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Relationship between Groundwater Level and Water Content in Oil Palm Plantation on Drained Peatland in Siak, Riau Province, Indonesia

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ABSTRACT

The decrease in groundwater level (GWL) on peatlands, especially in the dry season, can lead to extensive peat drying and making it more vulnerable to the occurrence of wildfire. This research aimed to study the relationship between GWL fluctuations and water content on the surface of peatlands. The study was carried out in a 14 to 17 years old palm oil plantation and a secondary forest located in Siak, Riau Province, Indonesia. Field observations were carried out by installing a water level data logger and soil moisture sensor at a depth of 10 cm and 30 cm from the peat surface, recorded at an hour interval for one year. The results showed that GWL fluctuation was highly correlated to the peat water content in the 10 cm layer both in oil palm plantation (R^2 = 0.65) and secondary forest (R^2 = 0.67). The peat water content in the 30 cm layer showed a low correlation with GWL fluctuation down to -90 cm in oil palm plantation (R^2 = 0.01), however, it was strongly correlated in secondary forests (R^2 = 0.89). Water capillarity in peat soils was able to increase to up to 10 – 30 cm layers from the surface, ranging from 284 to 476% w/w. The capillary water could rise to 68 to 76 cm. The result of the General Linear Model analysis showed that there was a significant influence of land cover, GWL, and peat bulk density on soil water content. Oil palm cultivation activities on peatlands increase the peat bulk density, which in turn increases water capillarity and soil water content.

Keywords: Capillarity, peat bulk density, soil moisture, tropical peatlands

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INTRODUCTION

The utilization of peatlands for agriculture in Indonesia, especially oil palm plantations, has reached a high number (i.e., 1.54 million ha from the total 13.4 million ha peatlands) in the past years (Ritung et al., 2019; Wahyunto & Dariah, 2013). Long-term use of peatlands and land drainage (Van Lanen et al., 2004) has resulted in a decrease in groundwater level, an increase in aeration, soil subsidence, and rapid compaction of peat (Rieley, 2007). In addition, peat excessive drainage may cause peat irreversible drying or hydrophobicity (Hooijer et al., 2010). This process may be accelerated if the peatlands' groundwater level (GWL) is too deep, especially during the dry season, causing the water capillarity inhibition. The critical water content where the irreversible drying occurs is 184 – 213% w/w for peat with hemic maturity and 118 – 126% w/w for peat with sapric maturity (Winarna et al., 2016). Putra (2003) reported that when the peat water content was lesser than 117% w/w, the flammability increased, thus might trigger a large-scale fire. Rein et al. (2008) also added that the peat soil water levels below 125% w/w could start a spontaneous peat ignition.

Over the past decades, Indonesia has experienced a series of drought-related major forest and land fires, such as those that occurred in 1982/83, 1997/98, 2009, and the most recent 2015 fire. Nearly 70 million people have been exposed to unhealthy air during the 2015 fire (Crippa et al., 2016). The fire had caused enormous economic and social consequences, for instance, the smoke/ haze pollution that caused billions of dollars economic loss (Varma, 2003; World Bank, 2016). When drought coincides with El Nino in the humid tropics area (e.g., Southeast Asia), the impact increases through forest fire which disrupts the global carbon cycle, including reduction of carbon stocks (Hooijer et al., 2010; Huijnen et al., 2016; Page et al., 2002; Page & Hooijer, 2016) and intensifies the danger of haze (Lee et al., 2016).

Peatlands can experience drought under an excessive drainage condition, thus increasing its susceptibility to fire (Szajdak & Szatylowicz, 2010). According to Wösten et al. (2008), peatlands' fire vulnerability will increase when GWL falls below 40 cm from the surface of peatlands (i.e., -40 cm). Agreeing to this, the Indonesian government has declared through its regulation (PP No. 71/2014 juncto PP No. 57/2016) that the peat ecosystems are considered degraded if the GWL is lower than -40 cm and an urgent mitigation act should be focused in these areas. Indeed, the construction of a massive drainage system has a real impact on peatland hydrology, causing a major decrease in GWL (Ishii et al., 2016). In turn, the decrease in GWL affects the distribution of moisture throughout the peat soil profile. GWL acts as a water reservoir in peatlands and the dynamics of peat water content are related to the bulk density and the water capillarity capacity of the peat soil (McLay et al., 1992). Agricultural development on peatlands has impacted the physical characteristics of peat that are relevant to the influence of humidity, including total porosity and soil bulk density (Radjagukguk, 2000).

