ABSTRACT  The restoration and proper agricultural use of tropical peatlands require knowledge of the physical properties of peat soils. Several physical properties related to changes in the hydrological potential of peat soils as affected by agricultural development were investigated. Selected parameters obtained in selectively logged peat swamp forest were compared with those obtained in clear-cut and maize-cultivated peatlands. In all cases, changes in selected hydro-physical properties were evidently in the top 0–15 cm layer of peat soils, and as in developed sites the top layer of peat soils was subjected to more decomposition as shown by an increase in bulk density and a decrease in fiber content. Bulk density of the top 0–15 cm layer was on average 0.14, 0.29, and 0.19 kg dm\(^{-3}\) in selectively logged peat swamp forest, clear-cut peatland and maize-cultivated peatland, respectively. Unrubbed fiber contents were on average 74, 35, and 58% volume basis, respectively. Water release potential, at low suction (high matrix potential), was significantly reduced in the top layer. Based on the three-parameter equation, reducing water release potential was attributed to decreasing the constant rate of water release \(k_\text{wr}\) and the maximum volume of water release \(V_\text{max}\). Values of \(k_\text{wr}\) and \(V_\text{max}\) in the top 0–15 cm layer of undeveloped site were 0.0346 cm\(^{-1}\) and 47.69%, whilst in the clear-cut and maize-cultivated sites they were respectively 0.0135 cm\(^{-1}\) and 44.03%, and 0.0363 cm\(^{-1}\) and 41.50%. This three-parameter model of water release potential may further be developed to estimate available water for growing crops on peat soils at different water table heights. At high matrix potential there was more water volume over air volume of peat soils under developed sites compared with undeveloped sites. This implies that as a growing medium the quality of peat soils decreases with agricultural development. Based on correlation analysis, changes in selected hydro-physical properties of peat soils were significantly related to changes in bulk density and fiber contents, and so related to the progress of peat decay.

Key words: available water, bulk density, fiber content, tropical peat soils, water release potential.

In their natural state peatlands have important roles involving carbon sequestration, regulation of hydrological and biogeochemical cycles, maintenance of biodiversity, and socio-economic values. On the other hand peatlands are viewed as fragile ecosystems sensitive to disturbances. Once a natural peatland is developed, its values will be changed.

In tropical areas the pressure to convert natural peatlands for economic development is increasing. Almost 20% of the natural peatland of Indonesia has been developed, for agriculture in particular (Rieley et al., 1997), while about 32% of Malaysian peatland has been converted into mainly oil palm, sago and pineapple plantations (Ahmad–Shah & Soepadmo, 1989; Mutalib et al., 1992; Ambak & Melling, 2000). More recently, the pressure on the natural peatlands has been especially intense, for example, the ill-fated Mega Rice Project in Central Kalimantan. This project initially involved the construction of drainage and irrigation channels, and by 1998, approximately 4,618 km of the channels had been constructed (Notohadiprawiro, 1998).

The obvious impact of the channel system on the peatland hydrology is to lower the water table (Takahashi et al., 2002). Decreasing the water table will in turn influence the distribution of moisture over the entire peat soil profile. Changes in peat moisture contents are evidently related to certain physical properties of peat soils (McLay et al., 1992). The impact of agricultural development on the physical properties of peat relevant to moisture measures includes decreases in field
moisture content, bulk density, total porosity, and available water (Radjagukguk, 2000). Although studies on peatland hydrology have been increasing, particularly in South East Asia (Stahlhut & Rieley, 2002; Takahashi et al., 2002), there is lack of information regarding the water storage capacity of reclaimed peat soils. The need for proper peatland management requires knowledge of hydro-physical properties of peat soils. This paper will provide some information on the physical properties related to the water storage capacity of peat soils.

METHODOLOGY

Study sites

The study sites were all located in Central Kalimantan, Indonesia. A peatland area of 10 x 15 km² was established to collect peat samples representative of undeveloped and developed sites. A selectively logged peat swamp forest located in east of the River Sebangau represented the undeveloped site. The forest canopy covered about 70% and was dominated by *ramin* (*Gonystylus bancanus*), *tumih* (*Combretocarpus rotundatus*), and *belangeran* (*Shorea balangeran*) (Tuah, et al., 2000). Members of the Pandanaceae, Orchidaceae, Arecaceae, and Nephetaceae families characterized the shrub layer. During peat sampling in the late rain season of 2001, the water table was positioned near the surface.

The developed area is being used for agriculture and is located in Kalampangan village. Local inhabitants have cultivated the area since the 1980s mostly for vegetables, pineapple, and maize. Peat samples were collected from an area in which most local inhabitants were cultivating maize. The water table in this area varied from between 30 and 60 cm below the surface during peat sampling. As well as a maize–cultivated area, one clear-cut peatland site was selected in an adjacent area of cultivated peatland overgrown mostly by *alang alang* (*Imperata cylindrica*).

