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Uncertainty in the Management of Tropical Peatlands for Oil Palm Plantations due to Drainage Practices

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ABSTRACT

The conversion of tropical peatlands to oil palm plantations has affected the long-term storage stability of water and carbon. The conversion requires a drainage system that results in land subsidence and, in turn, reduces the carrying capacity of water storage and carbon stocks. This study aims to analyze subsidence from long-term observations (2004-2020) to obtain an appropriate water management measure for three scenarios of drainage depths at the oil palm plantations in Jambi Province. It is found that the reduction is quite variable depending on the level of drainage depths. The subsidence was 55 cm, 49 cm, and 34.7 cm for deep, moderate, and shallow drainage conditions. The groundwater level was deeper than 100 cm, which is far below the threshold of 40 cm, as stated in the government regulations. However, the regulations are still debated since subsidence must occur in drained peatlands regardless of the water level. The observed large subsidence implies that better water management in a new site is crucial and necessary to reduce the impact of peatlands degradation relative to current conditions and that high rates of land subsidence should be accepted as an inevitable change from the conversion of tropical peatlands to oil palm plantations.

1. INTRODUCTION

Under natural condition, peat swamp land is inundated by water, especially during the rainy season. The watery condition over the land is not suitable for agriculture/plantation, especially oil palm. To make the land usable for agriculture or other purposes, a drainage system is required. It lowers the water table to a designated level. The removal of water, however, can cause land subsidence, peat loss, and shortage of water. To avoid high subsidence rates and water shortages during the dry season, it is very important to control the drainage and water level in peatland (Aswandi et al. 2017; Hooijer et al. 2012; Wösten et al. 1997).

A proper water management system in peatland must have several functions: (1) water flowing above the ground (drainage function); (2) water level control for cultivation (irrigation function); and (3) water conservation or water retention (restoration function) (Parish et al. 2012). In principle, the land development of peat swamp areas is to modify the hydrological system, which can have direct and indirect effects on the peatland ecosystem. On one hand the system will release more water, which may lead to unstable flow conditions. It also carries toxins (acids), nutrients and sediments on the water. On the other hand, it will cause a process of mineralization or oxidation, thus changing the rate of subsidence. The drainage also causes biodiversity drying up of the land, triggering peat fires during dry season. Moreover, a biodiversity loss is unavoidable over a drained peat land. Many plants and animals will disappear as their habitat is destroyed. To mitigate these impacts, an appropriate control of water table should be done.

The government has issued some regulations that intend to mitigate subsidence and peat loss in a drained peat land, namely PP.71 2014 and PP.57 2016 (Pemerintah Pusat 2014, 2016). The regulation states that the groundwater level depth cannot exceed a threshold of 40 cm when the water is drained. However, the regulation is still debatable whether the threshold is effective or not for the mitigation since the subsidence surely will happen due to drainage regardless of water level (Martin 2020). More studies related to subsidence in peat land are required to obtain more comprehensive knowledge about the damages of drainage, and eventually to improve the regulation.

Despite the knowledge of land change impact in peat swamp areas has been established, the lack of evidence from long monitoring of land degradation triggers discussions among researchers on degree of the impacts, especially the rate of subsidence. Therefore, this study aims to analyse subsidence obtained from long-term monitoring in a drained peatland in Jambi Province, Indonesia, that will provide information to obtain a better land management system. The results of this study try to open views and enrich the existing system approach, in accordance with the latest scientific developments, and the increasing number of available research data bases, as well as being supported by increasingly fast and accurate computing capabilities, to support agricultural systems and predict peat damage due to subsidence.

