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Predicting soil moisture and soil temperature in a tropical peatland using water table depth, surface temperature and rainfall

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ABSTRACT
Degradation of tropical peatland largely depends on water table depth and other soil physical properties like soil moisture and soil temperature. Empirical studies indicate positive relationships between water table depth, soil moisture and soil temperature. This paper aims to further investigate the relationship between soil moisture and soil temperature variability in time as a function of soil depth and their relationship with water table depth. Linear models for prediction of soil moisture and soil temperature at 70 cm using surface soil moisture and soil temperature measurements, rainfall and surface temperature are examined. In all the four plots used in the study, seasonality of soil moisture and soil temperature was confirmed as they strongly correlate with rainfall. Both soil moisture and soil temperature at 5 cm, as a result of storm events, experienced more fluctuations compared to the values recorded at 70 cm. The linear models give better prediction capabilities as predicted and observed values give good fits and coefficients of determination, R^2, is mostly above 0.5 with agreements within 0.05 – 0.1.

Keywords: *Peatland degradation , Soil moisture, Soil temperature, Tropical peatland, Water table depth*.

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1 INTRODUCTION

Peatlands, according to Parish et al., (2008), have been known to be long-term carbon stores storing this natural resource for thousands of years. But keeping these ecosystems functioning as carbon stores is of high importance to global environmental sustenance and also depends on certain factors like water table depths, soil temperature and soil moisture (Carlson et al., 2015), among other factors. Peats have been formed as a result of microbial transformation of soil organic matters to mineral forms which, according to Suseela et al. (2012), Preston et al. (2011) and Hagedorn and Joos (2014) has been largely influenced by soil temperature and soil moisture. According to Lakshmi et al. (2003), for the proper understanding of land surface- atmosphere interactions, soil moisture and temperature estimation is of critical importance. They further stated that soil moisture plays major roles in water and energy cycle which serves as one of the crucial variables of peatland water balance. In water cycle, soil moisture helps in determining parts of precipitation partitioned into other water cycle parameters like runoff, surface storage and infiltration. The role of solar energy in peatland water balance cannot be underestimated. Lakshmi et al. (2003) further stated that fluxes of outgoing longwave, sensible, and peatland heat surface temperature is attributed to surface temperature. With the points raised above, soil moisture and soil temperature are known to be interrelated.

Peatlands are known to be waterlogged which makes them unsuitable for agricultural activities except the water table is lowered to enhance their use for agriculture and for the purpose of peat extraction (Maljanen et al., 2012; Querner et al., 2012). In order to achieve this, drainage systems are put in place which controls the water table depths (Macrae et al., 2013; Potvin et al., 2015) and peat compaction in order to aerate the crop root zone while increasing the peat soil bulk density (Melling et al., 2012). Excessive lowering of water table as a result of peatland drainage has been known to have its own negative influence not only on the peatlands management (Adesiji et al., 2015) but also on peatland soil moisture (Couwenberg 2009). Soil moisture has been identified as a control on peat carbon loss (Jauhiainen et al., 2008; Couwenberg 2009). This is because it mediates the volume of peat substrate exposed to oxygen, thereby influencing microbial activity and decomposition (Carlson et al., 2015; Husen et al., 2014).