Peat sample collection and laboratory analysis

Peat samples were collected late in the rainy season of May 2001. Two types of sample were collected. Firstly, bulk samples were taken from the 0–15 cm, 15–45 cm and 45–100 cm layers of the profile. Secondly, peat cores were collected from the 5–10 cm, 25–30 cm and 55–60 cm layers of the profile using a metal cylinder (5 cm in diameter and height). Prior to introduction into the laboratory, the peat cores were placed inside plastic caps and coated with wax to prevent dewatering during transport and storage. Each sample for each layer was analyzed individually.

Peat properties determined included field moisture content, bulk density, fiber content, and several properties related to the hydro–quality of peat. Field moisture content and bulk density were determined using peat cores, whereas the other peat properties were determined using peat bulk. Field moisture content was determined gravimetrically after oven drying at 105°C for at least 4 hours (Houba et al., 1986). Values of the field moisture content were expressed in volume %. Bulk density was determined by oven–drying peat cores at 105°C to constant mass. Dry bulk density was calculated as the oven–dried mass divided by the field volume of each peat core and expressed in kg dm⁻³ (Black, 1965). This bulk density is termed "field bulk density" (Andriessen, 1988). Fiber content was determined volumetrically following the procedure proposed by Linn et al. (1974). Fiber content was calculated as volume % of fibers before and after rubbing.

On the basis of the determination of moisture retention at several levels of water suction (matrix potentials) together with of bulk density, the hydro–quality of the different peats was calculated and expressed as air volume, easily available water, water buffering capacity, and available water. Pore distribution could also be calculated and expressed as the range of equivalent diameter, total porosity, macro and micro pores. All calculations were run using the procedure described in Puustjarvi (1973) and Verdonck et al. (1973).

Data Processing

Comparison of the field moisture content, bulk density, and fiber content of peat soils from undeveloped and developed sites was analyzed using one–way analysis of variance (Anova) with land use types as the fixed effect (Sokal & Rohlf, 1969). All data were previously tested for variance homogeneity using Bartlett Test at \( P < 0.01 \). When the test indicated that raw data violated the assumption of variance homogeneity, the data were transformed using logarithmic transformation. The Duncan Multiple Range Test was used for comparison tests of means. The data were presented in means with standard deviation.

The strength of associations between bulk density and fiber content are regarded as the physical indices of peat decay (Blackford & Chambers, 1993; Brady, 1997) and the hydro–quality of peats was analyzed using analysis of correlation and the results were expressed in Pearson correlation coefficients. The significance of correlation tests was confirmed using Students t–Test (Sokal & Rohlf, 1969).
The water release capacity of peat soils under different land use types was assessed as a function of the suction height of the water column. A three-parameter equation was produced to fit the curve:

\[ V_w = V_{max} e^{-k_vh} + (1 - V_{max}) e^{-k_sV_{max}h} + V_s \]

where \( V_w \) is volume of water release (%), \( V_{max} \) is volume of maximum water release (%), \( V_s \) is volume of peat particles (%), \( k_v \) is the constant rate of water release (cm\(^{-1}\)), and \( h \) is suction height of the water column (cm).

The hydro-quality of peat soils as a medium of grown crops was evaluated by construction of an air: water ratio curve (Verdonck et al., 1973).

**RESULTS AND DISCUSSION**

**Physical indices of peat decay**

Several physical properties of peat, including bulk density, and rubbed and unrubbed fiber contents were compared of over land use types at the three peat layers presented in Table 1. These properties provide the basis for describing the progress of peat decay. In general the properties significantly changed in the top 0–15 cm layer and followed the order of peat decay.

Bulk densities in the study sites ranged from a minimum of 0.12 kg dm\(^{-3}\) for the top 5–10 cm layer in the undeveloped site, to a maximum of 0.31 kg dm\(^{-3}\) for the top 5–10 cm layer in the clear-cut site. The results were in general agreement with those of Driessen and Rochimah (1977). They surveyed Indonesian peat soils and showed that the bulk densities of peat soils sampled from the peat swamp forest in the River Sebangau, Central Kalimantan ranged from 0.10 to 0.21 kg dm\(^{-3}\), whereas the bulk densities of peat deposits in South Sumatra and Riau varied from 0.07 to 0.22 kg dm\(^{-3}\) (Brady, 1997). In general, wood–based peat deposits are characterized by a higher bulk density, as shown in this study. The study showed that the bulk density of peat soils, especially in the top layer of the developed site was significantly higher than that in the undeveloped site. In developed peatland peat materials are commonly more decomposed and subsequently result in finer materials. The arrangement of fine materials into the intrinsic peat structure, results in closer contact among particles and in turn, a lower total pore space. The lower the total pore space is, the higher the resulting bulk density.

Unrubbed fiber contents in the study sites varied from 30% in the top 0–15 cm layer of the clear-cut site to 84% in the top 0–15 cm layer of the undeveloped site. The fiber contents of peat soils were significantly lower in the top layer of developed sites compared to those in undeveloped sites. Based on USDA criteria (Soil Survey Staff, 1975), the degree of humification of peat material in the 0–100 cm layer of undeveloped sites is classified as fibric in the top 0–15 cm layer, followed by hemic in the lower layer(s). In developed sites, peat materials are classified as hemic in the 0–100 cm layer of the maize–cultivated site, and as sapric and hemic respectively, in the top 0–15 cm layer and the lower layer of clear-cut site. Unrubbed fiber contents evidently provide good agreement with bulk density as physical indices of peat decay.