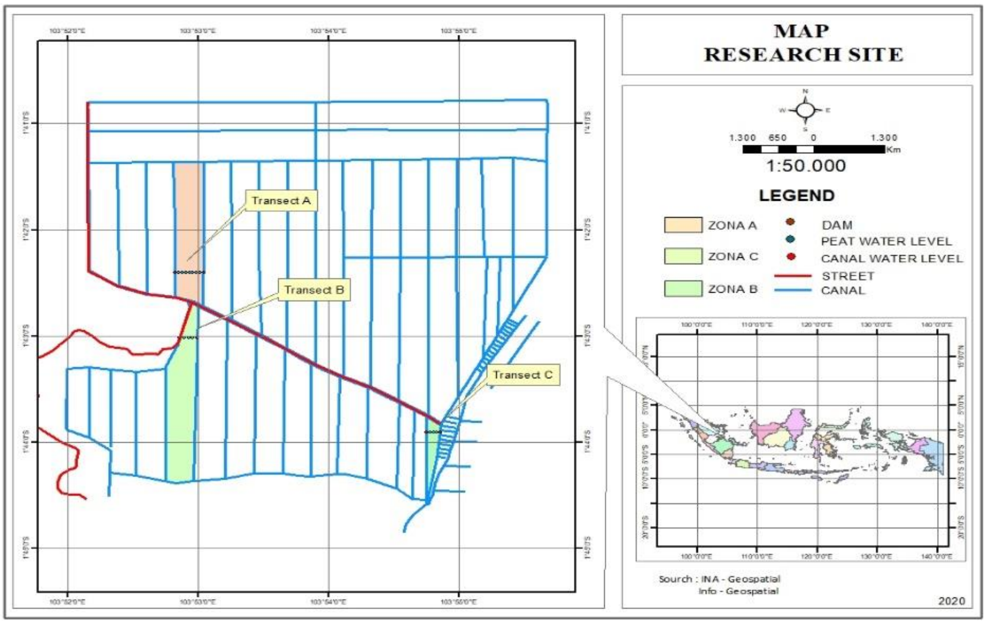

Figure 1 The research site map shows three zones and their transects for monitoring water level fluctuations and subsidence rate in a drained peatland in Jambi, Indonesia. The canals are separated by 200-300 m width.

2. METHOD

2.1 Study Area

The research site is in Muaro Jambi Regency, Jambi Province, Sumatera, Indonesia (Figure 1). The site was drained and developed for palm oil plantation in 1992. Peat thickness ranges from 5.29 to 10.77 metres. In the site, mature palm oil trees leaning due to peat subsidence can be observed. The area is heavily drained by 8 m wide and 3 m deep canals. There are three transects installed with dipwells, staff gauges, rain gauges and diver logger to measure data at three zones (Figure 1). The three zones are defined to study impacts of subsidence under different water management practices: deep water level (Zone B), medium/moderate water level (Zone A) and shallow water level (Zone C).

2.2 Monitoring and analysis method

Peat surface water and subsidence rates are measured daily in dipwells installed in the peat. The dipwells comprise of PvC pipes that were planted into the mineral soil. The anchoring allows these dipwells to be used as subsidence poles to monitor subsidence rate too. Overall, there are 20 dipwells installed on the three transects. Canal water levels are measured using gauges that record daily. One rain gauge has been installed to measure hourly rainfall. Measurements of peat depth and water table were done in 2004, 2009, and 2020. Analyses are carried out by comparing peat depth, water table, and subsidence rate between the three zones and relating them with past water management practices applied on the site.

3. RESULTS AND DISCUSSION

3.1 Peat depth

The depth of peat differs in each zone. In Zone A, the peat depth ranges from 5.29 m to 6.39 m. Peat in Zone B has similar thickness to Zone A (5.54 m to 6.21 m) but peat in Zone C is much thicker (8.84 m to 10.77 m). Detail peat depth measurement at all dipwells is shown at Table 1.

Table 1 Peat depth in oil palm plantation in the three zones

Scenario	Dipwell	Peat Depth (m)	Crop	Year of Planting
Moderate drainage (Zone A)	A1	5.66	Oil Palm	1992
	A2	5.81	Oil Palm	1992
	A3	6.00	Oil Palm	1992
	A4	5.70	Oil Palm	1992
	A5	5.90	Oil Palm	1992
	A6	5.29	Oil Palm	1992
	A7	6.38	Oil Palm	1992
	A8	6.39	Oil Palm	1992
	A9	6.38	Oil Palm	1992
Deep drainage (Zone B)	B1	5.54	Oil Palm	1992
	B2	5.74	Oil Palm	1992
	B3	6.12	Oil Palm	1992
	B4	6.11	Oil Palm	1992
	B5	6.21	Oil Palm	1992
Shallow drainage (Zona C)	C1	10.77	Oil Palm	1997
	C2	9.63	Oil Palm	1997
	C3	8.84	Oil Palm	1997
	C4	8.85	Oil Palm	1997
	C5	8.93	Oil Palm	1997

