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## Long term dynamics of surface fluctuation in a peat swamp forest in Sarawak, Malaysia

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## LETTER

## Long term dynamics of surface fluctuation in a peat swamp forest in Sarawak, Malaysia

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E-mail: [yimf93@gmail.com](mailto:yimf93@gmail.com)**Keywords:** peat surface fluctuation, surface fluctuation dynamics, tropical peatlands, water tableSupplementary material for this article is available [online](#)

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**Abstract**

Tropical peatland is a complex and globally important wetland ecosystem, storing an enormous amount of the Earth's terrestrial carbon from centuries of organic material accumulation. In this ecosystem, peat swamp forests developed over an ombrogenous peat where hydrology influences its physico-chemical properties, one of which is fluctuation of the peat surface. While several studies of tropical peatland surface fluctuation have been reported, most are based on relatively short measurement periods or focused on drained areas. Hence, the objective of this study is to determine the long-term dynamics of peat surface fluctuation from an undrained peat swamp forest in relation to its water table depth. Peat surface level, water table, and rainfall were measured monthly at three experimental sites in a peat swamp forest in Sarawak, Malaysia over a period of about 10 years (2011–2020). The sites were different in soil structure and vegetation community; namely mixed peat swamp, Alan Batu, and Alan Bunga forests. Throughout the measurement period the peat surface in all sites exhibited consistent oscillating movement that generally follow the fluctuation of water table, with swelling and subsidence occurring after water table increase following high rainfall and receding water during dry spells respectively. Positive linear relationships were also found between peat surface level and water table ( $p < 0.05$ ). Both the surface level and water table at all sites fell to their lowest during an intense dry period in 2019. Surface fluctuation at the Alan Batu site was most affected by seasonal changes in water table, which may be due to presence of vacant zones in the peat profile.

**1. Introduction**

Peatlands have been estimated to cover more than 4.2 million km<sup>2</sup>, equating to around 2.8%, of the total global land area (Xu *et al* 2018). A significant portion of global peatlands are in the tropical areas, particularly in Southeast Asia, central Africa, and South America, although the estimation of its size varied widely, cited values in the literature ranged from 440,000 km<sup>2</sup> (10% of global peatland area) to 1.7 million km<sup>2</sup> (40%) (Page *et al* 2011, Gumbrecht *et al* 2017). Tropical peatlands are known to be a major store of soil carbon, with recent research estimating the carbon stock of global tropical peatland to be 104.7 Gt C (Dargie *et al* 2017), which would amount to around 17%–21% of the carbon pool of peatlands globally (Page *et al* 2011).

A common phenomenon that is regularly observed in peatlands is the vertical fluctuation of the peat surface which is typically influenced by changes in water table (Strack *et al* 2006, Päivänen & Hånell 2012, Evans *et al* 2021). More attention in research is usually given to subsidence, the downward movement of the peat surface, due to its potentially damaging consequences. In tropical peatlands, especially those in Southeast Asia, peat surface subsidence has been cited as a consequence of drainage during conversion of natural peat forest into

plantations, either for agricultural or industrial use. Draining of forests lowers the groundwater level under the peatland and coupled with the low bulk density and high porosity characteristics of peat typically result in dewatering which then lead to consolidation that will bring about peat subsidence.

The study of subsidence in tropical peatlands is considered important as it had been identified as a possible key indicator of the emission of carbon stored in peatlands into the environment through oxidative peat decomposition. Previous studies have reported varying values of contribution towards subsidence by peat oxidation, from as low as 25% (Wakhid *et al* 2017) to as high as 92% (Hooijer *et al* 2012). Some studies from temperate or boreal peatlands suggests that physical changes such as compaction and shrinkage contribute more towards subsidence than oxidation in temperate conditions (Glenn *et al* 1993, Minkkinen & Laine 1998). Therefore, most studies that focus on peat surface fluctuation in tropical peatlands have been focused on subsidence in agricultural lands or those associated with land use change such as oil palm and *Acacia* plantations (Hooijer *et al* 2012, Couwenberg & Hooijer 2013), or areas abandoned following forest clearing (Nagano *et al* 2013). In drained peatlands, the dynamics of surface fluctuation are generally controlled by water table depth, time since drainage, land use, and climatic conditions (Hooijer *et al* 2012, Pronger *et al* 2014, Evans *et al* 2019).

A few studies have conducted measurements of subsidence in tropical peat forests, but results have varied due to different conditions in the study areas. Average values of subsidence rate have ranged from 2.4–3.4 cm yr<sup>-1</sup> in forest-plantation boundary areas (Hooijer *et al* 2012, Evans *et al* 2019), 0.5–2.2 cm yr<sup>-1</sup> in a logged-over forest with natural drainage (Khasanah & van Noordwijk 2019), and 0.0–1.0 cm yr<sup>-1</sup> in conservation areas at least 2 kilometres away from plantations (Hooijer *et al* 2012, Nagano *et al* 2013). However, these values are generally lower than those that have been reported in plantations which ranged from 3.7–5.96 cm yr<sup>-1</sup> (Couwenberg & Hooijer 2013, Wakhid *et al* 2017), although lower values of 1.23–2.02 cm yr<sup>-1</sup> have also been reported in an oil palm plantation (Ishikura *et al* 2018).

There have been several studies conducted in temperate and boreal peatlands which observed seasonal (reversible) swelling and shrinking of the peat surface level, usually in response to fluctuation of the water table (Roulet 1991, Fritz *et al* 2008, Nijp *et al* 2019). This phenomenon has been referred to in some publications as ‘mire-breathing’ or ‘bog-breathing’, translated from the German term *mooratmung* (Ingram 1983, Dise 2009, Howie & Hebda 2018). The effect of water table depth is also determined by Zanello *et al* (2011) to be the main control of long-term surface fluctuation in a drained Venetian peatland. In tropical peatlands, Evans *et al* (2019) reported water table depth as the best indicator of surface fluctuation rate based on analysis of measurements from more than 300 sites with various land uses in Indonesia. However, to the authors’ knowledge, no published study has continuously monitored the long-term variation of peat surface fluctuation and its response to changes in water table depth in a remote, undrained tropical peat swamp forest over a period of at least 10 years.