Influence of water table depth in peatland biogeochemical roles has been studied. It has been established that drainage systems in the peatlands control its water table depths (Hefting et al., 2004; Katimon et al., 2013) and that with excessive lowering of water table, soil carbon, methane and other GHGs are lost further fuelling the environmental degradation (Strack et al., 2008; Bhullar et al., 2013; Reddy 2015). Also the excessive drying of peats as a result of low or change in water table depths by compression and oxidation results in irreversible drying of peats and its change in volume, otherwise known as subsidence (Whittington and Price 2006; Couwenberg and Hooijer, 2013). Salm et al., (2012) and Carlson et al., (2015) attributed the emission of carbon and methane from peatland surface to depth to groundwater table and soil temperature. It has also been established that lowering the water table depths changes peatlands from carbon sinks to carbon sources, by largely reversing the C flux into net CO_2 emissions, while CH_4 emissions decrease (Furukawa et al., 2005; Couwenberg 2011). Therefore, the variation in environmental conditions and soil properties like soil temperature and soil moisture that drive these emissions and changes in peatland water table depth become important factors. Therefore, the need to study these variations for proper understanding of peatland biogeochemical activities and groundwater table fluctuation is essential. Wen et al., (2006) reported the importance of temperature and soil moisture in determining emissions of CO_2 from ecosystems. The reports concluded that seasonal fluctuation of terrestrial ecosystem respiration is accounted for by variation in temperature and soil moisture. Bellisario et al., (1999) also attributed the variation in soil temperature and soil moisture to the peatland water table fluctuations which in turn determine the emissions of methane and other GHGs from the peat surface.

Thus, in this study, variability and relationships between water table depth and soil moisture and soil temperature at two different depths were considered to ascertain the dependence of one over the other. The daily rainfall measurement, water table depth, and soil temperature at two different depths of 5 cm and 70 cm were also used in predicting soil moisture and soil temperature at 70 cm. In achieving the aim of this study, therefore, the objectives will be:

(1) to examine the hypothesis that peatlands soil moisture and soil temperature are seasonal and are statistically significant irrespective of soil depth.

(2) to predict, using a model, the peatland soil moisture (at a specific depth) using soil temperature, water table depth and rainfall as independent variables or predictors;

2 MATERIALS AND METHODS

2.1 STUDY AREAS

The study area is located in Sepang, the state of Selangor, Malaysia at Kuala Langat South Forest Reserve area, between latitude 02° 43’N and longitude 101° 39’E bounded to the West by Straits of Malacca. The study area experience tropical climate and high humidity with an annual rainfall between 2500 – 3000 mm. The monthly air temperature ranges between 32 °C and 36 °C, with the highest value recorded in May each year. For the 2014 water year under study, the lowest rainfall recorded was in February as 7.0 mm and highest in April as 437 mm (Figure 1). The average annual rainfall for the study year, 2014 was 2348 mm from the Malaysian Department of Irrigation and Drainage (DID) gaging station 2918101 in the study area. The study ran from June, 2014 to December, 2014, with both months inclusive. During this study period, the highest rainfall depth observed was in October as 338.5 mm as shown in Figure 1. Properties of peat soil available in the study area as shown in Table 1. The vegetation of the study area is characterized with oil palms since the peat swamp forests were converted to oil palm plantation in 1978.

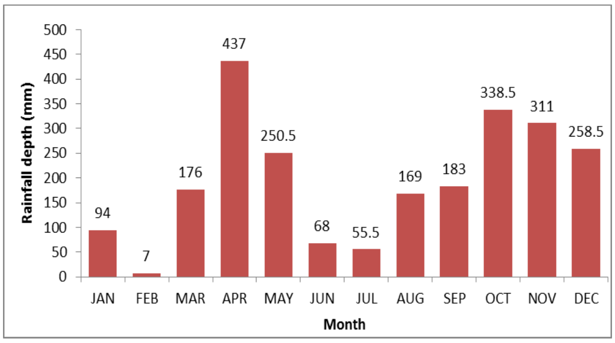


Figure 1: Monthly Rainfall Depth for 2014 in the Study Area

TABLE 1: PROPERTIES OF PEAT SOIL IN THE STUDY AREA

Index properties	Range	Average
Natural moisture content (%)	150-600	200
Peat pH.	3.10 - 3.82	3.65
Peat carbon content (%)	11.66 - 51.22	45.32
Peat nitrogen content (%)	0.24 - 1.93	1.45
Peat sulphur content (%)	0.07 - 0.22	0.136
pH of groundwater	3.09 - 4.4	3.42
Bulk density (g/cm^3)	0.18 - 0.397	0.276