3.2 Water depth patterns

The pattern of changes in the groundwater level in the three zones was caused by differences in the water level controls in the three zones (Figure 2). The dry and rainy season changes did not significantly affect changes in the groundwater level in the three research zones. Although the rainfall was higher starting at the end of August 2020, the groundwater level remained stable, possibly due to canal blocking. Water management with better operation and maintenance (OM) activities have been carried out in 2004-2015 (period of maximum palm production) but the OM activities were not good after 2015. The lack of OM was suspected to increase the speed of subsidence and changed the flow direction.

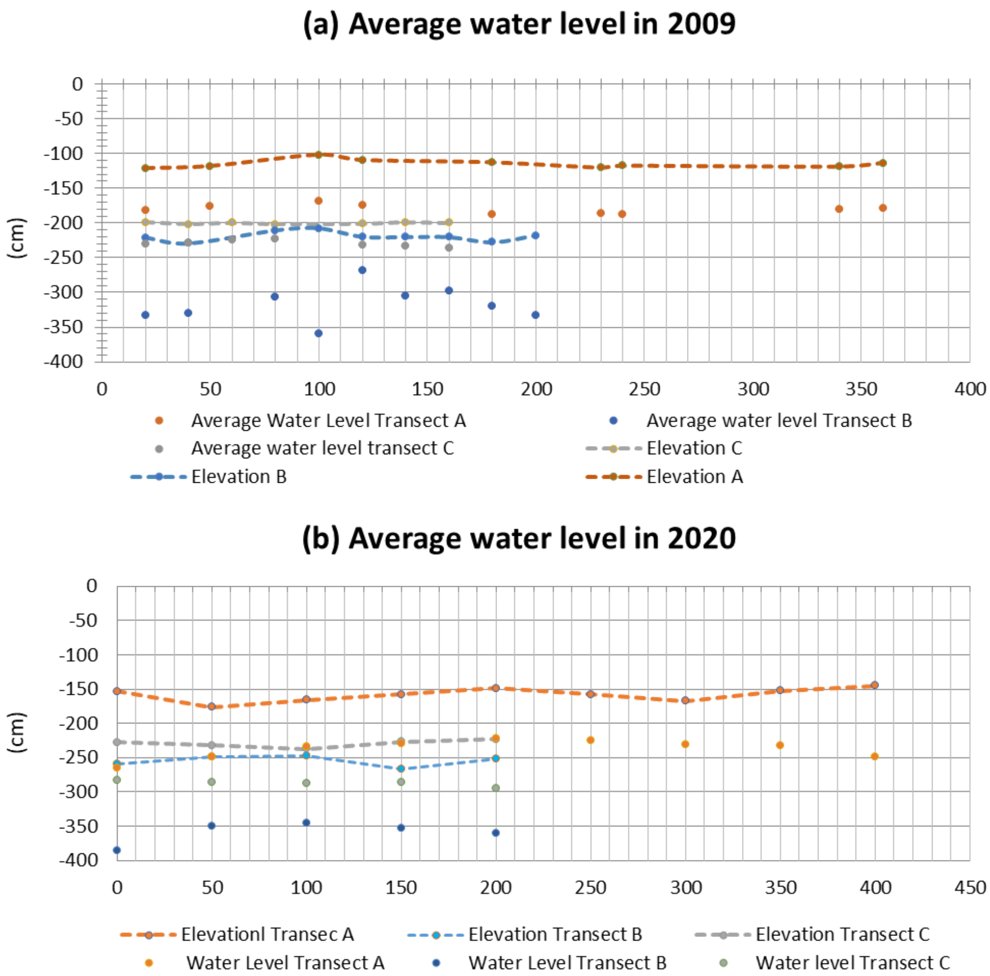

Figure 2 Average groundwater level and elevation change for the three transects in 2009 (above) and 2020 (below).