There have been several studies on the effect of groundwater level fluctuations on the upper-soil layer in peatlands, however, these studies did not cover peatland areas planted with oil palm, especially those planted for the long-term. The water capillarity characteristic of peat soils was shown able to maintain moisture on the soil surface (Nugraha et al., 2016) and is expected to support the sustainable use of peatlands for oil palm cultivation. Therefore, this study aimed to investigate the relationship between the groundwater level fluctuations and water content of peat soils in oil palm plantations and secondary forests by considering the peat soil bulk density of each type of land cover.

MATERIALS AND METHODS

Research Location

This study was conducted from January to December 2018 on tropical peatlands located in PT ABC, Koto Gasib Village, Siak Regency, Riau Province, Indonesia. Field observations were done at two different locations, i.e., oil palm plantation and an adjacent degraded secondary forest. The oil palm plantation was located at 0°43’34.10” N 101°45’33.40” E, while the secondary forest was located at 0° 44’44.70” N 101°46’24,20” E. The oil palm plants ranged from 14 to 17 years. The secondary forests were dominated by fast-growing species, e.g., *Macaranga* sp., *Acacia cracicarpa*, and *Acacia mangium*.

Characterization of Peat Soil

Field peat characterization was done at two study locations. Direct soil characterization was carried out in the field using peat drills; samples were taken and analyzed at the laboratory. Field peat soil characterization included was physical properties and maturity level of the soil. Peat samples were taken using cubicle metal boxes (10 cm x 10 cm x 5 cm) and samples were taken from different soil layers (i.e., 0 – 10, 10 – 20, 20 – 30, 30 – 40, and 40 – 50 cm) in three replications at each location. The laboratory analysis of peat soil characteristics included was water content, bulk density, and ash content.

The level of peat maturity was determined directly in the field by assessing the remnants of the fibers left in the hand upon squeezing (Wahyunto et al., 2005). Determination of water content and bulk density was carried out by gravimetry method with oven drying temperature at 65 ± 5°C for 2 x 24 hours until it reached a constant weight (Ng & Eischens, 1983). The determination of ash content was by the loss on ignition at 700°C.

Automatic Measurement of Fluctuations in Groundwater Level

Fluctuations in the groundwater level were measured using a 4-inch piezometer pipe completed with a water level data logger (HOBO U20L-40, USA). The water level data logger measured the pressure of the water column (kPa) in an hour interval. The data was then converted to the distance (meter) where the measurements were conducted. Recorded data were downloaded using a USB Base Station. A unit of data logger was installed each in oil palm plantation and the secondary forest. The design of the water level measurement is presented in Figure 1. The water level height from the land surface was calculated using the following equation:

GWL = S – (H + X)

where:

GWL : Groundwater level (m)

S : Length of the sling to the sensor at the water level data logger (m)

H : Height of piezometer head pipe (m), which is the length of the piezometer body above ground

X : Height of the water column recorded by the sensor (m)

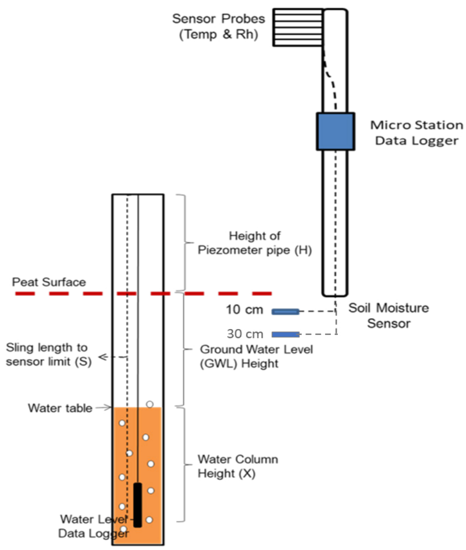

Figure 1. The design of groundwater level and peat water content measurement

Automatic Measurement of Peat Water Content

The automatic measurement of peat water contents was done using a soil moisture sensor (Decagon EC5 S-SMC-M005, USA) that can measure soil moisture content from 0 to 0.550 (v/v). Soil moisture sensors were installed at a depth of 10 cm and 30 cm from the soil surface at each studied location. Each sensor retrieved data every one hour and automatically stored it into the micro station data logger (Hobo H21-USB Micro Station, USA). The soil moisture sensor was installed close to the water level data logger (Figure 1). The peat water content in volume (v/v) recorded by the sensor was converted to percent weight (% w/w) by dividing it with the related bulk density of the soil at each depth.