To better understand the dynamics of peat surface fluctuation in a tropical peatland forest over a relatively long period, measurements of peat surface level and other variables such as water table and rainfall were made over almost ten years in a protected tropical peat swamp forest area within a national park in Sarawak, Malaysia. The objective of this study is to investigate the long-term variation of peat surface level fluctuation of a peat swamp forest and determine the influence of water table on surface fluctuation dynamics.

## 2. Methods

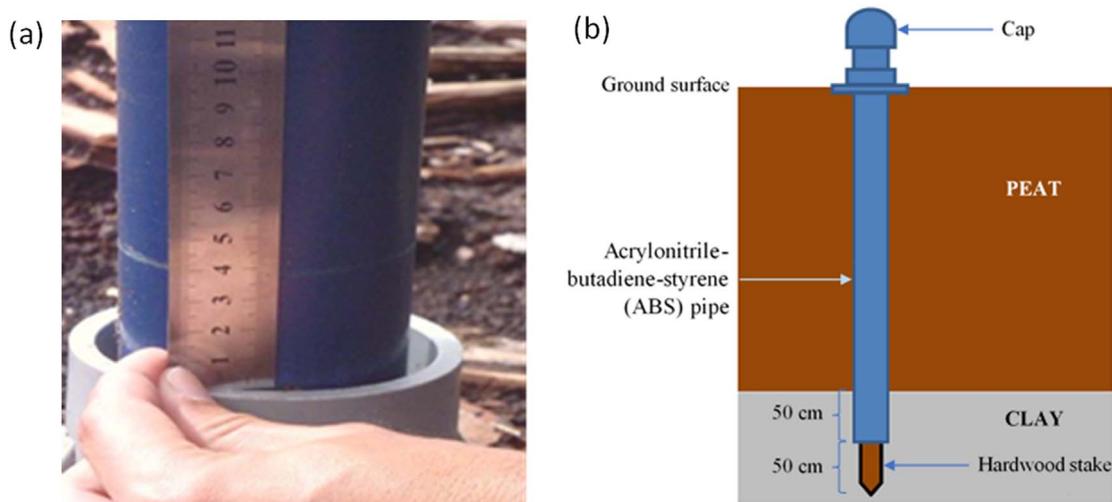
### 2.1. Site description

The study was conducted in a tropical peat swamp forest located within the Maludam National Park, in Betong Division of Sarawak, Malaysia. Covering most of the Maludam Peninsula that is bordered by the Saribas River in the north and the Lupar River in the south, the Park was officially gazetted in May 2000, originally comprising an area of 43,147 ha, before it was further extended by 10,421 ha in 2015. The forests within the Park area were subjected to selective logging without canals before it was gazetted as a Totally Protected Area. The Park largely consists of low-lying, flat peat swamp with uneven microrelief and hummocky surface (Melling & Hatano 2004). The peat displays a prominent dome shape characteristic of peat swamps in the region (Kselik & Tie 2004), with greater peat thickness going inland from the shore, rising to more than 10 m (Melling & Hatano 2004).

The study area generally follows a typical equatorial climate, characterized by uniform temperatures, high rainfall, and high humidity. The climate is influenced by two distinct monsoon seasons, the wet Northeast Monsoon and the dry Southwest Monsoon (Kselik & Tie 2004). Mean annual precipitation for 21 years (1998–2019) measured at the Lingga meteorological station about 12 km distance from the study sites was 3141 mm (Department of Irrigation and Drainage, Malaysia). The annual mean surrounding temperature at the study area in 2011–2014 was previously reported to be 26.9 °C ± 0.2 °C (Tang *et al* 2020).



**Figure 1.** Example of peat surface level measurement pole installed at the measurement sites.



**Figure 2.** (a) Demonstration of measurement of peat surface level; (b) Schematic of peat surface level measurement pole.

## 2.2. Measurements

Peat surface level was measured using a 7.5 cm diameter hollow acrylonitrile-butadiene-styrene (ABS) pipe inserted into the peat until it reaches the mineral substratum. A freely moving ABS flange ring was inserted at the bottom of the anchored pipe above the peat surface, and an ABS cap marked at the four cardinal directions (north, south, west, east) was placed on top of the pipe (figure 1). A graduated line on the pipe marked the initial surface level at the start of the measurement period. During each measurement, the length between the initial line and the top of the flange ring was recorded at all four directions (figure 2(a)). The value was recorded as negative if the peat surface subsides (downward movement), and vice versa. The surface level value was calculated as the mean of the four measured lengths. In total, three surface level measurement pipes were installed between September 2009 and April 2010 at sites with different forest types, vegetation community and soil properties with varying distance from the shore (table 1 and figure 3). The sites are named based on the forest type, i.e., mixed peat swamp (MPS), Alan Batu (ABt) and Alan Bunga (ABg), each with their own unique peat profiles (figure 4).

