Research article

A Comparison of Organic Matter Dynamics Among Degraded, Dam-Restored, and Preserved Peat Swamp Forests

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Abstract The exploitation of tropical peatlands has triggered serious environmental problems such as deforestation and peat fires, loss of biodiversity, and emission of greenhouse gases. This process includes peat drainage and drying, followed by peat degradation. Dam construction is expected to decrease the vulnerability of peatlands to fires and improve the regeneration of degraded peatland. This study investigated the effects of dam restoration for peat swamp forests degraded by drainage on the dynamics of organic matter that regulate peat conditions. We compared the organic matter dynamics of three types of forest in Palagnkaraya, Central Kalimantan, Indonesia: less-drained (almost natural), drained (degraded), and dam-restored forest. Both drained and dam-restored forests experienced drainage in 1995; however, dams were constructed at the dam-restored site in 2005. Within each site, we measured litterfall, fine root production, and decomposition as indices of the peat accumulation rate, water table, and soil moisture. The mean groundwater level at the dam construction site was significantly higher than that of the drained forest. Litterfall was highest in the drained forest and lowest in the dam-restored site. The decomposition rates were not significantly different among the sites. We estimated the changes in peat mass using a model. The amounts of peat accumulation after 5 years were found to be 3.46, -1.60, and -2.86 kg/m^2 in the less-drained, drained, and dam-restored sites, respectively. These results showed that peat deposition decreased at the dam construction site but decreased less in the drained forest. A possible explanation for the observed results is increased primary production in drained forests caused by reduced flooding stress and increased nutrient supply from oxidized peat for primary producers.

Keywords tropical peat swamp forest, dam restoration, decomposition, production

INTRODUCTION

The extensive peatland areas in Southeast Asia have been degraded by exploitation (Shimamura, 2016). The conversion of peatland to farmland involves processes such as drainage of peatland, clearcutting, and field burning. These activities have led to various environmental issues, including increased greenhouse gas emissions, loss of biodiversity, and peat fires. Excavated channels were used for logging and to dry out the peat, but excessive drainage has severely degraded the peatland. As peat dries, it becomes more susceptible to fires and undergoes faster aerobic decomposition. Peat consists mainly of dead plant matter and, when dried, behaves like kindling and firewood, burning easily. Consequently, drainage increases peat vulnerability to fire. Similarly, drainage exposes peat to an aerobic environment. Aerobic conditions accelerate decomposition, whereas flooded and anaerobic conditions inhibit peat decomposition. The frequent fires and accelerated aerobic decomposition result in the release of carbon accumulated in peat into the atmosphere as greenhouse gases. To address this issue and conserve peat, dams have been constructed. The goal of dam construction is to reduce the risk of fire and prevent aerobic peat decomposition by restoring water levels and re-saturating degraded peat.

Previous studies that examined carbon flux found that dam construction does not significantly improve carbon deposition (Jauhiainen et al., 2008; Darusman et al., 2022). However, there is limited knowledge about the impact of dam construction on organic matter dynamics, such as primary production and decomposition processes, which directly regulate changes in peat deposition.

OBJECTIVES

The objective of this study was to clarify the effects of dam restoration of peatlands on organic matter dynamics. To this end, we investigated and compared 1) water table and soil moisture, 2) above- and below-ground production, and 3) decomposition processes in undrained, drained, and restored peat swamp forests.

METHODOLOGY

Study Area

This study was conducted in tropical peat swamp forests in two areas: Setia Alam (2°18’ S, 113°55’ E) and Kalampangan (2°20’ S, 114°2’ E), Central Kalimantan, Indonesia. The mean (SD) annual temperature and rainfall averages between 2009 and 2020 were 29.1 (0.63) °C and 2725 (1161) mm, respectively (https://weatherspark.com/). Seasonality in rainfall is not fixed; however, in most years, a distinct dry season is evident from May to August.

Fig. 1 Dam constructed in the canal near the restored forest

Setia Alam is situated in the Natural Laboratory of Tropical Peat Swamp Forest, which is located in the upper watershed of the Sabangau River. This area consists of large, continuous areas of relatively undisturbed and undrained forests. Although the forests had been logged selectively until the late 1990s, they remained relatively intact because it was designated a National Park in 2006.