2.2 SITE SELECTION

The study area of 10,000 ha was divided into four different plots, each plot named according to the age of plantation, such as; 2000, 2002, 2006, and 2010/1978. The plots were further sub-divided into sampling points and labeled as; 2000-A2, 2000-B1, 2000-B2, 2000VP-1, 2000VP-3, 2000VP-5, 2002-1, 2006-1, 2006-2, and 2010-1, making 10 sampling points in the entire study area (6 sampling points in 2000-Year of plantation, 2 in 2006-Year of plantation, and 1 sampling point each in 2002 and 2010 years of plantation).

2.3 EXPERIMENTAL DESIGN AND SET UP

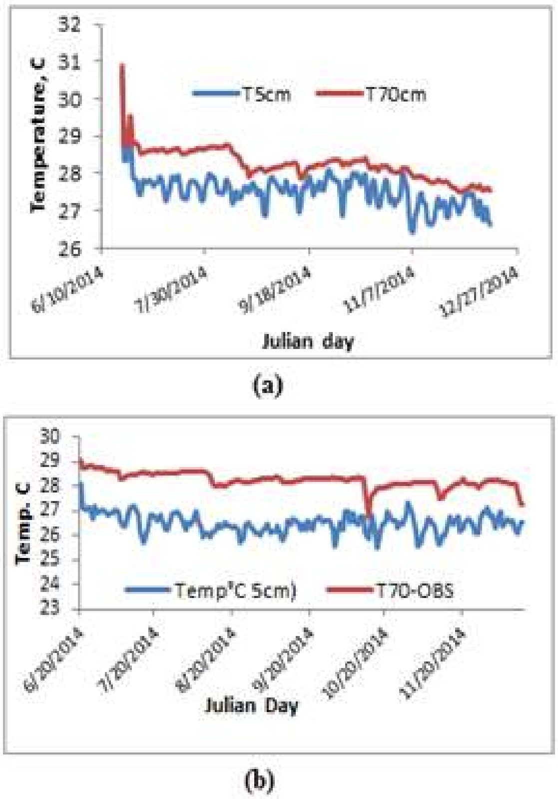
Surface and subsurface measurements were carried to determine water table depth, soil moisture and soil temperature which are in turn used as predictors with daily rainfall to predict the daily soil moisture. For soil moisture determination, 10 cm-long, 10HS soil moisture probes with 1 litre area of influence that estimates the volumetric water content VWC of the soil within that volume of influence were installed in undisturbed soil samples at two separate depths of 5 cm and 70 cm in all the 10 study sites.

The soil moisture probes and soil temperature sensors were installed by burying them into the soil. The installation began by excavating the soil to the depth of 80 cm below the ground surface in all the chosen stations. Two depths were chosen for the installation; 5 cm and 70 cm. The depths of 5 cm and 70 cm were chosen so as to check the influence of soil moisture and soil temperature with soil depth at near soil surface and deep beneath the soil. At the 70 cm depth, the soil moisture probe and soil temperature sensor were both inserted into the undisturbed soil, making sure the prongs are fully buried up to the black overmolding. The sharpened tip of each prong is in place in order to ensure easier pushing of the probe into the soil mass. It was ensured that there was a good soil-to-sensor contact at both chosen depths before the trench was backfilled ensuring that the bulk density of the backfilling materials was the same as that of the surrounding soil. Connecting sensor cables were well protected with a flexible PVC casing above the ground surface before being connected to the terminal block situated close to the installed sensors. The connecting sensor cables were well insulated with PVC in order to prevent them from environmental hazards. Water table depths were measured with the aid of pressure transducers inserted through the tube wells into the groundwater. Soil temperature and soil moisture at both 5 cm and 70 cm are compared to check their variations with soil depth and what influences their changes. Surface air temperature (SAT) which is the maximum daily air temperature in the study area was obtained from Malaysia Meteorological Department (MMD) station 48650 in Sepang KLIA adjacent to the study area. Statistical analysis (IBM SPSS statistics 21) was used to analyze the patterns of correlations among the variables.

