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CAPILLARY WATER RISE IN PEAT SOIL AS AFFECTED BY VARIOUS GROUNDWATER LEVELS

Kenaikan Air Kapiler di Tanah Gambut Akibat Pengaruh Berbagai Ketinggian Muka Air Tanah

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ABSTRACT

Capillary water in peatlands has a very important role in supplying water to the root zone of plants. The current water content in the root zone depends mainly on groundwater levels in some areas with shallow water levels. The study aimed to measure the capillary water dynamics in peat soils at various soil densities and groundwater levels which were observed from the changes in peat color, moisture distribution, water content and hydrophobicity of peat soil. The study was conducted in the greenhouse of Indonesian Swampland Agricultural Research Institute, Banjarbaru, South Kalimantan. The experiment was arranged in a randomized block design with two factors and three replications. The first factor was the bulk density (BD) of peat, namely BD-1 (on actual condition, 0.1 g cm^{-3}) and BD-2 (compressed into 0.2 g cm^{-3}). The second factor was simulated groundwater levels (GWL) consisting of GWL-1 (-100 cm), GWL-2 (-70 cm) and GWL-3 (-40 cm) from soil surfaces. The results showed that the rise of capillary water in peat soil reached a maximum height of 50 cm which was characterized by the increase in water content at the top layer in the range of 105–127% for BD-1 and 141–181% for BD-2. The highest value of water content (308%) was achieved in the treatment of GWL-3 with BD-2 and the lowest (37%) was in the treatment of GWL-1 with BD-1. The rate of capillary water rose progressively corresponded to the increase in BD value because the number of micropores of BD-2 was greater.

[***Keywords***: *Peat soil, capillary water, groundwater level, bulk density, water content*]

ABSTRAK

Air kapiler di lahan gambut memiliki peranan yang sangat penting dalam menyediakan air untuk zona perakaran tanaman. Kadar air tanah aktual pada zona perakaran sangat bergantung pada tinggi muka air tanah pada suatu kawasan yang mempunyai tinggi muka air yang dangkal. Tujuan penelitian adalah untuk mengukur dinamika kapilaritas tanah gambut pada berbagai faktor kepadatan tanah dan tinggi muka air tanah yang diamati dari perubahan warna, distribusi kelembapan, kadar air, dan hidrofobisitas tanah gambut. Penelitian dilaksanakan di rumah kawat Balai Penelitian Pertanian Lahan Rawa, Banjarbaru, Kalimantan Selatan. Penelitian menggunakan rancangan acak kelompok faktorial dengan dua faktor yang diulang tiga kali. Faktor pertama adalah tingkat kepadatan gambut (BD), yaitu BD-1 (kondisi aktual, 0,1 g cm^{-3}) dan BD-2 (dipadatkan menjadi 0,2 g cm^{-3}). Faktor kedua adalah simulasi tinggi muka air tanah (GWL) berdasarkan tinggi pipa mika, yaitu GWL-1 (-100 cm), GWL-2 (-70 cm), dan GWL-3 (-40 cm). Hasil penelitian menunjukkan tinggi kenaikan air kapiler di tanah gambut maksimum mencapai 50 cm yang dicirikan dengan meningkatnya nilai kelembapan tanah antara 105–127% pada BD-1 dan 141–181% pada BD-2. Nilai kadar air tanah tertinggi terlihat pada perlakuan GWL-3 dengan BD-2 sebesar 308% dan yang terendah pada perlakuan GWL-1 dengan BD-1 sebesar 37%. Kecepatan kenaikan air kapiler semakin tinggi dengan meningkatnya nilai BD tanah karena terkait dengan jumlah pori mikro yang lebih banyak pada BD-2.

[***Kata kunci***: *Tanah gambut, air kapiler, tinggi muka air tanah, kepadatan gambut, kelembapan tanah*]

INTRODUCTION

The use of peatland for agriculture and residential areas alters the distribution and fluctuation of groundwater. The construction of drainage channel decreased water level in peat soils. Szajdak and Szatylowicz (2010) stated that the use of peatland for agriculture in the long term and other forms of exploitation led to the decrease in groundwater level, increase in aeration and carbon emissions, and land subsidence. In the excessive soil drainage conditions, the peat could experience drought and led to irreversible dry or hydrophobic state. The decreased groundwater level also increased peat vulnerability to fires. Wösten *et al*. (2008) reported that fire vulnerability would increase when the groundwater level dropped below 40 cm, and it also contributed to CO_2 emissions in the peat.

A highly decreased groundwater level could disturb the capillary water flow from the groundwater to the surface of the peat. In the dry season, the capillary water flow possibly could not reach the surface layer of peat, and the peat became irreversibly dry, causing the peat vulnerable to fire and its soil organic matter was easily leached. As described in the Appendix Criteria of Unripe Damage Soil for Wetlands in Indonesia, the Government Regulation No. 150/2000 stated that the groundwater level is maintained below 25 cm to manage hydrophobicity of peat soil (based on the Regulation No. 23/1997 on Environmental Management), whereas in Article 23 Paragraph 3 of Government Regulation No. 71/2014 on the Protection and Management of Peatland Ecosystem, the groundwater level is set below 40 cm, having a legal basis of Regulation No. 32/2009 on the Protection and Management of the Environment.