The Kalampangan site is located between the Sabangau River and a large canal that runs from north to south. The large canal (25 m wide × 3.5-4.5 m deep) that was excavated in 1996 and 1997 functioned to facilitate drainage of the forest (Page et al., 2009). In June-August 2005, the canal was blocked at several points by small dams to facilitate hydrological restoration (Jauhiainen et al., 2008).

We established three sets of rectangular plots (50 m × 20 m) in the undrained forest (UF) in Sabangau, and the drained forest (DF) and restored forest (RF) in the Kalampangan site. Most of the field research was conducted between September 2005 and October 2006.

Water Table and Soil Moisture

The groundwater level (GWL) was measured monthly at a dip well between October 2005 and October 2006. The dip well was located at the centre of each plot. A PVC pipe perforated with small holes was vertically inserted into the peat, allowing the water level inside the pipe to be measured.

We established five points within each plot to measure soil moisture monthly. The distance between the points was more than 10 m. The volumetric water content of surface peat soil was measured monthly using a time domain reflectometry probe (UIZ3635-50mV) between September 2005 and September 2006, but not between October and November 2005 as we failed to collect data.

Organic Matter Dynamics

Litter was collected monthly in each plot from October 2005 to October 2006, using ten litter traps per plot. Each litter trap was a rectangular basket (0.75 m × 0.75 m) made from a 2 mm nylon mesh suspended from strings, and the device was held 1 m above the ground. After collection, the litter samples were sorted into leaves, flowers, branches, fruits, bark, and others, dried to a constant mass, and weighed. Traps were placed at points selected through random computation from grids of 5m intervals within each plot.

The litter deposits above the peat surface were collected in September and November 2005 and February and May 2006. All recognizable above-ground litter was harvested from five quadrats (50 cm × 50 cm) in each plot. When traces of disturbance from the previous sampling were observed, samples were collected at the nearest intact site. After collection, the litter samples were immediately dried in a self-made drying room to a constant mass and weighed.

The decomposition processes of leaf litter were studied using the litter bag method. To unify the litter samples, the leaves of *Combretocarpus rotundatus* (Miq.), one of the dominant species, were used. The litter (20 g in dry weight) was enclosed in a litter bag (20 cm × 15 cm) made of polypropylene cloth with a mesh size of 2 mm. Litter bags were set in September 2005. Five locations within each plot were selected, and five litter bags were placed on the ground floor at each selected point. The distance between each point was more than 20 m. Samples were collected five times in one year: October 2005, January 2006, April 2006, July 2006, and September 2006. A sample was collected from each sampling point. After transport to the laboratory, the dry weight loss was determined by drying the samples to a constant mass at 80 °C. Decomposition rates were estimated using Olson's k (Olson, 1963), given by Eq. (1):

$$W_{\mathrm{t}} = W_0 \times e^{-kt} \tag{1}$$

Where W_{t} is the litter weight after a given period, W_0 is the original litter weight, k is the decomposition rate, and t is time.

Ingrowth cores (20 cm length, 10 cm diameter), which were made of 2 mm nylon mesh, were filled with root-free soil and installed in the ground (0-20 cm in depth). The soil used for this purpose was taken from a nearby location, and care was taken to fill the cores so that the bulk densities were similar to the *original* levels. Ten locations per plot (distanced 10 m or more from each other) were selected, and an ingrowth core was buried in September 2005 and harvested 1 year later. At harvest, 12 cores from the UF were lost or broken. Consequently, the sample numbers were 13 from the UF and 25 from the others (DF and RF). After transporting them to the laboratory, root samples from each core were dried at 80 °C until they reached a constant mass and were then weighed.

Estimation of Change in Peat Depth

To understand the differences in the regimes of organic matter dynamics among the three types of forests, we used a model that simulates changes in peat depth (Shimamura and Momose, 2005). In the simulation, peat was characterized by two horizons: surface aerobic acrotelm and deeper anaerobic catotelm. Differences in acrotelm thickness strongly contributed to differences in peat thickness and peat deposition. On the other hand, the depth of the catotelm layer was defined by the height of the water table and the bottom of the peat. The peat deposition model expressed by Eq. (2) was used to simulate peat deposition in the acrotelm layer, which is influenced by organic matter dynamics.