3.3 Subsidence rates

PvC-pipe installation activities under subsidence observation began in 2004 then continued in 2009 and 2020. The subsidence rate was calculated over the period of 2004-2020 (Table 2). The table shows that subsidence in Zone A (moderate drainage) was between 30.6-39 cm, while in Zone B (deep drainage), it ranges from 36.2-40 cm and in Zone C (shallow drainage) the rate of subsidence ranges from 27-29.7 cm.

The recent subsidence values (2009-2020) are much higher than the peat subsidence in 2004-2009, which is approximately 10 cm. This is because in 2004-2009 it was known that water management on the land tended to be better managed, so that the depreciation of the peat surface height was slower. This is inversely proportional to the rate of decline in the height of the peat surface in 2009-2020 with worsening water management, so subsidence becomes faster.

The results showed that the highest subsidence rate occurred in Zone B where the groundwater level was at the deepest point (Figure 3). Based on 2020 monitoring data, the average land subsidence rate is estimated at 5.5 cm/year. Figure 3 shows the rate of decline for each transect during the dry period plotted against the average rate of decline for each transect. The annual rate of decline for each transect ranges from 4.4 cm/year - 6.5 cm/year. Given the large differences in water depth between transects, the variation in subsidence is actually very small. Transects 1 to 4, which have a much lower groundwater level than Transects 5 to 8 do not experience a higher land subsidence. During the dry season alone, the surface of the souls on each transect was found to have receded by 2.2 cm - 3.5 cm in 4 months.

Table 2 Results for subsidence measurement.

Scenario of WL	Point	Elevation in 2020 (cm)	Subsidence (cm)	
			2004-2009	2009-2020
Moderate (Zona A)	A1	0	10.7	32.1
	A2	-22.5		39
	A3	-11.5		31.2
	A4	-3.8		30.7
	A5	4.7		31.7
	A6	-4.5		30.6
	A7	-13.5		32
	A8	0.7		31.5
	A9	8.7		32.4
Deep (Zona B)	B1	0	11.2	40
	B2	9.5		36.7
	B3	12		36.2
	B4	-7.9		36.7
	B5	75		36.5
Shallow (Zona C)	C1	0	10.5	28
	C2	-4,5		27
	C3	-9,5		29.1
	C4	0,5		29.7
	C5	4,5		29.2

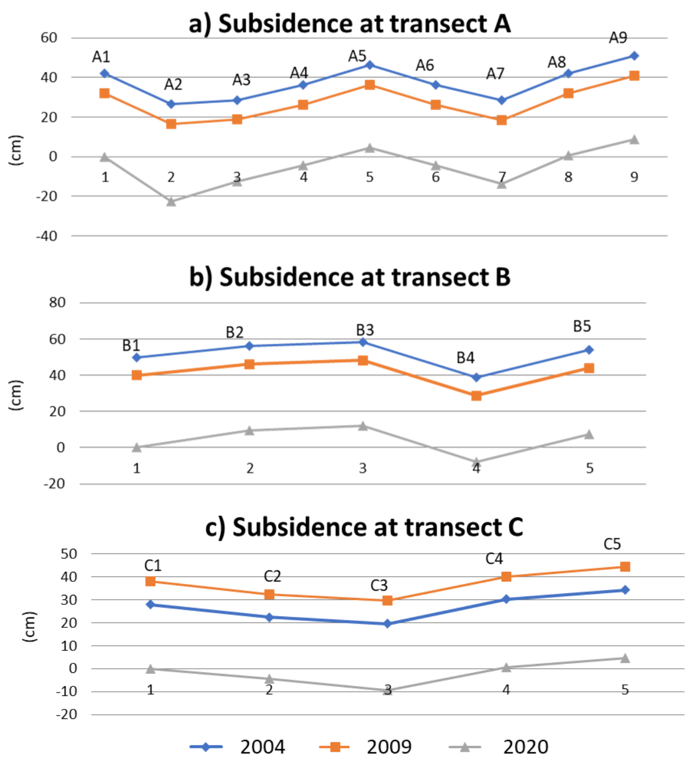

Figure 3 Land surface elevation at transect a) A, b) B, and c) C in 2004, 2009, and 2020. The decreasing of elevation indicates the subsidence.