**Hydro–physical properties of peat soils**

Table 2 shows the strength of association between the physical indices of peat decay and some of the hydro–physical properties of peat soils. With the exception of

<table>
<thead>
<tr>
<th>Table 1. Comparison of physical indices of peat decay under undeveloped peatland (I), maize-cultivated peatland (II), and clear-cut peatland (III) at three different peat layers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peat Properties</strong></td>
</tr>
<tr>
<td>Bulk density (kg dm(^{-3}))</td>
</tr>
<tr>
<td>Unrubbed fiber content (% v/v)</td>
</tr>
<tr>
<td>Rubbed fiber content (% v/v)</td>
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</table>

* Data presented as means and their standard deviation. Values followed by the same letter for each row are not significantly different after Duncan Multiple Range Test at \( P < 0.05 \).
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Table 2. Pearson’s correlation coefficient (r) between physical indices of peat decay and selected hydro-physical properties of peat soils

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Bulk Density</th>
<th>Unrubbed Fiber Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Porosity</td>
<td>-0.773***</td>
<td>0.5024***</td>
</tr>
<tr>
<td>Macro Pores</td>
<td>-0.829***</td>
<td>0.6318***</td>
</tr>
<tr>
<td>Micro Pores</td>
<td>0.6865***</td>
<td>-0.6111***</td>
</tr>
<tr>
<td>Air Volume</td>
<td>-0.6578***</td>
<td>0.6375**</td>
</tr>
<tr>
<td>Easily Available Water</td>
<td>-0.5333***</td>
<td>0.2704**</td>
</tr>
<tr>
<td>Water Buffering Capacity</td>
<td>-0.0990”</td>
<td>0.0725”</td>
</tr>
<tr>
<td>Available Water</td>
<td>-0.6307***</td>
<td>0.3360*</td>
</tr>
</tbody>
</table>

Significance test of r was carried out by t-test (n = 45). The r values followed by asterisk of * and *** indicate significant association among appropriate pairs of data at P < 0.05 and P < 0.001 respectively. Those followed by asterisk” indicate not significant association at P < 0.05.

water buffering capacity, all selected hydro-physical properties of peat soils significantly correlate with the fiber content and bulk density of peat soils. This implies that as peat decay progresses some hydro-physical properties of peat soils including field moisture content, air volume, available water, macro pores and total porosity decrease and micro pores increase. Peat materials were more decomposed as a result of cultivation, resulting in finer materials and closer contacts among peat particles.

Potentials of water release
Cultivation and development of peatland evidently influenced the water release potentials of peat soils at high matrix potentials. Potentials of water release were described by the three-parameter equation. Results of fitting water release data with the proposed model are presented in Fig. 1. The water release potentials of peat soils under clear-cut and maize-cultivated sites were lower than those under undeveloped sites. Reduced water release potentials could be attributed to the decreased rates of constant water release ($k_{wr}$) and maximum volume of water release ($V_{max}$). Values of $k_{wr}$ and $V_{max}$ in the top 0-15 cm layer of undeveloped peatland were 0.0346 cm$^{-1}$ and 47.69%, whilst in clear-cut and maize-cultivated peatlands they were respectively 0.0135 cm$^{-1}$ and 44.03%, and 0.0363 cm$^{-1}$ and 41.50%.

Changes in $k_{wr}$ and $V_{max}$ were consistent with changes in several hydro-physical properties of peat soils, showing a negative correlation with bulk density and in turn, negative correlation with micro pores and positive correlation with total porosity and macro pores. This signifies that the rate constant and maximum volume of water release decreased with the progress of peat decay.

Air: water ratio
The ratio of air and water volumes at high matrix potential values (low suction) is very important. The suction at

Fig. 1. Water release of three peat soil layers (a) 0-15 cm, (b) 15-45 cm, and (c) 45-100 cm under three different land use systems at different suction heights. Symbols and lines represent observed and simulated data respectively based the proposed model
which the volume of air is equal to the volume of water is shown by the intersection of the volume % of air and water curves (Fig. 2). The position of this point indicates the quality of peat (Verdonk et al., 1973). Compared to developed sites the suction on which the intersection occurs is lower in undeveloped sites. This implies that the quality of peat soils under developed sites is reduced.

CONCLUSION

1. Development and cultivation caused changes in the physical dimensions of the peat soil including increases in bulk density and decreases in fiber contents. This, in turn, changed some hydro-physical properties of peat soils.

2. Decreasing $k_w$ and $V_{m,0}$ reduced water release potential. They consistently changed the progress of peat decay and caused changes in certain hydro-physical properties of peat soils.

3. At high matrix potential there was more water volume than air volume in peat soils under developed sites compared with undeveloped sites. This implies that as a growing medium the quality of peat soils decreases with agricultural development.

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