Data Analysis

All collected data were tested for homogeneity of variance using Levene's test at $p < 0.05$ and the normality test using Kolmogorov-Smirnov at $p < 0.05$. The relationship between groundwater level and peat water content was analyzed using simple regression. General Linear Model analysis was used to study the effects of land cover, groundwater level, and peat bulk density on peat water content. Statistical analysis was conducted using SPSS version 16.0-2007 (SPSS Inc., USA). Groundwater level and soil moisture data processed using HOBOware Pro (Onset Computer Corp., Bourne, USA).

RESULTS AND DISCUSSIONS

Characteristics of Peat Soil

The peat soil characteristics are presented in Table 1. A sapric peat maturity level was found at the 0 – 20 cm layers of oil palm plantation and the 0 – 10 cm layer of the secondary forest (Table 1). Thus, in general, the oil palm plantation has a higher peat maturity compared to the secondary forest. The peat bulk density (BD) at 0 – 30 cm layer of oil palm plantation samples were relatively more compacted (0.09 – 0.15 g cm^{-3}) compared to the secondary forest (0.07 – 0.12 g cm^{-3}). In agricultural practice, compaction of peat due to draining of peatlands causes changes in the structure of peat, in particular the bulk density and cavity ratio (Camporese et al., 2006), and resulted in a higher BD in upper layers of the oil palm plantation compared to the secondary forest. The higher BD of the upper layers was also due to the higher degree of decomposition of peat at these layers.

Analysis of water content from each location showed that the water content surface was lower than the deeper layers of peat. The water content in 0-30 cm layers in the oil palm plantation ranged from 205 to 405% and in the 30-50 cm layer ranged from 461 to 474%. In the secondary forest, the water content in the 0-30 cm layers ranges from 208 to 316%, and in the 30-50 cm layers ranges from 401 to 490%. The higher water content in the deeper layers probably due to its closer distance to the groundwater level.

Dynamics of Groundwater Level

The observation of GWL dynamics in peatlands on the oil palm plantation and the secondary forest was carried out from January to December 2018. The

Table 1
Characteristics of peat soils at the study site

Land cover	Peat depth (cm)	Peat maturity	Peat water content (% w w^{-1})			
			Replicate 1	Replicate 2	Replicate 3	Avg.
Oil palm plantation	0 – 10	Sapric	138	323	153	205
	10 – 20	Sapric	198	315	318	277
	20 – 30	Hemic	415	405	396	405
	30 – 40	Hemic	501	469	414	461
	40 – 50	Fibric	540	440	441	474
Secondary forest	0 – 10	Sapric	300	163	160	208
	10 – 20	Hemic	225	247	202	225
	20 – 30	Fibric	335	314	298	316
	30 – 40	Fibric	504	304	395	401
	40 – 50	Fibric	466	430	575	490

Table 1 *(Continued)*

Land cover	Peat depth (cm)	Peat maturity	Bulk density (g cm^{-3})			
			Replicate 1	Replicate 2	Replicate 3	Avg.
Oil palm plantation	0 – 10	Sapric	0.18	0.11	0.16	0.15
	10 – 20	Sapric	0.11	0.12	0.12	0.12
	20 – 30	Hemic	0.10	0.09	0.08	0.09
	30 – 40	Hemic	0.09	0.09	0.09	0.09
	40 – 50	Fibric	0.09	0.08	0.08	0.08
Secondary forest	0 – 10	Sapric	0.09	0.13	0.14	0.12
	10 – 20	Hemic	0.07	0.10	0.09	0.09
	20 – 30	Fibric	0.07	0.07	0.08	0.07
	30 – 40	Fibric	0.08	0.09	0.08	0.08
	40 – 50	Fibric	0.08	0.07	0.06	0.07

Note. *WC = Water content (% w/w); BD = Bulk density (g cm^{-3})