Currently, there is no research carried out on the groundwater levels corresponding to potential water capillarity that affects moisture conditions of top layer of peat soil. The capability of capillary water in peat soil to retain moisture on the soil surface is considered promoting the sustainability of peat soil use. The objective of this study was to measure the dynamics of capillary water on various peat soil densities and groundwater levels which were referred to changes in peat color, moisture distribution, water content and hydrophobicity of peat soil.

MATERIALS AND METHODS

Experimental Design

The experiment was conducted in the greenhouse of Indonesian Swampland Agricultural Research Institute, Banjarbaru, South Kalimantan from April to June 2016. Soil samples were taken from Sebangau National Park, Central Kalimantan, located on latitude of 01°54'–03°0'S and longitude of 113°20'–114°03'E.

The experiment was arranged in a randomized block design with two factors and three replications. The first factor was the bulk density (BD) of peat, consisting of BD-1 (on actual condition, 0.1 g cm^{-3}) and BD-2 (compressed into 0.2 g cm^{-3}). The second factor was groundwater level (GWL), namely GWL-1 (-100 cm), GWL-2 (-70 cm) and GWL-3 (-40 cm). The combination of various treatments and layout of the experiment are shown in Fig. 1.

Experimental Setup

Soil samples were taken in the form of disturbed samples which had the original structure but had been partly or entirely modified. The soil samples were then air dried and stored in an enclosed space while waiting for preparation of the experimental setup in the greenhouse. Further, the peat soil was put into the capillary mica column with heights of 120 cm, 90 cm and 60 cm. The amount of soil sample used for the study was calculated based on the necessity of weight of the sample to produce self-determined bulk density (BD) (g cm^{-3}) in accordance with the volume of mica pipe (cm^3) being used. The experimental setup for the dynamics of peat soil capillarity is shown in Fig. 2. During the experiment, the peat had no cover (over the crop) on treatment, no water infiltration so that the peat relied only on capillary water (water in the tube) from a wet water table.

The parameters observed in the study included: (1) peat characteristics prior to the implementation of research; (2) change in peat color and distribution of soil moisture which were observed once a week in 8 weeks, and (3) water content and hydrophobicity of peat which were analyzed at the beginning and the end of the experiment. Characterization of peat included soil type, decomposition rates and hydrophobicity. Observation on change in peat color used Munsell Soil Color Chart. The color of the soil was determined by comparing the color of the soil with the color paper in Munsell Soil Color Chart and putting it next to the soil column. Observation on the

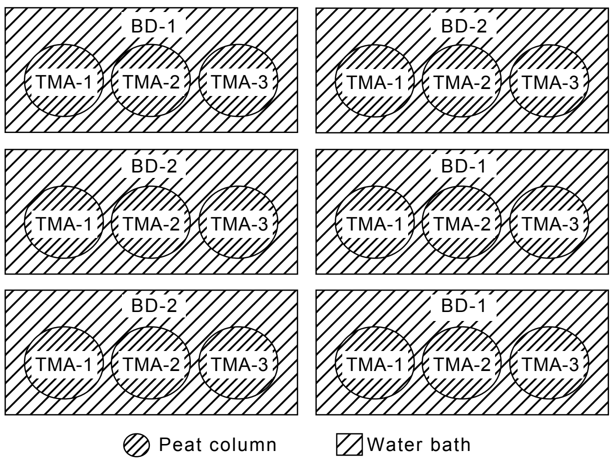

Fig. 1. Schematic layout of the experiment.

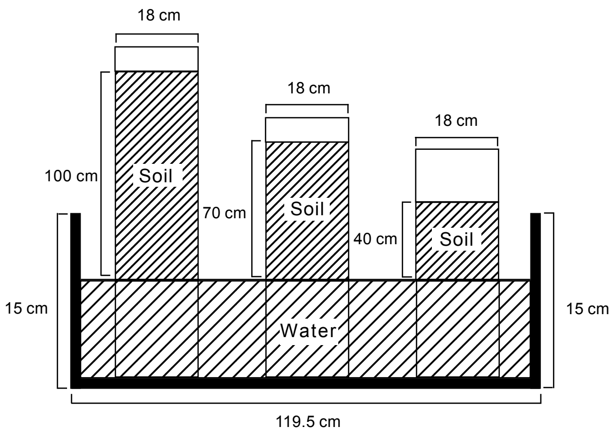

Fig. 2. Experimental setup for the dynamics of peat soil capillarity.

Table 1. Initial characteristics of peat soil of Sebangau National Park, Central Kalimantan.

Parameter	Unit	Value
Ash content	(%)	0.70
Water content	(%)	509.38
Bulk density	(g cm^{-3})	0.10
Functional groups		
Hydrophilic		
C=O stretch of COOH or COOR	(%)	-
□ (O-H) stretching	(%)	28.01
Hydrophobic		
Aromatic C=C stretching	(%)	6.07
Antisymmetric CH_2	(%)	4.37
Symmetric CH_2	(%)	15.07

moisture distribution used moisture probes ETP 300 with a 1–10 scale readings that had been modified so that it could measure each layer approaching groundwater level.