The average monthly subsidence in the dry period (0.55 cm / month to 0.88 cm / month) was higher than the annual subsidence rate (0.37 cm / month to 0.54 cm / month), as well as in the wet period which ranges from 0.1 cm / month to 0.39 cm / month. The results show large variations in the rate of settlement between wells within the transect itself, but limited variation between transects. When compared with the descent rate for each transect, there is a greater variation within the transect. A visual comparison of peat surface in 2004, 2009, and 2020 and mineral soil is shown in Figure 4.

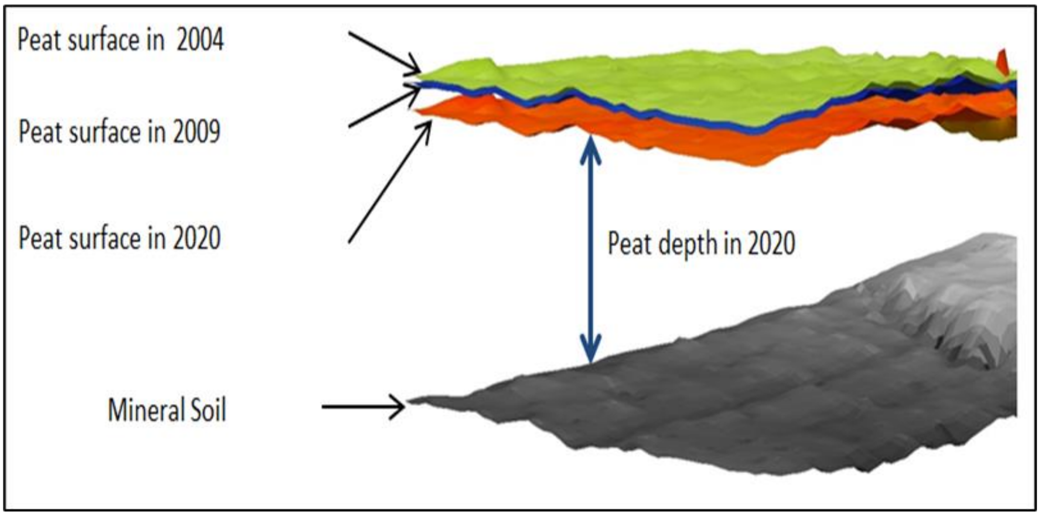

Figure 4 Schematic surface feature of relative height of peat in the study area from 2004-2020.

3.4 Loss of Peat Volume

The subsidence monitoring data for 2004 and 2020 can be used to calculate the volume of peat loss from 2004-2020. In Table 3 for zone A, the volume of peat loss is 415904.41 m3 from 2004-2020, in zone B is 532751.36 m3 and in zone C, the total volume of peat lost is 67285.645 m3. The deep drainage scenario (Zone B) has lost peat in a much larger amount compared to the peak in shallow scenario (Zone C).

Table 3 Total peat volume loss in 2004 - 2020

Location	Area (m^2)	Subsidence (m)		Peat volume loss (m^3)		Total loss (m^3)	Total loss per area (m^3/ha)
		2004-2009	2009-2020	2004-2009	2009-2020		
Transect A	965972,32	0.107	0.3236	103359.039	312545.175	415904.21	4305.55
Transect B	1091256,37	0.116	0.3722	126585.739	406165.623	532751.36	4882.00
Transect C	171559,52	0.105	0.2872	18013.7498	49271.8948	67285.65	3922.00

3.5 Direction of Water Flow in Canal

Because of changes in groundwater table and subsidence rate in each zone, the water flow in canals underwent changes in its direction. The flow direction of water in 2004 and 2020 is shown in Figure 5. The changes were also partly due to canal blocking or dams, which led to an increase in outlets and a reduction in water input into the land.