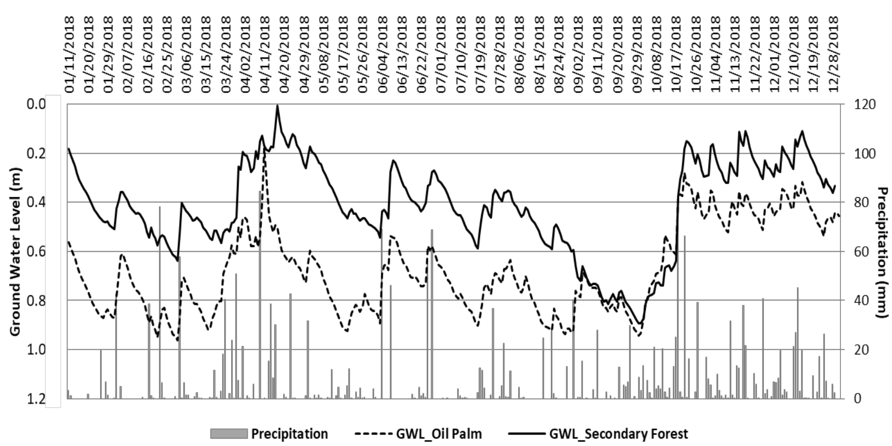

Figure 2. Groundwater level fluctuations in oil palm plantation and secondary forest

results showed that the fluctuations in the groundwater level were strongly influenced by the rainfall conditions at the studied sites (Figure 2). A similar GWL dynamics pattern was observed at the two studied locations. The annual rainfall at the research location in 2018 reached a maximum of 2,169 mm, with 2 wet periods in April-June and October-December, also 2 dry periods in January-March and July-September.

The wet period in October-December with rainfall of 8.62 mm day^{-1} reached the highest GWL average in both sites (-0.47 m in the oil palm plantation, -0.33 in the secondary forest; see Table 2). On the contrary, the dry period in July-September with rainfall of 3.82 mm day^{-1} reached the lowest GWL average (-0.80 m in the oil palm plantation, -0.56 m in the secondary forest; see Table 2). In general, the GWL in the oil palm plantation is deeper compared to that in the secondary forest. A possible explanation was due to the development of the canal system in the oil palm plantation to facilitate the rooting conditions of oil palm. The exploitation of forest resources on peat surfaces further reduces the ability of ecosystems to withstand rainfall, thus, water flows faster into rivers and the water level decreases in the dry season (Rieley, 2007).

Table 2

Seasonal period and groundwater level (GWL) at the study site

Period (Month)	Rainfall (mm/day)	Average GWL (m)	Land cover
Wet (April - June)	6.45	0.67	Oil palm plantation
		0.41	Secondary forest
Wet (October – December)	8.62	0.47	Oil palm plantation
		0.33	Secondary forest
Dry (January - March)	5.3	0.75	Oil palm plantation
		0.53	Secondary forest
Dry (July - September)	3.82	0.80	Oil palm plantation
		0.56	Secondary forest

Relationship between Water Level Fluctuation and Peat Water Content

The observation of peat water content at the oil palm plantation was successfully done in January to December 2018, while the observation in the secondary forest was only done from January until July 2018 due to the damage in the soil moisture sensor. The observation results of the peat water content and water level fluctuations are shown in Figure 3.

In both locations, the fluctuations of water contents to a certain extent were affected by the fluctuations of the groundwater level. The effects of GWL were more pronounced in the surface up to the 10 cm depth in the secondary forest and up to 30 cm depth in the oil palm plantation. The decrease in the groundwater level decreases soil water content in the entire soil profile and resulting in the release of a number of groundwater volumes from the above layers (Kurnain et al., 2006). A high reduction of GWL in the oil palm plantation during the dry months (January-March and July-September) to around -0.90 m was related to

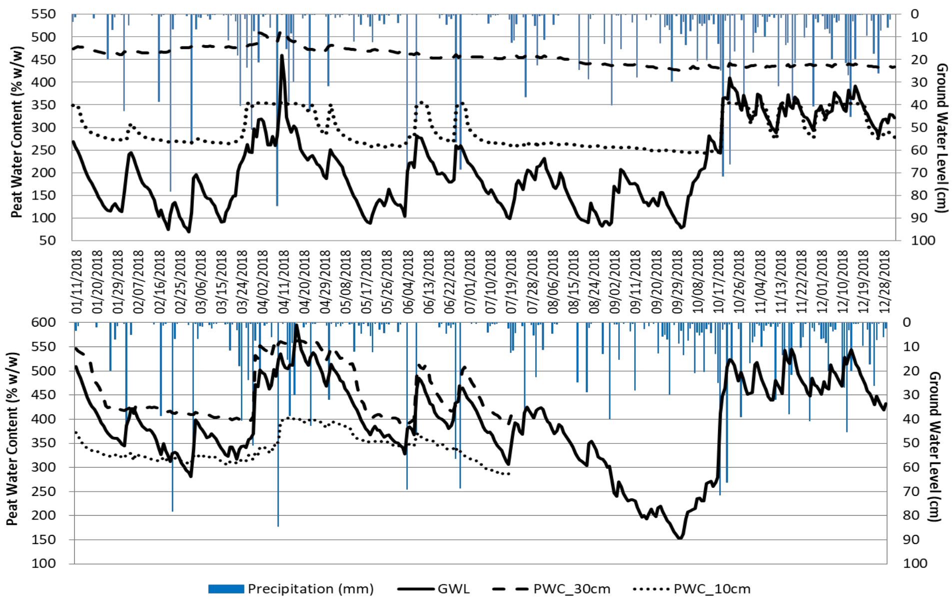

Figure 3. Groundwater level and peat water content in (a) oil palm plantation and (b) secondary forest (*Note*. GWL = groundwater level; PWC = peat water content]