Soil samples were tested at the beginning of the experiment to retrieve water content and hydrophobicity, and at the end of the experiment. The studied peat samples were dismantled and separated to retrieve data on soil water content of each 10 cm layer and hydrophobicity in the upper layer (0–10 cm) of peat soil. Hydrophobic and hydrophilic functional carrier groups in peat soil samples were analyzed using FTIR spectrophotometer. Interpretation of the results of FTIR analysis was performed according to Artz *et al*. (2008).

RESULTS AND DISCUSSION

Initial Characteristics of Peat Soil at Field Conditions

Peat soil used in this study was omborogenous peat characterized by ash content <1% and BD < 0.1 g cm^{-3}. Percentage of ash content indicated the amount of minerals in the peat soil. Table 1 shows characteristics of peat soil at field conditions.

Result of observations in the field showed that the decomposition degree of the peat was hemic based on the bare-hand squeezing method, the remaining fiber left in the hand were 1/4–3/4 of initial volume. The soil was brown in color because it was inherited from the swampy forests. Soil conditions were hydrophilic, which were supported by the peat water content which reached 509.38% by weight and a hydrophilic component in the peat soil which were dominanted by 28.01% of □ (O-H) stretching. Dried peat with a water content of <100% by weight could not absorb any water when moistened (Agus and Subiksa 2008). In addition to water content, hydrophilic properties were also determined by the hydrophilic components available in the soils. The greater the percentage of hydrophilic components in the peat soil, the stronger the binding between peat and water (Utami *et al*. 2009).

Dynamics of Peat Soil Capillarity

In dry conditions (dry season), capillary water in the peat has a very important role in supplying water for roots of plants. The current water content in the root zone depends heavily on groundwater levels, decomposition degree and type of subtratum in some areas with shallow water levels. Capillary rise is a well known soil phenomenon that describes the movement of pore water from lower elevation to higher elevation. According to Lu and Likos (2004), there are three fundamental physical characteristics related to the capillary rise: (1) maximum height of capillary rise, (2) fluid storage capacity of capillary rise, and (3) rate of capillary rise. Capillary rise was also affected by evaporation. Water in the soil can be lost by evaporation (outflow) and capillary rise can recharge the water (inflow). Evaporation and capillary rise were important processes in soil water balance because they affected the inflows and outflows of water in the soil (Kowalik 2006). However, this study was focused on GWL and BD while the evaporation was not considered.

Results of the study showed that peat soil experienced shrinkage when the initial height of peat column (100 cm, 70 cm and 40) decreased to 80 cm, 50 cm and 30 cm, respectively (the incubation period). Soil shrinkage is a natural behaviour of peat soil, which is a reduction of the volume of peat above the groundwater level due to the drainage or drying (Agus and Subiksa 2008). Peat soil has numerous macrovoids which cause the peat volume to shrink. Anwar (2003) stated that peat soil with a hemic decomposition degree had macrovoids of 86.42% to the total voids. In this sudy, drying occurred when the peat was air-dried in experimental setup stage and got heat during the study making the peat volume reduced rapidly.

Changes in Peat Color

Water content or hydration level affected the color of the soil. The soil in moist to a wet condition would be darker. The level of hydration associated with the position of the groundwater level, leading to a reduction of soil color (gleization), the bluish gray to greenish gray (Sutedjo and Kartasapoetra 2005). Observations using the Munsell Soil Color Chart showed that the color of peat soil changed from GLEY 1 5/1 or greenish gray to GLEY 4/1 or dark greenish gray due to the wetting of peat soil. The results of the study (Fig. 3) showed that the soil color was changed due to rising capillary water to the top layer. The soil in the bottom layer which was already saturated with water will push the water to the upper layer so that the color of the soil at the top gradually turns darker. Capillary water on peat column with surface area of 254.34 cm^2 rose up to 40–50 cm layer on GWL-1 and GWL-2, but on GWL-3 it reached only 30–40 cm layer because the maximum height of GWL-3 was 40 cm. Schindler *et al*. (2003) and Schwärzel *et al*. (2006) stated that capillary water could reach the root zone in a subtropical peatland drained up to 70 cm dept with the reed canary grass cover crop. Smaller pore tended to make stronger capillary rise (Lu and Likos 2004; Chesworth 2008; McCarter 2012). Capillary forces act to maintain moisture between pores. Subtropical peatland was generally dominated by moss peat which had smaller pore than wooden peat in tropical peatland. Peat and bog soils in temperate zone were often in sapric type with low C/N ratio (Chesworth 2008) because the sub-tropical and boreal peat was formed in a slower rate than the tropical peat, namely 0.1–1.0 mm yr^{-1} for temperate peat and 0.4–2.2 mm yr^{-1} for tropical peat (Purwanto and Gintings 2011).