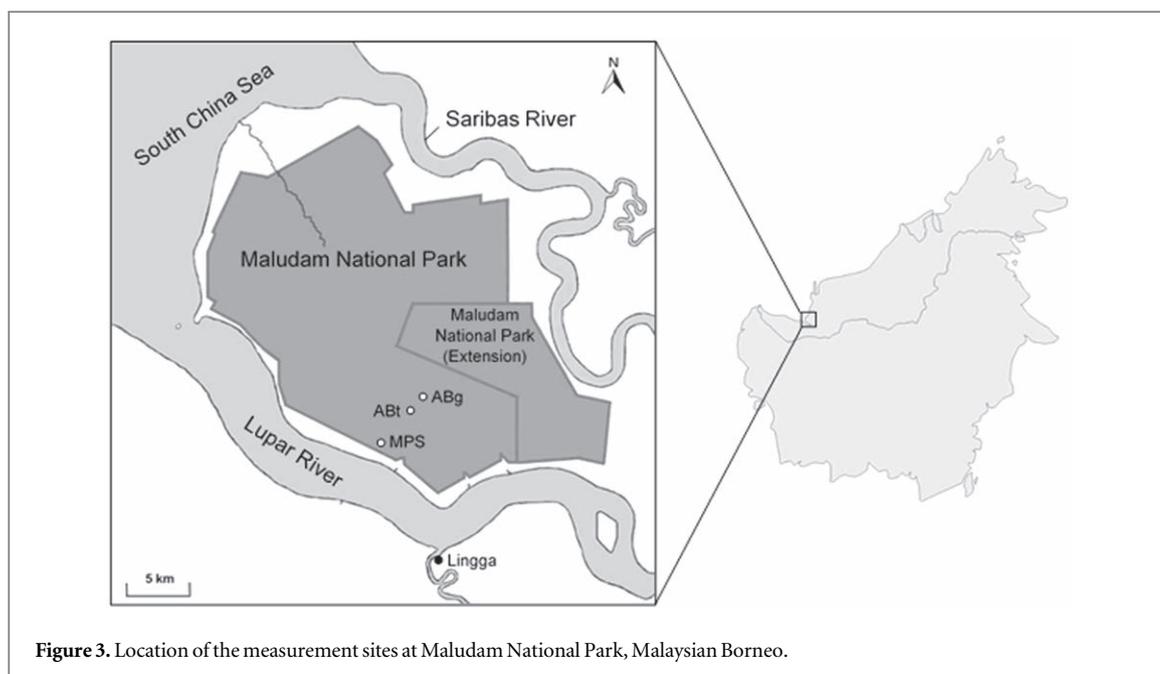


Figure 3. Location of the measurement sites at Maludam National Park, Malaysian Borneo.

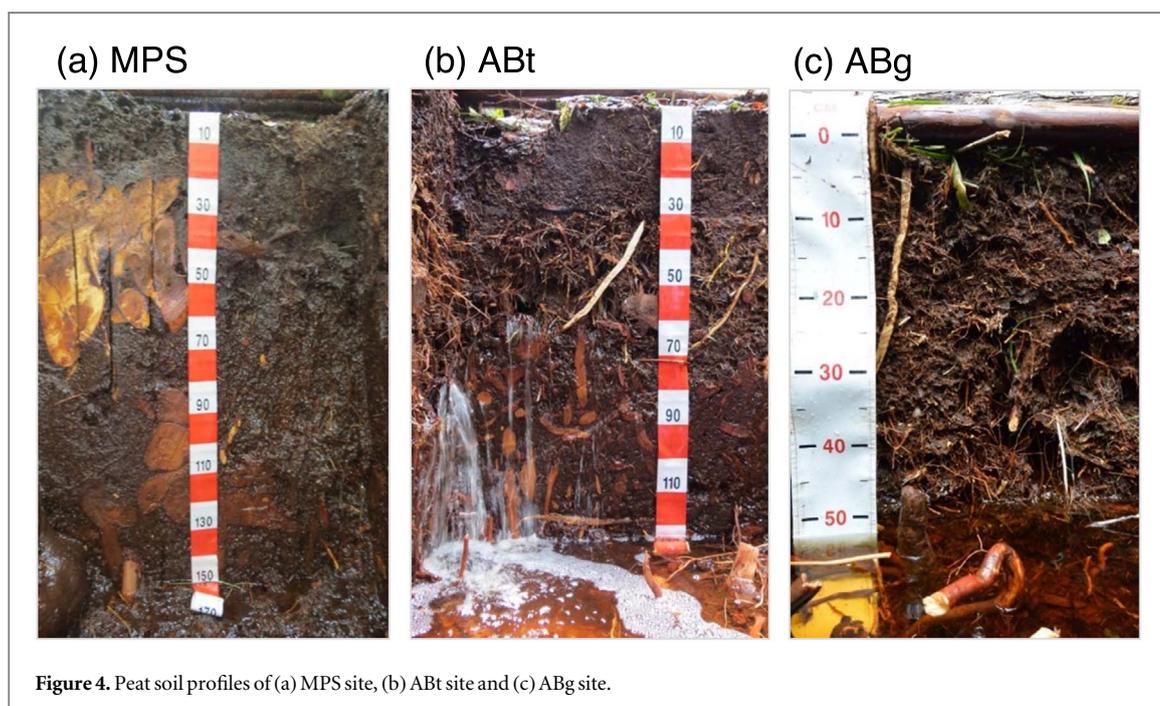


Figure 4. Peat soil profiles of (a) MPS site, (b) ABt site and (c) ABg site.

Water table depth was measured using water level loggers (HOBO U20, Onset Computer Corporation, Bourne, MA, USA) installed within two piezometers located at each site. The loggers continuously recorded data for every 30 min which was then processed using HOBOWare Pro version 3.7.10, before monthly averages were taken. The value was measured relative to the peat surface and recorded as positive if the water was above the surface, or negative if below. Rainfall was collected and measured using a rain gauge. Air temperature was measured using a digital thermometer (TESTO 625, Testo SE & Co. KGaA, Lenzkirch, Germany). Soil moisture content was determined to be the gravimetric water content in soil samples collected from the topsoil (0–25 cm) using a core ring (5 cm diameter, 5.1 cm height). Eight soil samples were collected monthly at each site.