4. DISCUSSION

4.1 Water depth as primary factor influencing subsidence rate and future water management strategies

Degradation and conversion of peatlands due to plantation opening or flood control have been known to disrupt natural hydrological functions (Sim & Balamurugan 1991). Reported by Hooijer et al.

(2012), the average rate of subsidence of tropical peat soils is 5.5 cm/year. This is consistent with what we found in our research site in Jambi, which was started to drain in 1992. The last measurement is 28 years after planting and drainage.

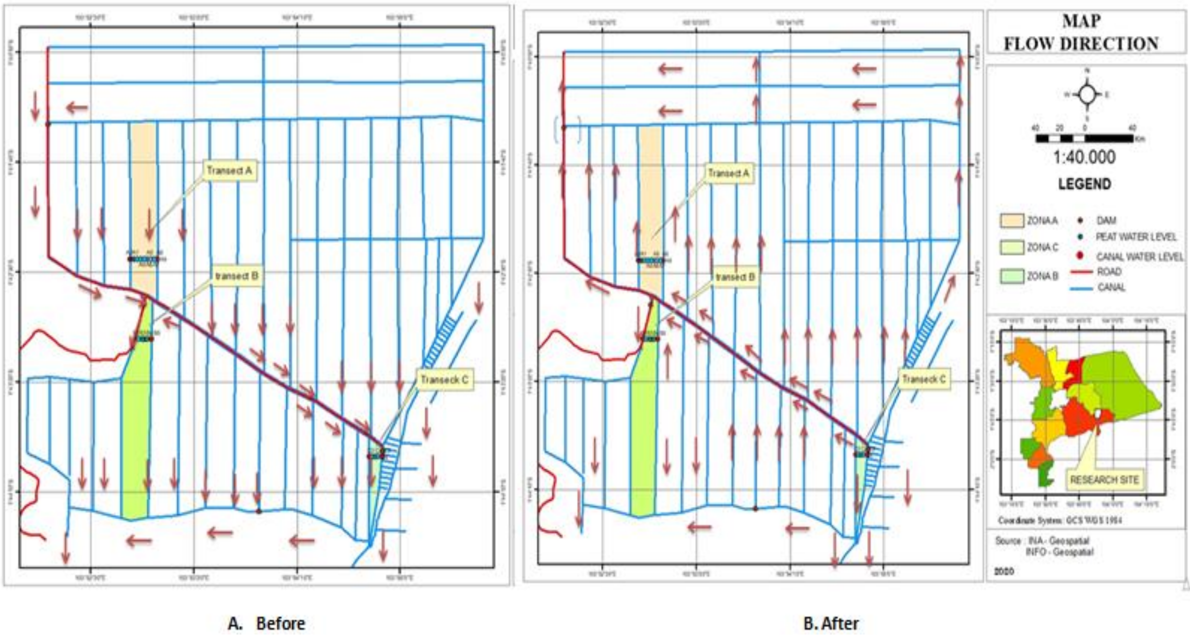

Figure 5 Map of changes in the direction of water flow in the drainage system (Canal system), as a result of subsidence from 2004 – 2020 in the research area.

In theory, the land subsidence ($\boldsymbol{S}$) consists of two subcomponents (Aswandi et al. 2017; Hooijer et al. 2012): (a) subsidence due to oxidation of peat mass loss (S_E) and (b) subsidence due to physical compaction (also called consolidation) (S_c),

$$\boldsymbol{S = S_E + S_C}, \tag{1}$$

where S_E is a function of CO_2 emission (E) and bulk density (N_c),

$$\boldsymbol{S_E = \frac{E\left(\frac{M_C}{M_C+2M_O}\right)}{\rho_b N_c}}. \tag{2}$$

The M_C, M_O, and ρ_b are atomic weight of carbon, oxygen, and fraction of carbon content, respectively. On the other hand, S_c is linearly proportional to change in effective stress due to groundwater decrease (ΔP):

$$\boldsymbol{S_C \sim \Delta P}. \tag{3}$$

During the monitoring period from 2004-2020, the observed subsidence suggests that groundwater table change may be a key factor influencing subsidence. Previous studies have suggested that lower groundwater levels lead to higher subsidence rates (Kværner & Snilsberg 2008; Wösten et al. 1997). This shows that the combined rate of environmental change (groundwater level and subsidence rate) associated with the conversion of peatland forest to plantations, with the concept of drainage, is the contributor to land subsidence.