Soil Moisture Distribution

Peat soil moisture distribution is also influenced by the rate of capillary rise. The results based on the ETP300 probe data (Fig. 4) showed that moisture distribution on the peat layer at GWL-1 was very slow (almost stagnant on the last 3 weeks), while at GWL-2 and GWL-3, peat soil moisture distribution increased that indicated a capillary water rising to the top layer until the end of the observation. In boreal peatlands, the influences of GWL on capillary rise and root-zone moisture content are essential to the self-regulatory features of peatland hydrology and C

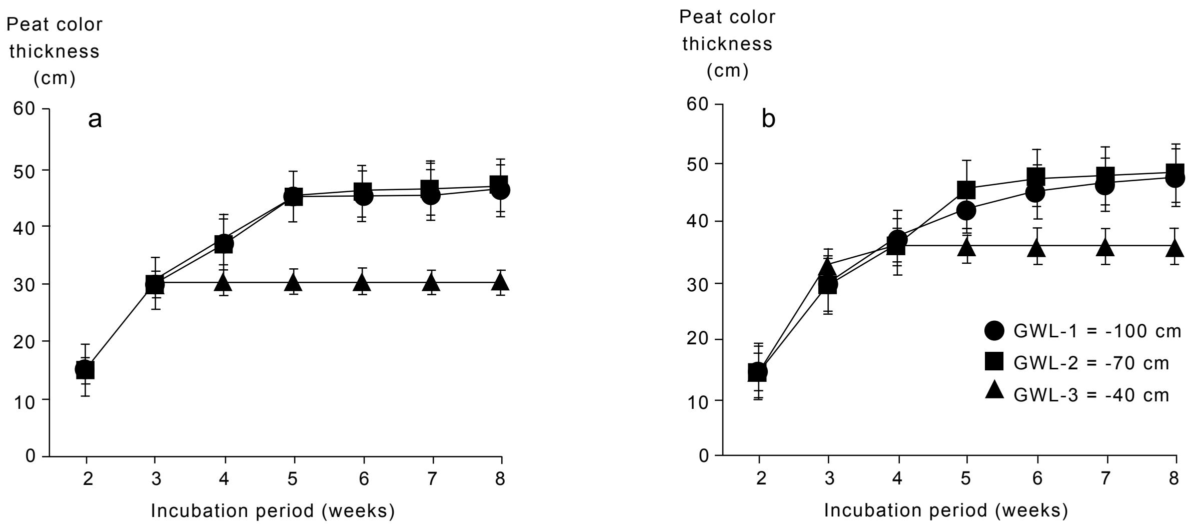

Fig. 3. Changes in peat color at different bulk densities (a = 0.1 g cm^{-3} and b = 0.2 g cm^{-3}), groundwater levels (GWL) and incubation periods.

balance under climatic force (Gong *et al*. 2012). The higher the groundwater table, the less the water supply to the top layer (Kurnain *et al*. 2006). Again, this phenomenon was also affected by evaporation which was not considered on this study. Capillary water will recharge when soil moisture at the upper layer decreased due to evaporation. Yazaki *et al*. (2006) and Chesworth (2008) reported that an amount of water lost due to evapotranspiration was re-supplied from deeper layers to the surface. Furthermore, soil water pressures in cutover peat may be below the threshold at which the capillary forces generated by the mosses can extract enough water to offset evaporative losses, preventing recolonization of cutover surfaces (Price and Whitehead 2001; Taylor and Price 2015).

Water Content of Peat Soil

Water content of peat soil is a major factor limiting the ignition and smoldering fires. Hydrophobicity of peat will appear when the water content decreases and passes over the critical water content for the occurrence of hydrophobicity, where the values vary depending on peat properties.

Humidity gauge in the dry season determines the water content that can be used as an indicator of fire hazard. The water content greater than or equal to 30% of the fuel is considered safe against fire hazards, but with decreasing percentage of water content, fire danger could increase (Syaufina 2008).

Soil water content of each layer at the end of the study could be seen in Fig. 5. The figure showed that

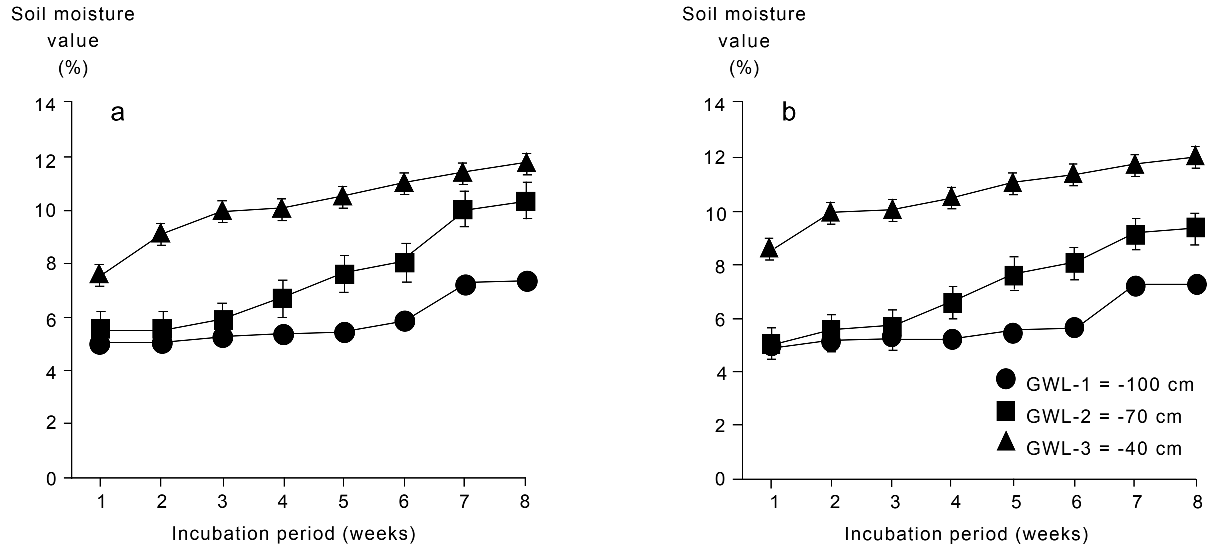

Fig. 4 Soil moisture distribution at different bulk densities (a = 0.1 g cm^{-3} and b = 0.2 g cm^{-3}), groundwater levels (GWL) and incubation periods.