### 2.3. Data processing and analysis

In this study, data collected between February 2011 and December 2020 were used. The data were processed and analyzed using the R software (R Core Team 2021). Seasonal mean values were calculated with the assumption that the typical dry season in the study site is from May to August, while the wet season is from October to

**Table 1.** Summary of measurement site details.

Site	MPS	ABt	ABg
Coordinates	N: 001° 25' 51.2' E: 111° 07' 52.0'	N: 001° 27' 12.7' E: 111° 08' 57.4'	N: 001° 27' 47.9' E: 111° 09' 29.0'
Date of pole installation	17 September 2009	18 September 2009	23 April 2010
Distance from riverbank (km)	1.2	4.3	5.7
Peat depth (cm)	454	835	860
Bulk density (g cm <sup>-3</sup> )	0.14	0.11	0.10
Forest type	Mixed Peat Swamp	Alan Batu	Alan Bunga

**Table 2.** Seasonal and overall mean values of environmental variables at the measurement sites (mean  $\pm$  1 standard deviation (SD)). For the overall mean, different letter superscripts denote significant differences between sites (Tukey's HSD).

Site	Seasonal period	Air temperature (°C)	Soil moisture content (%)
MPS	Dry	28.18 $\pm$ 1.22	521.73 $\pm$ 123.39
	Wet	27.50 $\pm$ 1.05	528.30 $\pm$ 78.98
	Overall mean	27.95 $\pm$ 1.16 <sup>a</sup>	530.12 $\pm$ 95.20 <sup>a</sup>
Abt	Dry	27.76 $\pm$ 1.36	626.85 $\pm$ 87.21
	Wet	27.58 $\pm$ 1.19	643.60 $\pm$ 94.27
	Overall mean	27.74 $\pm$ 1.23 <sup>a</sup>	643.99 $\pm$ 93.72 <sup>b</sup>
Abg	Dry	31.30 $\pm$ 2.13	686.48 $\pm$ 116.21
	Wet	30.05 $\pm$ 1.90	703.96 $\pm$ 118.43
	Overall mean	30.78 $\pm$ 1.96 <sup>b</sup>	706.17 $\pm$ 119.32 <sup>c</sup>

February (Ishikura *et al* 2019). Outliers in the environmental data were detected using Tukey's boxplot method (Tukey 1977), and subsequently removed from the data analysis. Two-sample *t*-test was conducted to compare the seasonal mean of air temperature and soil moisture content. The non-parametric Mann-Kendall test was conducted to investigate potential trends in the peat surface level and water table depth across all measurement sites, using R's *trend* package (v1.1.4; Pohlert 2020). All statistical tests of significance were conducted based on a 5% significance level ( $p = 0.05$ ).