the water content (10 cm layer: 244 - 267% in 10 cm layer 426 - 476% in 30 cm layer; see Figure 3a). During the dry months, GWL in the secondary forest only decreased to around -0.65 m and also related with its water content (284-312% in 10 cm layer and 389 – 415% in 30 cm layer; see Figure 3b). The observed water contents were much higher than the critical irreversible dry water content according to Winarna et al. (2016), which were 184-213% for hemic maturity and 118-126% for sapric maturity. The observed water contents were also much higher than the water content of a potentially burned peat material at 117% (Putra, 2003) or a peat material that can spontaneously ignite below 125% (Rein et al., 2008).

Fluctuations in peat water contents were strongly influenced by the groundwater level dynamics (Figures 3 and 4). A strong correlation was found between GWL depth and water content in the 10 cm layer in both sites (plantation $R^2 = 0.65$; $p < 0.05$ and secondary forest $R^2 = 0.67$; $p < 0.05$; see Figure 4a). A very strong correlation ($R^2 = 0.89$; $p < 0.05$) between GWL depth and water content in the 30 cm layer was found in the secondary forest (Figure 4b). Contrary to other results, there was only a very weak correlation ($R^2 = 0.01$; $p < 0.05$) between the GWL and the water content in the 30 cm layer in the oil palm plantation (Figure 4b). As presented in Figure 3a, there were only low fluctuations in the water content of the 30 cm layer (435 to 510%) although there were high fluctuations in the related GWL (about -0.18 to -0.94 m). The relatively stable water content in this

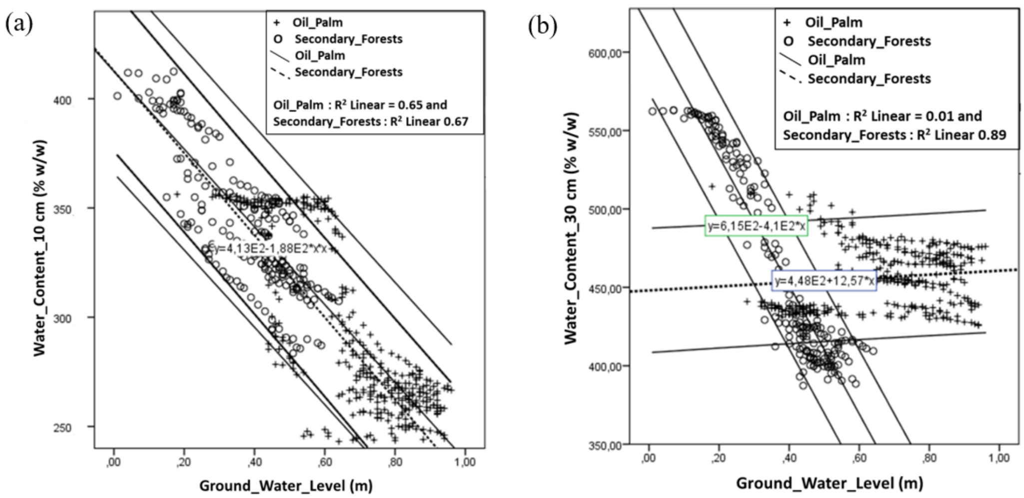

Figure 4. Correlation of groundwater level with peat water content in oil palm plantation and secondary forest on (a) 10 cm layer from the surface (a) and (b) 30 cm layer from the surface

layer was probably due to the higher bulk density and maturity of peat in the profile of the oil palm plantation (Table 1), allowing a higher raise of water capillarity compared to that in the profile of the secondary forest. Capillary water can replace water lost by evapotranspiration in the upper layers (Chesworth, 2008; McCarter, 2012; Yazaki et al., 2006). The rise of capillary water in this study can be observed from the rainfall data, water content, and GWL during the dry period in the oil palm plantation. During the dry period of February 5-16 and June 28 to July 8 with daily rainfall of 0.5 mm, peat water contents in the 30 cm and the 10 cm layers were around 455-466% and 284-294%, respectively. These numbers were much higher than the hydrophobicity water content according to Masganti et al. (2002) and Winarna et al. (2016). The peat water contents were related to the GWL fluctuation (-78 to -86 cm) in the oil palm plantation. Considering the recorded water content in the 10 cm layer, it can be suggested that the capillary water in the oil palm plantation could rise from about 68 to 76 cm. This result is higher compared to the laboratory study of Nugraha et al. (2016), where the water capillary increased for 50 cm.