3 RESULTS AND DISCUSSION

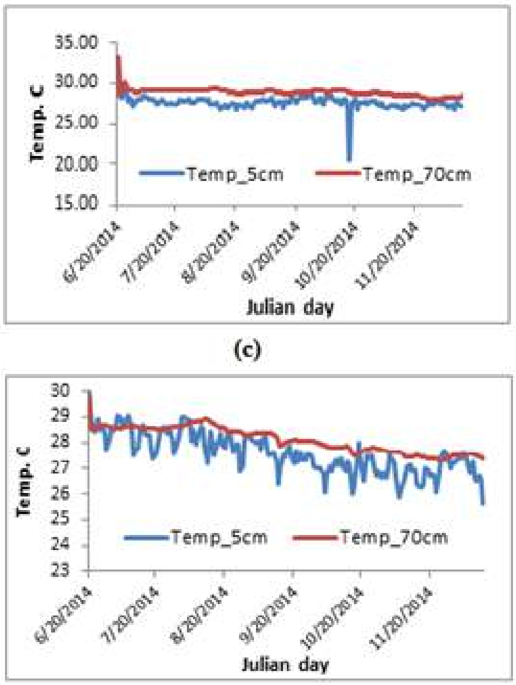
3.1 SOIL TEMPERATURE

Seasonal variations in soil temperature at 5 cm and 70 cm in the selected study plots covering the study area are shown in Figure 2 (a-d). In all the study plots, the average daily soil temperature recorded at the surface, 5 cm, ranged from 22.80 ºC to 30.21 ºC 33.11 ºC while at 70 cm, the average daily soil temperature ranged from 23.20 ºC to 34.50 ºC (Figure 2 a-d). A seasonal variation of soil temperature as shown in Figures 2(a-d) revealed that soil temperature seems to become more constant at 70 cm compared to soil temperature at 5 cm which shows the correlation of soil depth with soil temperature ($P < 0.05$, $n = 178$). In other words, soil temperature at 5 cm exhibited prolonged fluctuations compared to soil temperature at 70 cm.



(a)

(b)



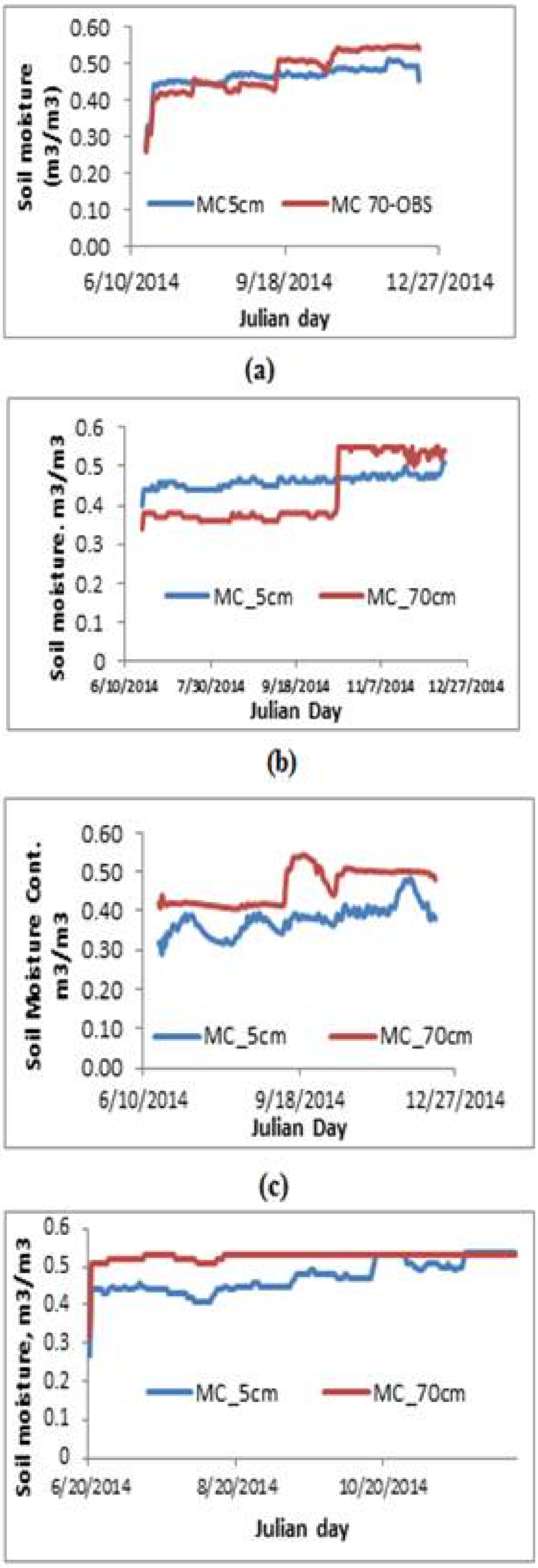
(c)