$$m_A = A\exp(p_A/b-k_A)t + sk_L(p_L/k_L-m_{L0})\exp(-k_Lt) / (k_L + (p_A/b-k_A)) - (sp_L-m_Ck_C) / (p_A/b-k_A) \quad (2)$$

where m_A is the acrotelm layer mass, A is an integral constant, p_A is the root input per unit depth, b is the bulk density of the acrotelm layer, k_A is the rate of mass loss from the acrotelm materials through respiration, t is the time, s is the portion of fragmented litter not lost from soils by respiration or leaching, k_L is the decomposition constant of litter, pL is litterfall mass, m_C is the catotelm layer mass, m_C is the mass of the catotelm layer, and k_C is the decomposition constant of the catotelm layer. Eq. (3) yields the integral constant A.

$$A = m_{A0} - sk_L(p_L / k_L - m_{L0}) / (k_L + (p_A / b - k_A)) + (sp_L - m_Ck_C) / (p_A / b - k_A) \quad (3)$$

where m_{A0} is the initial acrotelm layer mass and m_{L0} is the initial mass of the litter layer. In this study, we focused on the changes in peat mass and thickness over a relatively short period (5-10 years). The change in elevation (Δh) is given by Eq. (4).

$$\Delta h = (m_A - m_{A0}) / b \quad (4)$$

Most variables in the model were estimated based on the present study; however, for the variables k_A, s, and k_C, we applied data from PI9 and PI12 in Brady (1997) to the DF, RF, and UF sites, as the bulk densities of these combinations were similar. For variable b, we used data collected from the study sites (Shimamura et al., unpublished data).

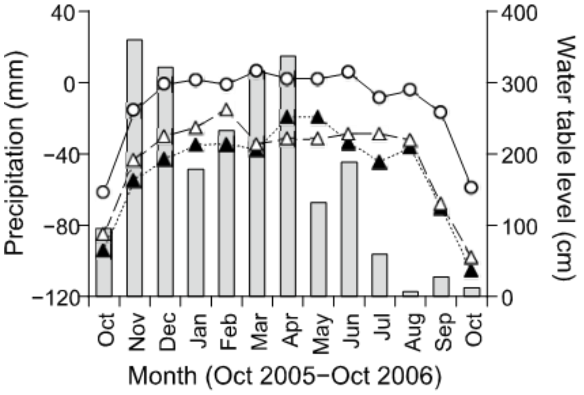

Fig. 2 Monthly precipitation at Cilik Riwut Airport and water table for UF (open circle), DF (shaded triangle), and RF (open triangle)

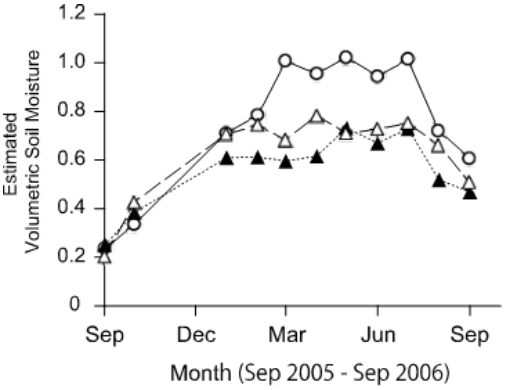

Fig. 3 Estimated surface peat moisture for UF (open circle), DF (shaded triangle) and RF (open triangle)

RESULTS

Water Table and Soil Moisture

During the study period, the rainy season began in November 2005 and ended in June 2006 (Fig. 2). The GWLs of the study sites showed similar trends; they increased during the rainy season and decreased during the dry season. The GWL at the UF sites was the highest throughout the study period. The GWL of the RF sites was higher than that of the DF sites, except between April and May 2006. The mean annual (SD) GWLs were -7.5 (18.6), -43.5 (23.2), and -37.8 (20.2) cm in the UF, DF, and RF, respectively. The results of the General Linear Model (GLM) analysis showed that there were significant effects based on the month ($F_{12,78} = 66.5$, $p < 0.001$) and site ($F_{2,78} = 190$, $p < 0.001$), but the interaction between month and site was not significant ($F_{24,78} = 1.6$, $p = 0.056$). Post-hoc multiple comparisons (Holm's method) showed that all pairs of sites showed significant differences ($p < 0.01$).