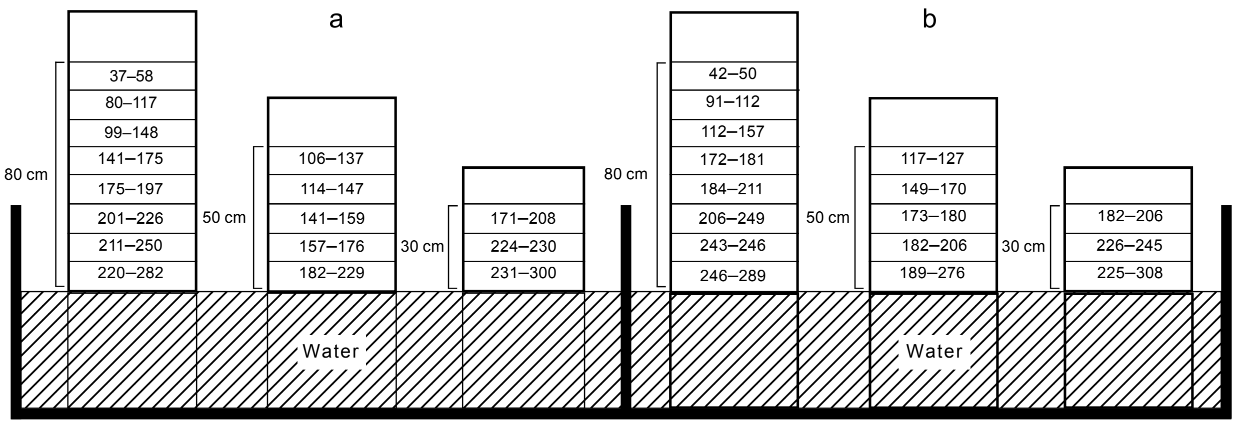

Fig. 5. Soil water content (%) of each 10 cm peat layer at the end of experiment: (a) 0.1 g cm^{-3} and (b) 0.2 g cm^{-3} bulk density (BD).

the highest soil water content was observed on treatment GWL-3 with BD-2 which was 308.1%, while the lowest water content was on treatment BD-1 with GWL-1 (37%). Kurnain *et al*. (2006) reported when the decrease in ground water level is too deep, it will affect the distribution of soil moisture throughout the peat soil profile and result in the release of a number of volumes of groundwater from the upper layer. BD also affected water content in peat soil. The higher the BD, the smaller the pores in peat soil. Fine textured soil had smaller pores which made a greater capacity to hold and retain water than coarse soils with larger pores (Cannavo and Michel 2013; Bodner *et al*. 2014; Kurnain 2015). Nurzakiah (2014) also reported that water content was influenced by groundwater levels, parent materials and peat decomposition rate. The conditions of the soil water content of 37% potentially caused the land vulnerable to fire. Putra (2003) reported that peat with soil moisture of less than 117.39% had potential to burn and could be the start of the fire on a larger scale.

Water content of the soil in the GWL-2 in a layer within 50 cm of GWL ranged from 105% to127%, while in the GWL-1 (-100 cm) in the same layer it ranged from 141% to 181%. The results showed that soil water content in the same layer on two different GWLs which were -100 cm and -70 cm had different soil moisture conditions. The difference was because the treatment of GWL-1 (-100 cm) still had the soil cover with a thickness of 30 cm above the layer so that moisture can be held. While in the treatment of GWL-2 (-70 cm), interaction with air was stronger due to the layer conditions (no cover above the layer in the form of a thick soil) resulting in faster soil evaporation.

The critical moisture content of peat experiencing ignition varied from 40% to 125% (Frandsen 1987; Rein *et al*. 2008). Rein *et al*. (2008) also reported that peat soil moisture content above 135% still experienced ignition. Conclusion from the above discussion is that the maximum increase in capillary water was 50 cm of water level with the soil water content ranged from 141% to 181%, but if the top layer of soil was already open (GWL-2), so the top layer had entered the critical water content at a range of 105–127% at the end of observation.

Hydrophobicity of Peat

Hydrophobicity is a state of the surface of particles of peat soil that could not withstand or hold water back after dried up. Matejkova and Simon (2012) and Winarna (2015) stated that hydrophobicity is the ratio between hydrophobic components and hydrophilic components in peat soil. Szajdak and Szatylowicz (2010) stated that the groundwater fluctuations affected the hydrophobicity of the peat as it could affect chemical composition of humic substances in peat soil. Hydrophobicity in peat increased functional groups namely hydrophobic lignin and lipid (C-H and C=C) and reduced hydrophilic cellulose and carboxylic acid (O-H and C=O) (Utami *et al*. 2009). The graphic result can be seen in Fig. 6.