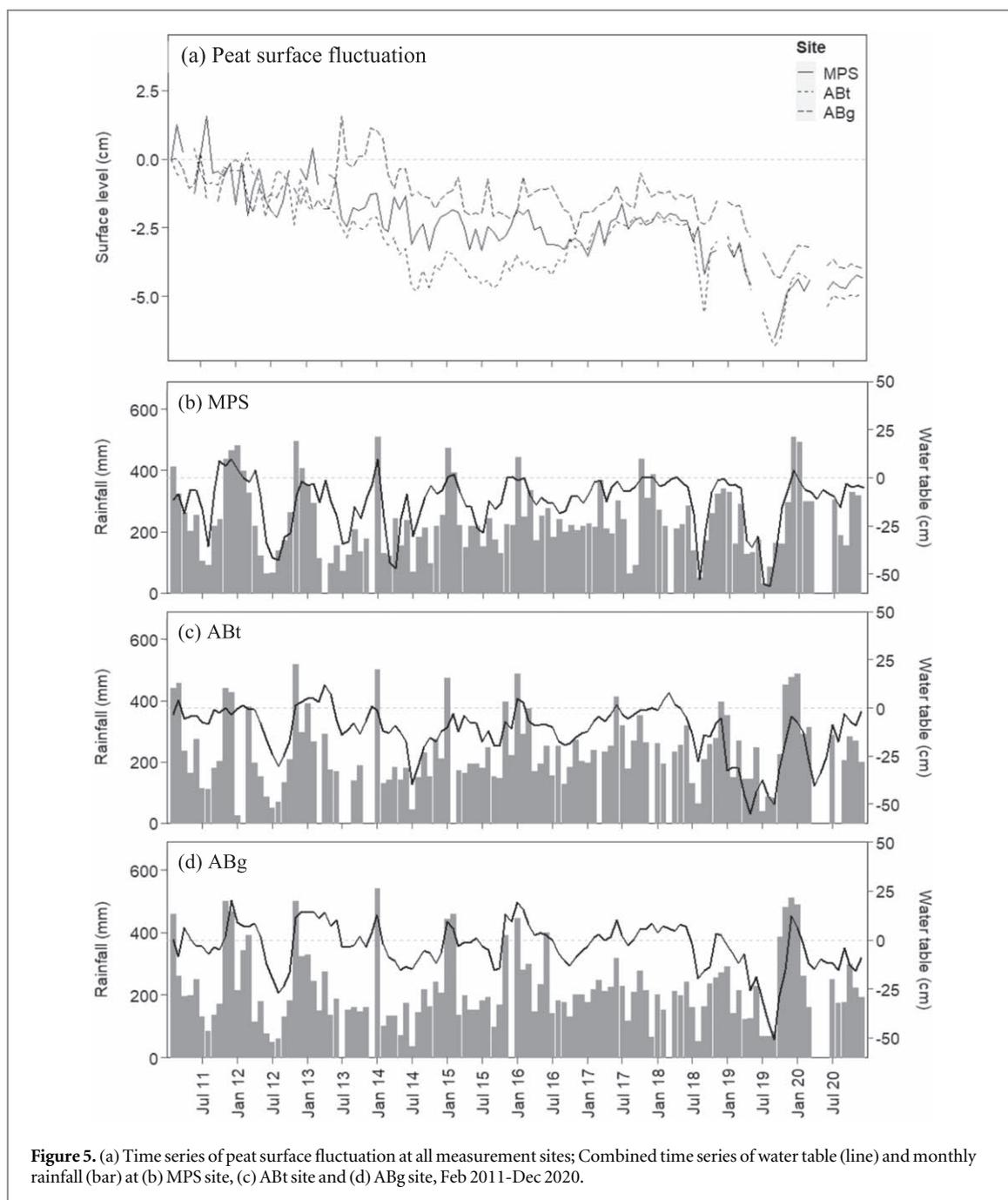
### 3. Results

#### 3.1. Environmental variables

The seasonal and overall mean values of environmental variables measured throughout the study period is shown in table 2. The overall mean air temperature measured at the sites ranged between 27.7 °C–30.8 °C, which are higher than the average value of 26.9 °C for the area cited from Tang *et al* (2020). Using Tukey's Honest Significant Difference (HSD) test, the air temperature was found to be significantly higher at the ABg site, while the soil moisture content was found to have significant differences across all sites. The highest soil moisture content was at the Abg site (706.17%) whereas the lowest was at the MPS site (530.12%). Meanwhile, seasonal mean values showed that the air temperature at the sites were lower during the wet season at all measurement sites, while the soil moisture content were higher during the wet season compared to the dry season. However, only the seasonal difference in air temperature at MPS and Abg sites were found to be significant using the two-sample *t*-test.

#### 3.2. Peat surface fluctuation and hydrological variables

Within almost 10 years of measurement, the peat surface in all three sites had seen downward movement from the initial surface level at the start of the measurement period (figure 5(a)). The peat surface level at the ABt site has subsided the most (4.88 cm) below the level in February 2011 (considered to be at 0 cm in all sites), while the ABg site has subsided the least (3.98 cm). At the same time, occurrence of peat surface swelling was also observed at various points during the measurement period, with evidence of the peat surface rebounding even after phases of relatively continuous subsidence. For example, in 2015 the peat surface in the ABt site subsided by 1.35 cm between January and September, before rebounding by almost 1 cm in November.



Throughout the measurement period, periods of subsidence were observed generally during and immediately after dry seasons, particularly between May to October. The subsidence in these periods were observed across all sites, however it was more apparent in the MPS and ABt sites. This downward movement of the peat surface then almost always transitioned to swelling as the climate moves toward the wet season, this swelling commonly peaked in January before plateauing as the next dry season approached. An exception to this pattern was seen in 2017 where no period of gradual subsidence occurred, instead the peat surface steadily swelled until around the second half of that year.

The water table in our sites was shown to largely respond positively to changes in rainfall, with water table drawdown occurring after a period of low rainfall, followed by upward movement in response to high precipitation (figures 5(b)–(d)). In the MPS and ABt sites, the water table usually lied below the peat surface (dashed grey line in figures 5(b)–(d)), sometimes moving above the surface following high rainfall, while in the ABg site the water table usually goes above the peat surface through the wet season, moving down during dry periods with low rainfall.

The mean values of parameters that were measured in this study is shown in table 3. The ABt site recorded the most rapid annual peat surface fluctuation rate ( $-0.49 \text{ cm yr}^{-1}$ ), although the variability of the rates across the three sites is small. The ABg site had the highest water table ( $-3.29 \text{ cm}$ ) but recorded the lowest mean annual

**Table 3.** Mean values of surface fluctuation and hydrological variables at the measurement sites. For water table and rainfall, mean  $\pm$  1 SD is shown. For rainfall, mean annual total is shown.

Site	Annual surface fluctuation rate (cm yr <sup>-1</sup> )	Water table (cm)	Annual rainfall (mm)
MPS	-0.44	-12.25 $\pm$ 13.92	2890 $\pm$ 349
ABt	-0.49	-11.60 $\pm$ 13.14	2886 $\pm$ 372
ABg	-0.40	-3.29 $\pm$ 12.00	2731 $\pm$ 347

**Table 4.** Seasonal mean values of surface fluctuation and hydrological variables at the measurement sites (mean  $\pm$  1 SD). Mean monthly rainfall is shown.

Site	Surface level (cm)		Water table (cm)		Monthly rainfall (mm)	
	Dry	Wet	Dry	Wet	Dry	Wet
MPS	-2.54 $\pm$ 1.64	-2.42 $\pm$ 1.46	-20.70 $\pm$ 15.16	-4.36 $\pm$ 7.54	166.18 $\pm$ 77.79	306.91 $\pm$ 116.02
ABt	-3.18 $\pm$ 1.62	-2.91 $\pm$ 1.47	-16.08 $\pm$ 14.26	-7.81 $\pm$ 9.32	178.94 $\pm$ 87.55	294.40 $\pm$ 120.17
ABg	-1.51 $\pm$ 1.15	-1.55 $\pm$ 1.31	-7.12 $\pm$ 11.64	0.68 $\pm$ 10.90	162.81 $\pm$ 78.62	284.14 $\pm$ 129.18

rainfall (2731 mm). On the other hand, the MPS site recorded the lowest mean water table (-12.25 cm) but the highest mean annual rainfall (2890 mm).

The seasonal mean values of the surface fluctuation and hydrological variables are shown in table 4. All sites consistently exhibited higher surface level, water table and monthly rainfall during the wet season compared to the dry season, the only exception being the peat surface level at ABg which is very slightly higher in the dry season. This seasonal variation becomes more apparent when the variables were ensemble averaged by month (figure 6).