The rank of the estimated annual mean soil moisture among the three sites was in the order UF > RF > DF, and the values (SD) were 0.812 (0.286), 0.670 (0.196), and 0.593 (0.214), respectively. It should be noted that the estimated values at the UF sites often exceeded 1.0; such values are not realistically possible but can be used as a guide. The results of GLM analysis showed that there were significant effects based on month ($F_{10,551} = 58.1$, $p < 0.001$), site ($F_{2,551} = 63.7$, $p < 0.001$), and interaction between the two ($F_{20,551} = 3.8$, $p < 0.001$). Post-hoc multi-comparison (Holm) showed that all pairs of sites showed significant differences ($p < 0.01$) (Fig. 3).

Table 1 Summary of organic matter dynamics and the values applied in the peat surface profiling model

	UF	DF	RF
Litterfall (kg/m^2/y)	1.03^{a}	1.10^{a}	0.923^{b}
Initial mass of litter layer (kg/m^2)	0.738	0.787	0.744
Litter decomposition constant	0.708	0.749	0.737
Fine root production (kg/m^3)	3.44^{a}	2.25^{b}	1.86^{b}
Initial acrotelm thickness (water table) (m)	0.075^{a}	0.435^{b}	0.378^{c}
Leaf litter respiration rate*	0.0681	0.0681	0.0681
Peat loss rate in acrotelm*	0.00103	0.0094	0.0094
Proportion of fragmentation loss of litter**	0.904	0.909	0.907
Bulk density (kg/m^3)***	71	129	129
Output to catotelm (m_ck_c) (kg/m^2/year)****	1.06	1.70	1.95
Catotelm			
Peat thickness***	4	5.07	5.12

*Note: Means for different variables within a row followed by the same letter are not significantly different at p = 0.05. *Data from Brady (1997), **calculated from: leaf litter respiration rate/litter decomposition constant, *** Shimamura et al. (unpublished data). The values of k_c and m_c were obtained from Brady (1997) and Shimamura et al. (unpublished data), respectively.*

Above and Belowground Production

The rank of annual litterfall among the three sites was in the order DF > UF > RF, and the values (SD) were 11.0 (3.07), 10.3 (2.12), and 9.23 (2.27) ton/ha/year, respectively. The monthly amount of litterfall was higher during the dry season, when the GWL was low. The results of GLM analysis showed that there were significant effects based on month ($F_{12,1105} = 12.4$, $p < 0.001$), site ($F_{2,1105} = 1.90$, $p < 0.001$), plot ($F_{6,1105} = 4.04$, $p < 0.001$), and the interaction between month and site ($F_{24,1105} = 1.61$, $p < 0.001$). Multiple comparison (Holm) showed that the annual litterfall of the RF site was significantly lower than that of both UF and DF, and that there was no significant difference between UF and DF (Table 1, Fig. 4). The rank in above-ground litter mass among the sites was in the order DF > RF > UF, and the values (SD) were 7.87 (2.24), 7.44 (2.00), and 7.38 (4.82) ton/ha, respectively. The results of GLM analysis showed that neither month, site, nor the interaction had significant effects on above-ground litter deposition. The rank of root production among the sites was in the order UF > DF > RF, and values (SD) were 3.44 (2.00), 2.25 (0.97), and 1.86 (1.28) kg/m^3/year, respectively (Fig. 5). The results of GLM analysis showed that there was a significant effect of site ($F_{2,59} = 5.86$, $p < 0.01$). Post-hoc multiple comparison (Holm) showed that the annual root production of UF was significantly higher than that of the other sites, whereas there was no significant difference between RF and DF. The ranking of litter decomposition constants among the sites was in the order DF > RF > UF, and the values (SEB) were 0.749 (0.016), 0.737 (0.021), and 0.708 (0.027), respectively (Table 1, Fig. 6). The results of GLM analysis showed a significant effect of time ($F_{1,216} = 51.1$, $p < 0.001$) but no significant effect of site or interaction.