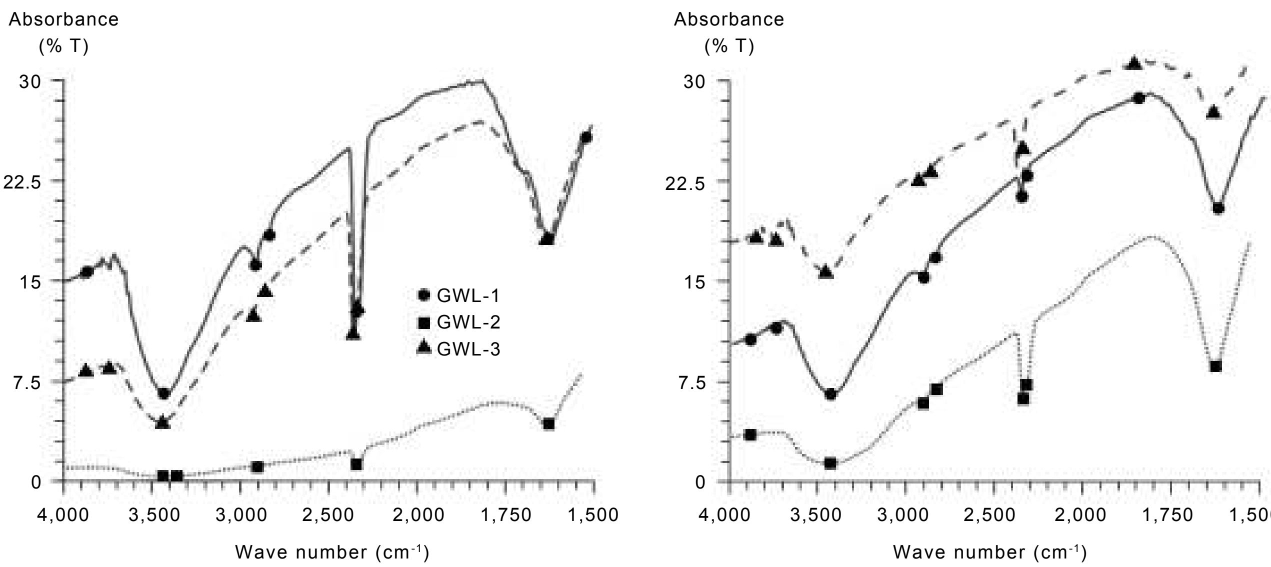

Fig. 6. FTIR spectra of ombrogenous peat at different bulk density: (a) actual conditions of 0.1 g cm^{-3} (BD-1) and (b) compressed to 0.2 g cm^{-3} (BD-2).

The decrease in groundwater levels led to an increase in the ratio of hydrophobic component and hydrophilic component, thus encouraging the peat in hydrophobic conditions. The results in Table 2 for BD-1 and Table 3 for BD-2 showed that GWL treatments increased the ratio of hydrophobic to hydrophilic components. GWL-1 treatment on BD-1 and BD-2 increased the ratio of hydrophobic to hydrophilic components by 1.18% and 7.25%, respectively. This increase was due to the hydrophobic groups which were still high and the decrease in hydrophilic groups during the study. The decrease in hydrophilic group associated with the decrease in water content in the soil. The ratios decreased in the GWL-2 treatment which were 4.35% for BD-1 and 11.77% for BD-2, while those on GWL-3 were 0.31% on BD-1 and 11.69% on BD-2. The decrease was influenced by the decrease in hydrophobic group and the increase in hydrophilic group during the study so that the top layer of peat on GWL-2 and GWL-3 was hydrophilic.

The existence of carboxyl group in peat is important because it is closely related to water saving properties of soils (Utami *et al.* 2009). The functional groups C-H, C=C, OH and C=O attributed the nature of irreversible drying (hydrophobicity) on peat soil (Urbanek *et al.* 2007; Utami *et al.* 2009; Dlapa *et al.* 2012; Matejkova and Simon 2012). Results of hydrophobicity interpretation showed that GWL-1 treatment with a final moisture content of 37% for BD-1 and 49.9% for BD-2 had entered the hydrophobicity. Conversely, on GWL-2 and GWL-3 treatments, both BD-1 and BD-2 were still hydrophilic.

Table 2. Composition, peak area and percentage of functional groups of peat soil at bulk density of 0.1 g cm^{-3} and three groundwater levels (GWL).

Wave number (cm^{-1})[a]	Functional group	Characterization	GWL-1		GWL-2		GWL-3	
			Initial (%)	Final (%)	Initial (%)	Final (%)	Initial (%)	Final (%)
1600–1660	Aromatic C=C stretching and/or asymmetric C–O stretch in COO–	Lignin and aromatic or aliphatic carboxylates	6.01	6.18	6.95	5.75	8.43	7.60
1720–1725	C=O stretch of COOH or COOR	Free organic acids	0.00	0.00	0.00	0.00	0.00	0.00
2850	Symmetric CH_2	Fats, wax, lipids	17.77	15.89	0.00	13.09	14.55	14,60
2900–2940	Antisymmetric CH_2	Fats, wax, lipids	4.92	3.84	20.53	3.63	2.86	5.07
3300–3800	γ(O–H) stretching	Cellulose	33.92	30.01	39.57	34.10	43.43	46.08
	C-H/O-H		0.67	0.66	0.52	0.49	0.40	0.43
	C=C/O-H		0.18	0.21	0.18	0.17	0.19	0.16
	C=O/O-H		0.00	0.00	0.00	0.00	0.00	0.00
	(C-H+C=C)/(O-H+C=O)		0.85	0.86	0.69	0.66	0.59	0.59

[a]Hydrophilic group: 1600–1660, 1720–1725 and 3300–3800; Hydrophobic group: 2850 and 2900–2940

Table 3. Composition, peak area and percentage of functional groups of peat soil at bulk density of 0.2 g cm^{-3} and three groundwater levels (GWL).