### 3.3. Exploratory data analysis

A clear trend can be seen when the peat surface level was plotted against water table at every site (figures 7(a)–(c)). Lower water table generally corresponded to lower peat surface level and vice versa, as evidenced by the significant linear positive correlation seen in all three sites. The steeper gradient of the best fit line for the ABt site suggested that the rate of lowering of peat surface level was faster in that site for the same lowering of water table, compared to the other two sites. By observing the coefficient of determination ( $R^2$ ), the relationships were relatively weak for all sites ( $R^2 < 0.30$ ), with the ABt site seeing the strongest correlation ( $R^2 = 0.27$ ) and MPS site the weakest ( $R^2 = 0.05$ ). In addition, when all sites were combined in a single plot, a similar trend between peat surface level and water table was also observed ( $R^2 = 0.19$ ) (figure 7(d)).

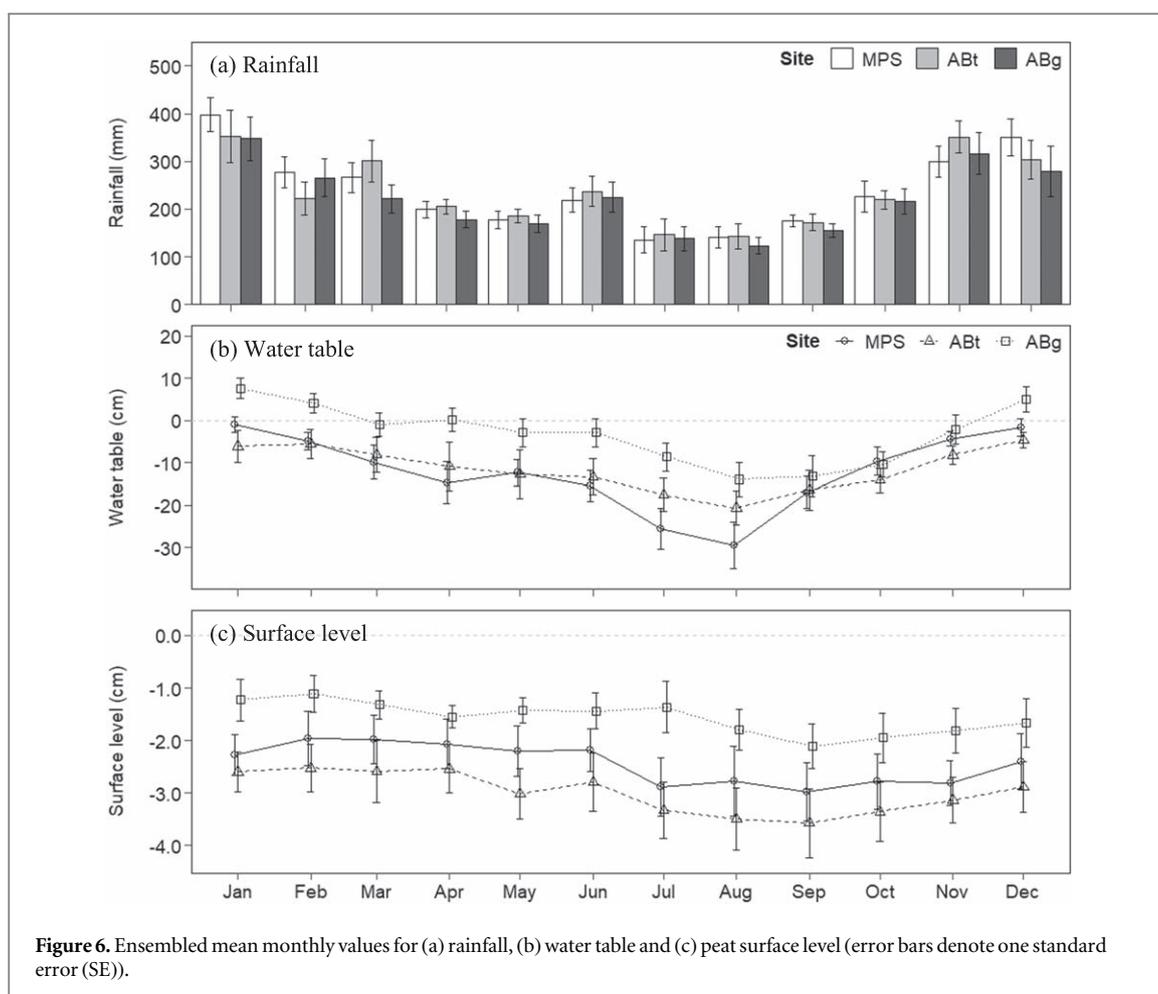
Based on results of the Mann-Kendall test conducted on the monthly surface level measurements, all three sites have undergone a significant downward trend in their peat surface level since the beginning of the measurement, as evidenced by their negative  $\tau$  values. (supplementary table 1 (available online at [stacks.iop.org/ERC/4/041001/mmedia](https://stacks.iop.org/ERC/4/041001/mmedia))). The same test conducted on monthly water table data showed that both the ABt and ABg site exhibited significant downward trend while the MPS site showed an upward trend, however it was not significant (Supplementary table 2).

## 4. Discussion

### 4.1. Peat surface fluctuation trend and effect of water table

The peat surface in this study showed evidence of a subsiding trend, with a similar decreasing trend in the water table in two of the three measurement sites. There is evidence that water table is one of the main controls of peat surface fluctuation in our study sites, based on the correlation plots between surface level and water table (figure 7). The ABt site has subsided the most throughout the measurement period, as well as being the site with the strongest downward trend in water table based on the Mann-Kendall test. However, the annual downward movement rate of the peat surface in all sites were relatively small, less than 0.5 cm yr<sup>-1</sup>, which corresponds to previously recorded values of 0.0–1.0 cm yr<sup>-1</sup> in conservation areas located far from plantations (Hooijer *et al* 2012, Nagano *et al* 2013).