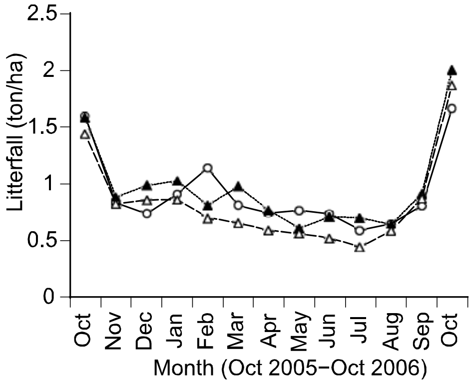

Fig. 4 Monthly litterfall for UF (open circle), DF (shaded triangle), and RF (open triangle)

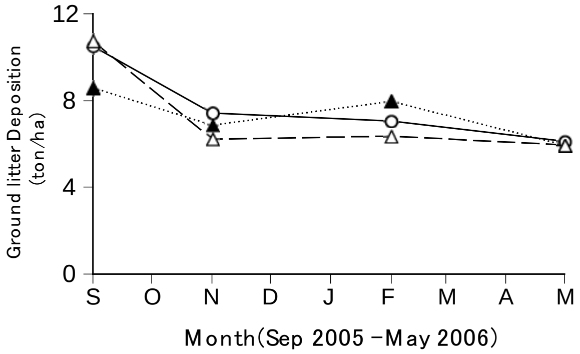

Fig. 5 Seasonal changes in the mass of litter deposition on the forest floor for UF (open circle), DF (shaded triangle), and RF (open triangle)

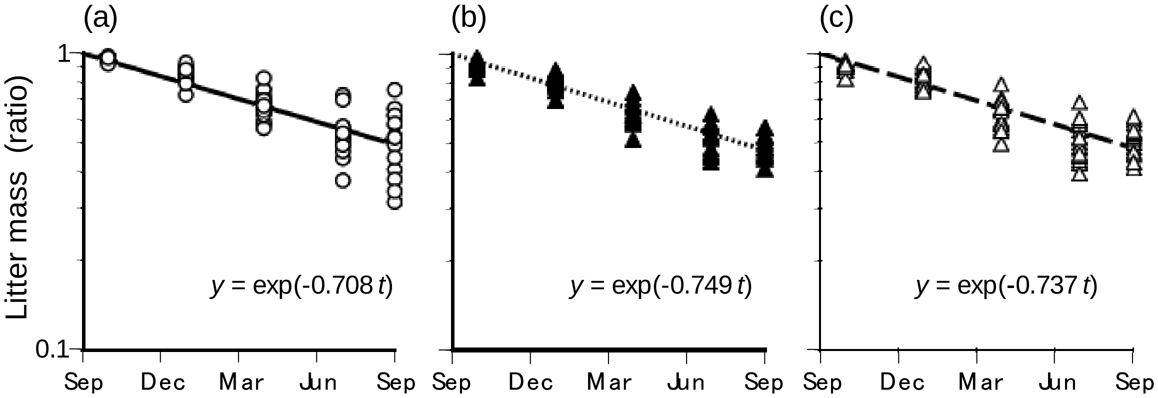

Fig. 6 Changes in the dry weight of *Combretcarpus rotundatus* leaf litter during the decomposition experiment for UF (a: open circle), DF (b: shaded triangle), and RF (c: open triangle)

According to the model estimation, peat deposition increased in UF, whereas it decreased in DF and RF. The thickness of the acrotelm layer rose to 4.9, -1.2, and -2.2 cm 5 years later in CF, DF, and RF, respectively. The amount of peat layer increased to 3.46, -1.60, and -2.86 kg/m^2 5 years later in UF, DF, and RF, respectively (Fig. 7).

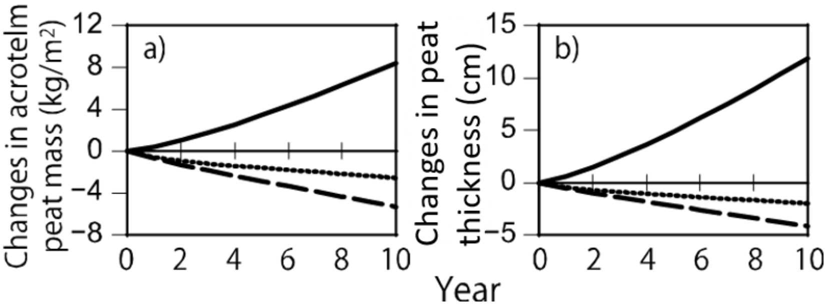

Fig. 7 Changes in a) peat deposition and b) peat surface height within 10 years as simulated by the model for UF (solid line), DF (dotted line), and RF (broken line)

DISCUSSION

The results of this study showed that the difference in mean annual GWL between DF and RF was 5.6 cm. Compared with the GWL of UF, which was near the peat surface during the wet season, the GWL of RF did not improve significantly. This is in line with the results of a previous study (Jauhiainen et al., 2008). This result was attributed to water seeping away from the dam surrounding the peat. The estimated volumetric soil moisture showed a trend similar to that of GWL. Soil moisture at the RF site was higher than that at the DF site, although it was far lower than that at the UF site. These results indicate that both GWL and surface soil moisture improved to some extent upon dam construction but did not return to pre-drainage levels.