Effects of Land Cover, Groundwater Level, and Bulk Density on Soil Water Content

There were two General Linear Model (GLM) models developed in this study. The model I studied the effect of land cover (F1), depth of soil moisture sensor (F2), and groundwater level (X1) on peat water content (Y) (Table 3). The results of the GLM model I showed the significant influence of each of the factors and interactions between land cover factors (F1), depth of soil moisture sensor (F2) and groundwater level (X1) on peat water content (Y) with $R^2 = 0.960$ at the significance level $\alpha < 5\%$. Model II studied the effect of land cover (F1), depth of soil sample (F2), and bulk density (BD) on peat water content (Y) (Table 4). The results of the model II GLM analysis showed the significant effect of land cover factor (F1) and interactions between land cover (F1) and bulk density (BD) on peat water content (Y) with $R^2 = 0.955$ at the significant level $\alpha < 5\%$.

Table 3

Effect of land cover (F1), depth of soil moisture sensor (F2) and groundwater level (X1) on peat water content (Y)

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	5561113.51[a]	7	794444.78	2713.20	.000**
Intercept	11232491.28	1	11232491.28	38361.37	.000**
F1	11838.62	1	11838.62	40.43	.000**
F2	184386.09	1	184386.09	629.72	.000**
X1	742117.84	1	742117.84	2534.49	.000**
F1 * F2	63755.93	1	63755.93	217.74	.000**
F1 * X1	103420.29	1	103420.29	353.20	.000**
F2 * X1	2545.10	1	2545.10	8.69	.003**
F1 * F2 * X1	151419.36	1	151419.36	517.13	.000**
Error	231903.37	792	292.80		
Total	129349953.22	800			
Corrected total	5793016.89	799			

[a]) $R^2 = 0.960$ (Adjusted $R^2 = 0.960$); **) significant at $\alpha < 5\%$

Table 4

Effect of land cover (F1), depth of soil sample (F2) and bulk density (BD) on peat water content (Y)

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	416251.46[a]	19	21907.97	11.17	.000**
Intercept	22674.11	1	22674.11	11.56	.007**
F1	9898.57	1	9898.57	5.05	.048**
F2	16682.66	4	4170.66	2.13	.152
BD	1532.91	1	1532.91	0.78	.397
F1 * F2	16427.08	4	4106.77	2.09	.156
F1 * BD	12264.76	1	12264.76	6.25	.031**
F2 * BD	13895.27	4	3473.82	1.77	.211
F1 * F2 * BD	17278.75	4	4319.69	2.20	.142

Table 4 *(Continued)*

Source	Type III sum of squares	df	Mean square	F	Sig.
Error	19605.15	10	1960.51		
Total	4029419.829	30			
Corrected total	435856.606	29			

[a]) R^2 = 0.955 (Adjusted R^2 = 0.870); **) significant $\alpha < 5\%$

CONCLUSION

This study showed that the peat soil water content on the surface of peatlands was greatly affected by the fluctuations in the groundwater level (GWL), land cover, and peat density. Strong correlations were shown between GWL and peat soil water content in the 10 cm layer in oil palm plantations (R^2 = 0.65) and secondary forests (R^2 = 0.67). A very strong correlation was found between GWL and peat soil water content in the 30 cm layer at the secondary forest (R^2 = 0.89). The peat soil water content in the 30 cm layer of the oil palm plantation remains high despite the fluctuations in GWL, due to the higher bulk density which allows an increase in water capillarity. The capillary water in the oil palm plantation during the dry period could rise to 68 to 76 cm marked by the high peat water content in the 10-30 cm layers, ranging from 284 to 476%. The result of the General Linear Model analysis showed that there was a significant influence of land cover, GWL, and peat bulk density on soil water content. Oil palm cultivation on peatland increases the peat bulk density and water capillarity, also maintains a high peat soil moisture, thus reducing peat vulnerability to fire.

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