(d)

Figure 2a-d: Seasonal Variations of Soil Temperature at 5cm and 70 cm Depths from Selected Study Plots

3.2 SOIL MOISTURE

Soil moisture at 5 cm experienced much fluctuation compared to the soil moisture at 70 cm, varying from 0.46 m3/m3 to 0.54 m3/m3 while the average soil moisture at 70 cm varied between 0.51 m3/m3 to 0.53 m3/m3 (Figure 3 a-d). Soil moisture at both depths showed similar patterns with soil temperature. Soil moisture at 5 cm, like soil temperature at 5 cm, is lower than that of 70 cm, with the exception of period with sizeable amount of rainfall as represented with the intercept between the two graphs in 2002 study plot (Figure 3b). Like the soil temperature at 70 cm, soil moisture at 70 cm was also observed to be more constant compared to the soil moisture at 5 cm which could be due to the contribution from groundwater body or base flow.



(a)

(b)

(c)

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Figure 3a-d: Seasonal Variations of Soil Moisture at 5cm and 70 cm Depths from Selected Study Plots

3.3 PREDICTION OF SOIL MOISTURE AND TEMPERATURE AT 70 CM

Water table depth, soil moisture at 5 cm and temperature (at 5 cm and 70 cm) with rainfall and surface temperature were used in models to predict soil moisture and soil temperature at 70 cm soil depth in all the sampling points. In this approach, all the six study areas under age ‘2000’ were grouped together as a single plot. The same went for site ‘2002’, ‘2006’ and site ‘2010’. Thus, 4 equations (one from each of the 4 study areas of 2000, 2002, 2006, and 2010) predicting the values of soil moisture and soil temperature were developed for prediction. From the models developed in Tables 2 and 3, the empirical equations predicting these variables will take the form of Equations 1 and 2;

$$MC_{70} = [K]_{MC} + [A]\mathrm{TEMP}_5 + [B]\,\mathrm{TEMP}_{70} + [C]\mathrm{MC}_5 + [D]\mathrm{RAINFALL} + [E]\mathrm{WATB} + [F]\mathrm{SAT} \qquad [1]$$

$$TEMP_{70} = [K]_{MC} + [A]MC_5 + [B]\,\mathrm{TEMP}_5 + [C]\mathrm{MC}_{70} + [D]\mathrm{RAINFALL} + [E]\mathrm{WATB} + [F]\mathrm{SAT} \qquad [2]$$

Where MC70 represents soil moisture at 70 cm in m3/m3; TEMP70, Temperature at 70 cm in oC; WATb, Water table depth in cm, TEMP5, Temperature at 5cm in oC;; MC5 represents soil moisture at 5 cm in m3/m3; SAT, Surface air temperature in oC and a, b, c, d, & e are coefficients. The intercept K corresponds to the theoretical soil moisture, soil temperature or water table depths of the study area depending on which parameter is being considered while the rest of the coefficients represent the expression of the independent variables.

