, and particularly micro-charcoal, preserved in peatland peat deposits may have different characteristics from
those preserved in lake sediments. This is because of differences in fire locality, depositional processes and depositional
environments. Lakes behave only as a depositional environment for charcoals produced by fire in the perimeter of, or far
from, the lake. Charcoal transportation, either by wind or surface processes is necessary prior to lake. Open space over lakes
promotes deposition by wind.

Peatland behaves as the depositional environment for charcoals produced by local fire. Dense forest canopies of tropical
peatland forests may prevent deposition through aerial fallout of wind-transported charcoal produced by fire from other
areas. Surface processes, such as water runoff, which may move significant amounts of macroscopic charcoal after a fire,
hardly occur in peatlands due to their gentle slopes. For that reason, micro-charcoal peaks in the palaeoecological record of
peatlands, including the C/P ratio peaks demonstrated in this study, likely indicate local fires. This is in agreement with an
experimental burning that showed an abundance of micro-charcoal resulting from local fires (Pilkänen et al., 1999).

On the other hand, variation in thickness of charcoal layers and in C/P ratios indicates variation in charcoal abundance
and thus variation in fire severity and intensity. Charcoal abundance is a result of complex interactions between fire severity
and fire intensity. Charcoal yields decrease with increased heating rates due to the complete volatilization of fuels (Bradbury
et al., 1979). Consequently, high burning temperature, (intensive) fire yield comparatively less charcoal than low
temperature fires. The peat studied was formed between ca. 7624 - 7424 cal. yr BP and 9472 - 8981 cal. yr BP, coeval with
the development of the wet and warm climate of the Southeast Asia region (Haberle et al., 2001). Considering this, intensive
fires probably did not occur during this time period. Low charcoal values in sediment indicate low fire susceptibility during
this period and were commonly found in fire-history studies in the Southeast Asia region (Haberle et al., 2001). For that
reason, variation of C/P ratios indicates changes in fire severity, rather than changes in fire intensity. Furthermore, prominent C/P peaks between ca. 7300 and ca. 7500 cal yr BP and between ca. 8500 and 8650 cal. yr BP, indicate increased
fire severity, which is probably related to increases in anthropogenic disturbances. People inhabited inland Kalimantan at
least 35,000 years ago (Flood, 1995).

In addition, low intensity fires may have allowed continuous formation of peat, as indicated by the relatively
uninterrupted radiocarbon dates. The fires may have destroyed ground biomass and litter layers, but not below ground peat.
In the case of high intensity fires, not only above ground biomass and litter layers, but also below ground peat, would have
been destroyed, resulting in a stratigraphic sequence with age-gaps.

**Organic Geochemical Properties and Their Relationship to Fire Events**

It is reasonable to assume that fire events occurred when C/N increased and the TN decreased, while the TC was relatively
stable along the core. This indicates that the fires resulted in a comparatively higher loss of nitrogen from the peat, than
carbon. Abundant wood in peat and low temperature fire may explain this phenomenon. An abundance of wood indicates that
the carbon stock is mostly in the form of lignin. Lignin requires relatively high temperatures (280-500°C) for pyrolysis
(Roberts, 1970) while it yields less volatiles and more char (Shafizadeh & deGroot, 1976; Drysdale, 1985). On the other hand,
nitrogen starts to volatilize at 200°C (Weast, 1988). The maximum peat fire temperature was 270°C during the 2002 peatland
fire in Central Kalimantan (Usup et al., 2003). Assuming that the peat fire temperatures in the past were in the range of 200-
300°C, the fires would have significantly volatilized nitrogen, while having only modestly volatilized carbon.

The decrease of TN indicates that the fires caused nitrogen to be lost from the ecosystem. However, the decrease of
TN along with relatively unchanged δ15N between 12-16, 22-26, 36-38, 54-58, 64-68, 74-78, and 88-96 cm, indicate minor
nitrogen loss. Minor nitrogen loss is not likely to alter nitrogen the cycle, allowing the δ15N values to remain relatively
constant. This loss might be the result of direct nitrogen loss during a single, or short period of, low temperature fire(s).