Wave number (cm^{-1})[a]	Functional group	Characterization	GWL-1		GWL-2		GWL-3	
			Initial (%)	Final (%)	Initial (%)	Final (%)	Initial (%)	Final (%)
1600–1660	Aromatic C=C stretching and/or asymmetric C–O stretch in COO–	Lignin and aromatic or aliphatic carboxylates	9.14	5.83	9.88	5.74	3.81	6.89
1720–1725	C=O stretch of COOH or COOR	Free organic acids	0.00	0.00	0.00	3.53	0.00	0.00
2850	Symmetric CH_2	Fats, wax, lipids	15.25	14.30	17.30	21.59	18.50	17.46
2900–2940	Antisymmetric CH_2	Fats, wax, lipids	2.91	4.54	2.98	21.59	18.50	17.46
3300–3800	γ(O–H) stretching	Cellulose	39.41	33.30	35.45	33.10	33.30	40.41
	C-H/O-H		0.46	0.57	0.57	0.65	0.65	0.51
	C=C/O-H		0.23	0.18	0.28	0.17	0.11	0.17
	C=O/O-H		0.00	0.00	0.00	0.11	0.00	0.00
	(C-H+C=C)/(O-H+C=O)		0.69	0.74	0.85	0.75	0.77	0.68

[a]Hydrophilic group: 1600–1660, 1720–1725 and 3300–3800; Hydrophobic group: 2850 and 2900–2940

CONCLUSION

The capillary rise of water in peat soil reached a maximum of 50 cm in height which was characterized by the change in peat color up to 40–50 cm, distribution of peat soil moisture with potential humidity ranging from 9.0 to 10.4, water content on peat layer within 50 cm of the surface water had entered the critical moisture content on ignition which was equal to 105–127% in GWL-2 but the water content in GWL-3 (141–181%) is not exceed the limit of critical moisture content. Also, the decrease in the ratio of hydrophobic to hydrophilic component in the treatment of GWL-2 by 4.35% for the BD-1 and 11.77% for the BD-2. Soil with fine textured had smaller pores resulting a greater capacity to hold and retain water than coarser soil with larger pores. This greater capacity was showed by the highest soil water content corresponded to the capillary rise of treatment GWL-3 and BD-2 equaled to 308% and that the lowest water content occurred in the treatment GWL-1 and BD-1 equaled to 37%.

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REFERENCES

Agus, F. dan IG.M. Subiksa. 2008. Lahan Gambut: Potensi untuk pertanian dan aspek lingkungan. Balai Penelitian Tanah dan World Agroforestry Centre (ICRAF), Bogor.

Anwar, S. 2003. Characterization of Tropical Peat Soils. [Dissertation]. Kyoto University, Kyoto.

Artz, R.R.E., S.J. Chapman, A.H.J. Robertson, J.M. Potts, F. Laggoun-De´ farge, S. Gogo, L. Comont, J.R. Disnar and A.J. Francez. 2008. FTIR Spectroscopy can be used as a screening tool for organic matter quality in regenerating cutover peatlands. Soil Biol. Biochem. 40(2): 515–527. DOI: 10.1016/j.soilbio.2007.09.019.

Bodner, G., D. Leitner and H-P Kaul. 2014. Coarse and fine root plants affect pore size distributions differently. Plant Soil 380(1–2): 133–151. DOI: 10.1007/s11104-014-2079-8.

Cannavo, P. and J-C Michel. 2013. Peat particle size effects on spatial root distribution, and changes on hydraulic and aeration properties. Sci. Hort. 151: 11–21. 10.1016/j.scienta.2012.12.021.

Chesworth, W. 2008. Encyclopedia of Soil Science. Springer, Dordrecht.

Dlapa, P., M.B. Bodi, J.M. Solera, A. Cerda and S.H. Doerr. 2012. FT-IR spectroscopy reveals that ash water repellency is highly dependent on ash chemical composition. Catena 108: 35–43. DOI: 10.1016/j.catena.2012.02.011.

Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smouldering forest duff. Can. J. Forest Res. 17(12): 1540–1544. DOI: 10.1139/x87-236.

Gong, J., K. Wanga, S. Kellomäkia, C. Zhanga, P,J, Martikainenc and N. Shurpalic. 2012. Modeling water table changes in boreal peatlands of finland under changing climate conditions. Ecological Modelling 244: 65–78. DOI:10.1016/j.ecolmodel.2012.06.031

Kowalik, P.J. 2006. Drainage and capillary rise components in water balance of Alluvial soils. Agric. Water Manage. 86(1–2): 206–211. DOI: 10.1016/j.agwat.2006.08.003.