Several studies in tropical peat swamp forests have also recorded peat subsidence occurring in undisturbed and undrained conditions, sometimes even in areas that are flooded most of the time. Evans *et al* (2019) measured peat subsidence occurring in forest sites located 2.5 km from adjacent plantations but suggested that



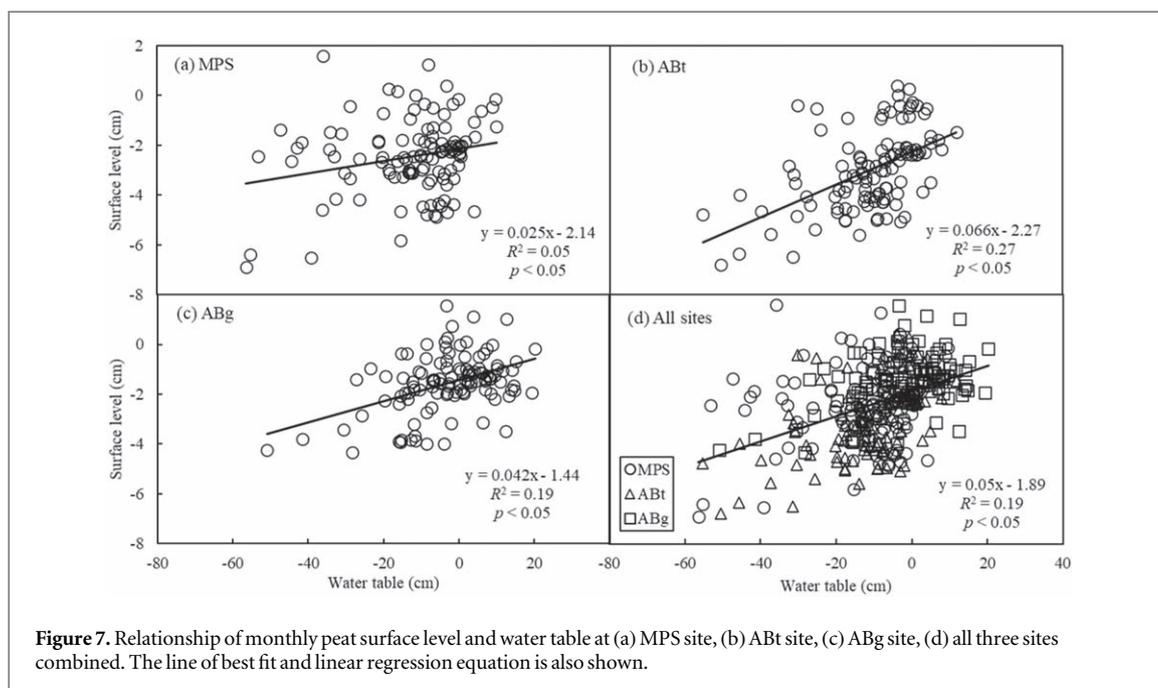
**Figure 6.** Ensembled mean monthly values for (a) rainfall, (b) water table and (c) peat surface level (error bars denote one standard error (SE)).

the clear effects of drainage from nearby agricultural plantations extend to only within 300 m into native forests. Previously, Cobb *et al* (2017) suggested that entire peat domes may be affected by subsidence through drainage, based on modelling of data from a pristine Bruneian peatland. The measurement sites in the current study are located much further from any plantation boundaries (the closest estimated distance is around 10.7 km), however there remains a possibility that drainage in these plantations could have contributed towards downward movement of the peat surface in our sites.

The graphs of relationship between peat surface level and water table shown in figure 7 assumed a linear relationship between the two variables. Linear relationships between peat surface level and water table have been proposed by several studies on both tropical (Hooijer *et al* 2012, Evans *et al* 2019) and temperate/boreal peatlands (Price & Schlotzhauer 1999, Howie & Hebda 2018). On the other hand, other studies suggested a more complex, non-linear relationship between peat surface level and water table (Stephens *et al* 1984, Wösten *et al* 1997, Fritz *et al* 2008), the former two studies cited suggesting inclusion of the soil temperature variable in a model to predict subsidence from water table depth. Based on figure 7, a linear relationship seems to be a reasonable approximation of the connection between peat surface level and water table fluctuation at least for the ABt and ABg sites.

#### 4.2. Comparison among the sites

After 10 years of nearly continuous measurements, it was observed that the ABt site showed the lowest mean surface level ( $-3.00$  cm) and most rapid surface fluctuation rate ( $-0.49$  cm yr<sup>-1</sup>), it is consistently followed in both measures by the MPS and ABg sites (table 4). The surface fluctuation trend shown in figure 5(a) also indicated that the ABt site is the one most affected by subsidence events, this was more evident during the dry periods of 2014, 2015 and 2018. The Alan Batu forest of the ABt site is known to be characterised by prevalence of vacant zones of around 20–30 cm in diameter within the top 100 cm of the peat profile under the root mats, on the other hand these vacant zones are generally less common in mixed peat swamp forests such as those found in the MPS site (Yonebayashi *et al* 1995, Melling 2016) (figure 4). Drawdown of water table could induce consolidation of the upper peat layers due to loss of water in the vacant zones, which may explain the more rapid subsidence seen in ABt during dry periods compared to the MPS site.



Contrastingly, the surface level at the ABg site appeared to stay above the other two sites as the measurement progressed, although much of this could be explained by a sudden swelling of the peat surface that occurred at the site in July 2013. If this phase is disregarded from the data analysis by taking the swelling peaks seen in all sites in June 2014 as the starting point instead, the peat surface at the ABg site had in fact subsided the most in the period that followed (3.63 cm) compared to the MPS and ABt sites (3.00 cm and 1.63 cm respectively). This may indicate that most of the downward peat surface movement that was recorded at ABg happened more recently, while those at ABt mostly took place earlier in the study period. Decreasing water table in these two sites could have affected the ABt site more in the first few years as the peat consolidates into vacant zones, while this process was not as evident in ABg. As this process continues, the lower bulk density in ABg ( $0.103 \text{ g cm}^{-3}$ , compared to  $0.111 \text{ g cm}^{-3}$  in ABt) may increasingly become a factor in maintaining consolidation at the site while the subsidence trend in ABt slows down following the initial rapid consolidation period.