Above-ground litter production was significantly higher in the DF site than in the RF site, whereas it was lower in RF than in UF. We do not know exactly if dam construction reduced the surface production to such an extent. One possible explanation for the decrease in production is the increase in flooding stress in RF. In general, flood tolerance may have a physiological cost because anaerobic conditions under the water level require oxygen transportation from above-ground organs. In addition, a lowered water table level puts peat under aerobic conditions and promotes decomposition. As peat decomposes, the plant-available nutrients are released. As a result, above-ground production increases. A higher water table level caused by dam construction possibly masked these effects and led to a decrease in above-ground production at the RF site. However, this does not explain why the UF site has a higher litter production than the RF site, despite having the highest water table. This possibly be explained by the condition of the UF site. The UF site is remote from the other two sites and is less intact. Therefore, the above-ground biomass is slightly higher than the other two sites (Neishi et al., unpublished data). It is possible that this difference in above-ground biomass may have led to the difference in litterfall volumes.

Belowground production was highest at the UF site, where the GWL was the highest. This result seems to contradict the case of above-ground production. Trees in wetland forests often allocate more to root biomass than other forms of forests, which can be attributed to their tolerance against water-saturating conditions (Khan et al., 2009). Thus, the flooding stress associated with the higher water table at the UF site increased the belowground production.

The higher water table level at the UF site is assumed to have reduced aerobic decomposition, resulting in a large amount of undecomposed litter deposits. However, neither the leaf litter decomposition constant nor above-ground litter deposition showed a significant effect on the sites. We are not sure why a significant difference in the decomposition constant was not found. In general, aerobic decomposition requires an appropriate humidity range. If this range is exceeded, the rate of decomposition decreases significantly. The sites where the experiments were conducted were on the peat surface and above the mean GWL, and it is possible that this is because none of the sites deviated from the appropriate humidity range. If there is a difference in the decomposition process among the sites, it would have been detected in the belowground process.

CONCLUSION

We found that restoration of peatlands by dam construction did not increase carbon storage. The possible reasons for this result are a decrease in above-ground production and no change in the decomposition rate at the peat surface. On the other hand, we found that dam construction led to some improvement in water levels and surface peat moisture content, which possibly reduced the fire risk to some extent. In addition, this study indicates the importance of organic matter dynamics in the subsurface area, particularly at the height where the water table changes due to dam construction; this was not investigated. Further studies are required to better understand the effects of dam construction on peat restoration.

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REFERENCES

Brady, M.A. 1997. Organic matter dynamics of coastal peat deposits in Sumatra, Indonesia. Ph. D. Dissertation, Department of Forestry, University of British Columbia, Canada.

Darusman, T., Murdiyarso, D., Impron, I., Chaniago, I.A. and Lestari, D.P. 2022. Carbon dynamics in rewetted tropical peat swamp forests. Climate, 10, 35.

Jauhiainen, J., Limin, S., Silvennoinen, H. and Vasandar, H. 2008. Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration. Ecology, 89, 3503-3514.

Khan, M.N.I., Suwa, R. and Hagihara, A. 2009. Biomass and above-ground net primary production in a subtropical mangrove stand of *Kandelia obovate* (S., L.) Yong at Manko Wetland, Okinawa, Japan. Wetlands Ecology and Management, 17, 585-599.

Olson, J. S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology, 44, 322-331.

Shimamura, T. 2016. An overview of tropical peat swamps. In Mizuno, K., Fujita, M.S. and Kawai, S. (Eds.), Catastrophe and Regeneration in Indonesia's Peatlands, NUS Press, Singapore, 123-147.

Shimamura, T. and Momose, K. 2005. Organic matter dynamics control plant species coexistence in a tropical peat swamp forest. Proceedings of the Royal Society B, 272, 1503-1510.