Most of the main crops will not thrive in waterlogged natural peat swamp conditions (Andriesse 1988). The two most common commercial uses of peatlands are for oil palm cultivation and Acacia species (especially A. mangium or A. crassicarpa), both of which do not have good yields in waterlogged conditions. Furthermore, the shallow water level hinders fertilizer application, and interferes with access to the planting area by workers and machines. Hence, from the outset, the strategy for plantation agriculture on peatlands in the tropics was to adjust the water table to improve crop conditions. For example, Best Management Practices for Cultivating Oil Palm from the 2012 Roundtable for Sustainable Oil Palm recommends that the water table be maintained at a depth of 40–60 cm below the peat surface (Parish et al. 2012). Water table arrangement is usually achieved by a hierarchical network of channels with a tree topology (Andriesse 1988). Water regulation in managed peatlands is essentially passive, with a drainage network that provides an easy passage for water plus rainfall to leave the peatland.

Water and drainage management and site preparation for plantations change the hydraulic properties of peat. This results in shrinkage and compaction of the peat surface and a decrease in the mean pore size in the peat matrix, leading to an increase in peat bulk density in the first 1-5 years after drainage (Hooijer et al. 2012). Furthermore, lower levels of groundwater in peatlands prepared for plantation agriculture can lead to changes in the peat surface temperature regime, and the decomposition of organic matter, like most metabolic processes, is strongly influenced by temperature (Lloyd & Taylor 1994). Specifically, deep groundwater levels are associated with greater fluctuations in peat surface temperature and greater daily fluctuations in CO_2 release from the peat surface (Jauhiainen et al. 2012, 2014; Hirano et al. 2014).

In tropical peatland management, “wetting” involves measures to reverse the hydrological effects of drainage for agriculture by closing ditches and canals to maintain higher water levels (Jaenicke et al. 2010). The effectiveness of wetting in reducing tropical peat decomposition has been evaluated by experiments involving controlled mesocosms or direct hydrological interventions in the field (Jauhiainen et al. 2012), and by modeling approaches (Jaenicke et al. 2010). The results of this study, however, are inconclusive. Thus, although wetting has the potential to reduce the rate of peat decomposition due to water saturation and anaerobic conditions, this may be offset by fermentation or anaerobic respiration. Although not well studied in peatlands, the drying-wetting cycle is also likely to stimulate microbial activity and therefore organic C decomposition (Kuzyakov et al. 2000), partly through a stimulating 'priming' process involving unstable compounds. used by microbes to further break down stubborn materials (Fontaine et al. 2004). In short, due to the effects of continuous drainage on their structure and chemistry, wetted peatlands cannot be expected to behave like natural peatlands in their hydrology, soil ecology, or gas exchange.

5. CONCLUSION

The following list summarizes key points that are resulted from this research:

- The subsidence over the period 2004 to 2020 was confirmed to be sensitive to different drainage scenarios. The subsidence averages were 55 cm (deep drainage), 49 cm (moderate drainage), and 34.7 cm (shallow drainage).
- More than 28 years of peatlands, the peat subsidence were caused by drainage practices (canal), so that the peat oxidation was out of control.
- The relationship with the depth of the water level shows that land subsidence is still quite large. The groundwater level is very deep exceeding the allowed maximum depth of 40 cm (PP.71 2014 and PP.57 2016). Nevertheless, the regulation on groundwater level threshold should be evaluated to effectively mitigate the impact of drainage.
- The results implies that a better water management in a new site is required to reduce the impact of peatlands degradation and high rates of land subsidence should be accepted as an inevitable change from conversion of tropical peatlands to oil palm plantations regardless the groundwater depth.

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