#### 4.3. Effect of climatic conditions

In 2015, a strong El Niño-Southern Oscillation (ENSO) event was known to have affected Southeast Asia (Tacconi 2016, Lee *et al* 2017, Wakhid *et al* 2017). Droughts caused by the event were among the possible explanations to the previously mentioned subsidence observed in remote forest locations by Evans *et al* (2019). Yet, this study showed that the event did not significantly affect the fluctuation of the peat surface level in all three sites, possibly explained by the fact that the sites still received around the average rainfall expected during the periods. On the other hand, intense dry period did occur around July-August 2019 which had a substantial effect on the peat surface level in our sites, with all sites seeing record low peat surface levels between August and October that year (figure 5(a)). This period also saw record low water tables in all measurement sites.

Lowering of water table and higher surrounding temperature that were observed during dry periods in this study may have exposed the upper layers of peat to oxidation due to decreasing moisture content, which could lead to acceleration in decomposition and peat loss thus leading to irreversible subsidence. Towards the end of 2020, the peat surface level did not seem to have recovered to the level it attained before the start of the 2019 dry period even after periods of high rainfall immediately following it, a possible sign of such subsidence taking place. However, there is evidence of recovery occurring in the ABt site, where the peat surface showed near continuous subsidence between January-July 2014 but would later swell and eventually recovered to the level it reached before that period, almost three years later in mid-2017. Further measurements would be needed to determine if the surface level in all sites will return to their pre-2019 level in the next few years, though this also depends on any extensive dry periods that may develop in the future.

The influence of global warming conditions on water table may also impact the dynamics of peat surface fluctuation. Swindles *et al* (2019) investigated the impact of human-induced changes and warming climate on drying of peatlands across Europe based on a meta-analysis of testate amoeba-based reconstructions of historical peatland water table, which found that 60% of peatland sites analysed have moved to drier conditions over the past 200 years. At present such studies are scarce for tropical peatland areas, and the measurement period of

10 years in the current study is probably too short to properly capture the effect of climate warming on surface fluctuation dynamics. Plotting the annual mean value of water table at the sites revealed that the water table at the ABt and ABg sites have visibly receded over the measurement period, however they were mostly affected by the 2019 dry spell and no significant trend in the annual mean values was detected by the Mann-Kendall test (supplementary figure 1).

#### 4.4. Limitations and uncertainties

In this study, measurements were taken monthly instead of hourly/daily, which may not have captured the actual effect that water table movement had on the peat surface fluctuation. Several studies in temperate peatlands found evidence of a delay in peat surface subsidence as water level receded after precipitation events, with the peat surface continuing its upward movement for a short period even as the water table moves downwards (Fritz *et al* 2008, Howie & Hebda 2018). Assuming this hysteresis is also observed in tropical peatlands, monthly measurements in this study may only captured the condition of surface level and water table on the exact time that they are measured, which limited the ability of this study to fully capture the true relationship that may exist between the two variables as for example, the peat surface may still be in the swelling phase even when the water table is receding. On the other hand, using higher-frequency (hourly) measurements, Evans *et al* (2021) found little to no evidence of hysteresis occurring in water table and peat surface level fluctuations at tropical peatland sites with various land-uses.

This study also recorded apparent subsidence occurring in undrained forest sites, but the rate is small and comparable to previous measurements done in similar sites. Most factors that may account for this observation have been discussed in this article, though there are other possible causes that could be considered including disturbance during field measurements and historical logging using canals (Evans *et al* 2019), however it should be noted that no evidence of artificial canals was discovered at the current study sites. These factors emphasises the need for a more robust monitoring system for peat surface fluctuation in tropical peatlands which will enable the establishment of baseline values for tropical peatland areas and ensure a more accurate interpretation of results involving peat surface fluctuation in this important yet fragile ecosystem.

## 5. Conclusions

This study has shown the trend of peat surface fluctuation in an undrained and protected tropical peat swamp forest over a long-term period across several sites with differing forest type. It revealed that fluctuation of the peat surface is greatly influenced by its underlying water table, with subsidence occurring after water table drawdown following dry periods and swelling after the water table increases that ensued after high rainfall. The trend of fluctuation also differed slightly across the measurement sites, which may be explained by variations of structure in the peat profile. It was also discovered that the peat surface at the sites have moved downward throughout the 10-year period of measurements, even with no artificial drainage happening around the area. The cause of this observation is likely to be a gradual decrease in water table, although potential effects of the surrounding environment or disturbances during measurements may also play a factor.

While the monthly measurements used in this study have captured the trend of peat surface fluctuation and its relationship with water table reasonably well, interpretation of the results are limited by possible effect of hysteresis between peat surface and water table fluctuation or other events which may affect the peat surface level at the sites that were missed in-between the monthly measurements. However, the methods used in this study that relied on manual measurements at hard-to-access sites have rendered higher-frequency (hourly/daily) measurements, which could catch these data artifacts in real time, impractical. New on-the-ground data collection methods, such as the camera-based system proposed by Evans *et al* (2021), could improve the interpretation of results of similar studies in the future and may give new insight into the dynamics of peat surface fluctuation at undrained tropical peatland sites through more frequent measurements and ability to monitor more sites in remote areas. Continuous and frequent monitoring of undrained or protected sites is important to determine the benchmark values that can be referenced by other studies of peat surface fluctuation in tropical peatlands, especially those in drained areas.

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## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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