Kurnain, A., T. Notohadikusumo and B. Radjaguguk. 2006. Impact of development and cultivation on hydro-physical properties of tropical peat soils. Tropics 15(4): 383–389. DOI: 10.3759/tropics.15.383.

Kurnain, A. 2015. Moisture release of tropical peat soils as decreasing water table. Trop. Wetland J. 1(1): 33–37.

Lu, N. and W.J. Likos. 2004. Rate of capillary rise in soil. J. Geotech. Geoenviron. Engin. 130(6): 646–650. DOI: 10.1061/(ASCE)1090-0241(2004)130:6(646).

Matejkova, S. and T. Simon. 2012. Application of FTIR spectroscopy for evaluation of hydrophobic/hydrophilic organic components in Arable soil. Plant Soil Environ. 58(4): 192–195.

McCarter, C. 2012. The Hydrology of The Bois-Des-Bel Bog Peatland Restoration: A Tale of Two Scales [Tesis]. University of Waterloo, Ontario.

Nurzakiah, S. 2014. Prediksi Potensi Emisi Karbon pada Lapisan Gambut Akrotelmik dan Katotelmik [Tesis]. Institut Pertanian Bogor, Bogor.

Price, J.S. and G.S. Whitehead. 2001. Developing hydrologic thresholds for sphagnum recolonization on an abandoned cutover bog. Wetlands 21(1): 32–40. DOI: 10.1672/0277-5212(2001)021[0032:DHTFSR]2.0.CO;2.

Purwanto, I. dan A.N. Gintings. 2011. Potensi lahan gambut Indonesia untuk menyimpan karbon**.** J. Hidrolitan. 2(1): 1–10.

Putra, N.S.S.U. 2003. Hubungan Kadar Air dengan Konsentrasi Emisi Gas Rumah Kaca pada Kebakaran Gambut [Tesis]. Institut Pertanian Bogor, Bogor.

Rein, G., N. Cleaver, C. Ashton, P. Pironi and J.L. Torero. 2008. The severity of smouldering peat fires and damage to the forest soil. Catena 74: 304–309. DOI: 10.1016/j.catena.2008.05.008.

Sutedjo, M.M. and A.G. Kartasapoetra. 2005. Pengantar Ilmu Tanah: Terbentuknya tanah dan tanah pertanian. PT Rineka Cipta, Jakarta.

Schindler, U., A. Behrendt and L. Müller. 2003. Change of soil hydrological properties of fens as a result of soil development. Volume 166(3): 357–363. DOI: 10.1002/jpln.200390055.

Schwärzel1, K., J. Šimùnek, M.T. van Genuchten and G. Wessolek. 2006. Measurement and modeling of soil-water dynamics and evapotranspiration of drained peatland soils. J. Plant Nutr. Soil Sci. 169(6): 762–774. DOI: 10.1002/jpln.200621992.

Syaufina, L. 2008. Kebakaran Hutan dan Lahan di Indonesia: Perilaku Api, Penyebab, dan Dampak Kebakaran. D. Satyawan, dan E. Solahuddin (Ed.). Bayumedia Publishing, Malang.

Szajdak, L. and J. Szatylowicz. 2010. Impact of drainage on hidrophobicity of fen peat-moorsh soils. *In* M. Klavins (Ed.). Mires and Peat. 6th Ed. University of Latvia Press, Riga. pp. 58–174. http://www.lu.lv/fileadmin/user_upload/lu_portal/apgads/PDF/mirespeat.pdf

Taylor, N. and J. Price. 2015. Soil water dynamics and hydrophysical properties of regenerating sphagnum layers in a cutover peatland. Hydrol. Process. 29(18): 3878–3892. DOI: 10.1002/hyp.10561.

Urbanek, E., P. Hallett, D. Feeney and R. Horn. 2007. Water repellency and distribution of hydrophilic and hydrophobic compounds in soil aggregates from different tillage systems. Geoderma 140(1/2): 147–155. DOI: 10.1016/j.geoderma.2007.04.001.

Utami, H.N.S., A. Maas, B. Radjagukguk, dan H.B. Purwanto. 2009. Sifat fisik, kimia dan FTIR spektrofotometri gambut hidrofobik Kalimantan Tengah. J. Tanah Trop. 14(2): 159–166.

Winarna. 2015. Pengaruh Kedalaman Muka Air Tanah dan Dosis Terak Baja terhadap Hidrofobisitas Tanah Gambut, Emisi Karbon, dan Produksi Kelapa Sawit [Disertasi]. Institut Pertanian Bogor, Bogor.

Wösten, J.H.M., E. Clymans, S.E. Page, J.O. Rieley and S.H. Limin. 2008. Peat–water interrelationships in a tropical peatland ecosystem in Southeast Asia. Catena 73(2): 212–224. DOI: 10.1016/j.catena.2007.07.010.

Yazaki, T., S. Uranoa and K. Yabeb. 2006. Water balance and water movement in unsaturated zones of *Sphagnum* Hummocks in fuhrengawa mire, Hokkaido, Japan. J. Hydrol. 319(1–4): 312–327. DOI: 10.1016/j.jhydrol.2005.06.037.