On the other hand, a decrease in TN in a relatively long interval, together with more negative δ15N values observed
between 90 and 102 cm, 114 and 118 cm, 132 and 142 cm, and 156 and 162 cm depths, suggests changes in the nitrogen cycle
due to serious fires or fire periods. Continuous fire events were reported to be important factors causing nitrogen limitation in
terrestrial ecosystems (Vitousek & Howarth, 1991; Toda & Takeda, 2002). Repeated fire might alter the vegetation cover by
changing the soils’ physical and chemical properties. Plant communities, which are tolerant of low-nutrient soil, replace the
former vegetation after fires in normal vegetation succession. This new plant community gains nitrogen for photosynthesis through fixation of atmospheric nitrogen, due to the lack of nitrogen in the repeatedly burned soil. The fixation results in a relatively more negative $\delta^{15}$N ratio of the new plant community than the prior (original) plant community. For this reason, the new plant community produces low-quality litter and thus low peat TN with more negative $\delta^{15}$N prior to the complete recovery of the forest results.

General Discussion

This is the first study to show that ancient fires occurred in the tropical peatland of Central Kalimantan. The record demonstrates that fires occurred during the wet and warm climatic period. The record correlates with the low regional charcoal values from other areas in the Southeast Asia region. This implies that tropical peatland may not be uniquely fire resistant and its fire-pattern may be similar with that of other tropical areas. Consequently, the incidence of fire in the tropical peatland of Central Kalimantan might have increased in the period from 5000 yr BP to the present, because of increased human disturbance, particularly after the intensification of agriculture activity, and droughts, due to the intensification of El-Niño Southern Oscillation (ENSO) climate phenomena from around 5000 yr (Haberle et al., 2001).

Furthermore, increases in fire in tropical peatland might have influenced the sustainability of peat formation to some extent. It has been reported that the age of the youngest peat deposit in Kalampangan and in the upper catchment of Sebangau River is ca. 5000 yr BP of (Sieferrman et al., 1988; Neuzil, 1997, Page et al., 1999). Peat degradation due to intensive decomposition has been proposed to be the cause of this phenomenon (Neuzil, 1997). However, this study provides evidence that fire is one of the causes for peat degradation. Increased drought conditions due to strengthening El-Niño activity and increased human disturbances after 5000 yr BP, might have promoted intensive fires, leading to peat degradation in Central Kalimantan. Therefore, fire may be an alternative explanation for the degradation of peat younger than 5000 yr BP in the tropical peatland of Central Kalimantan. Additional studies are needed to verify the history pattern of the area from approximately 5000 yr BP to the present. Confirmation that fire influences peatland plant communities is also necessary. Addressing these issues will deepen our understanding of the role of fire in tropical peatland dynamics.

CONCLUSION

Charcoal, organic geochemistry and radiocarbon dating of a-1.53 m peat core from tropical peatland of Central Kalimantan indicate that the peat was formed between ca. 9472 - 8981 cal. yr BP to ca. 7624 - 7424 cal. yr BP, coeval with the development of the wet and warm climate of the Southeast Asia region. Fire frequently occurred in the area during the peat formation. The intensity of the fires was low, allowing continuous peat formation. However, fire severity did fluctuate with time. Severe fires, or fire periods, occurred between ca. 7300 to ca. 7500 cal yr BP and between ca. 8500 to 8650 cal. yr BP.

The LOI, TC and $\delta^{13}$C curves show no variation, while the TN, C/N and $\delta^{15}$N show evidence of fire events. During fire events, TN and $\delta^{15}$N decreased while C/N increased. This might be a result of significant fire-induced nitrogen loss from the ecosystem and replacement of plant communities.

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