For soil moisture at 70 cm as a dependent variable, soil moisture at 5 cm, soil temperatures at 5 cm and 70 cm, rainfall depth, water table depth and surface air temperature, (SAT) are the environmental parameters accounting for its variance (Table 2, equations 1-4). Thus the model is a combination of in situ data (water table depth, soil moisture and soil temperature at 5 cm and 70 cm) and meteorological data (daily rainfall and surface air temperature, SAT) which were used as observed data in predicting and computing accurately the daily soil moisture and temperature at 70 cm. The models utilized these data collected for prediction within the study period. The models predicting these variables (soil moisture and temperature at 70 cm) are as shown in Tables 2 and 3.

The results of the comparison of soil moisture and soil temperature for observed and predicted values using 45° line of best fit for all the four study plots are as shown in Figures 4 and 5 respectively. From the figures, it can be deduced that there is a very reasonable agreement between the observed and predicted soil moisture and temperature in all the study plots.

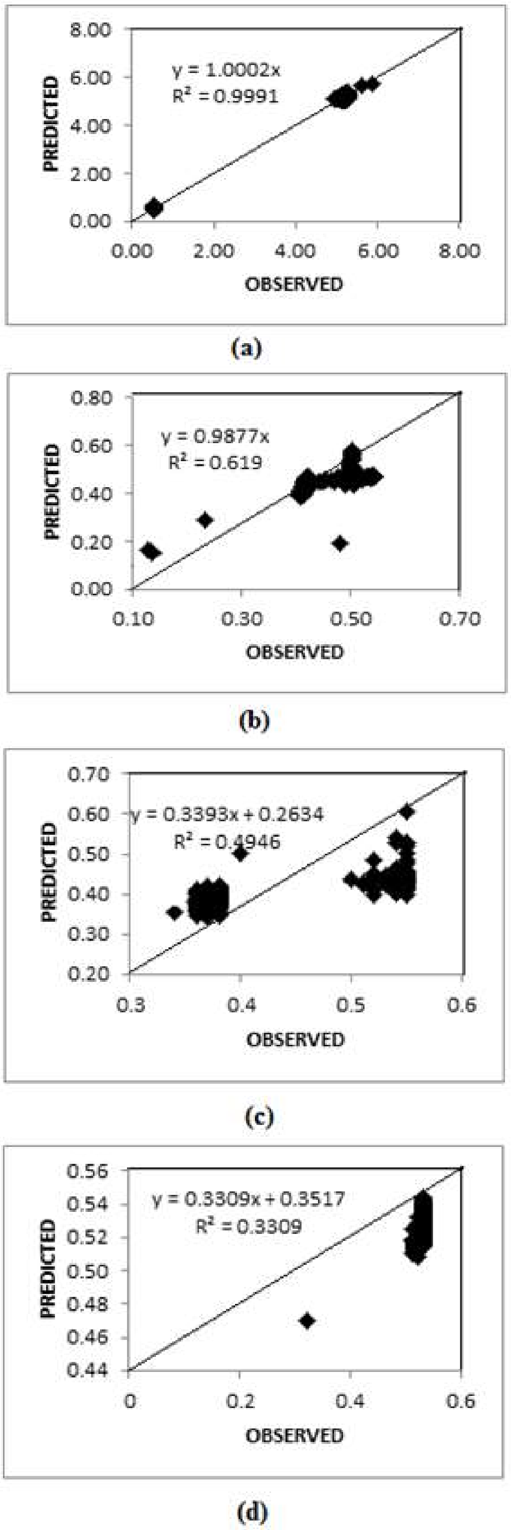
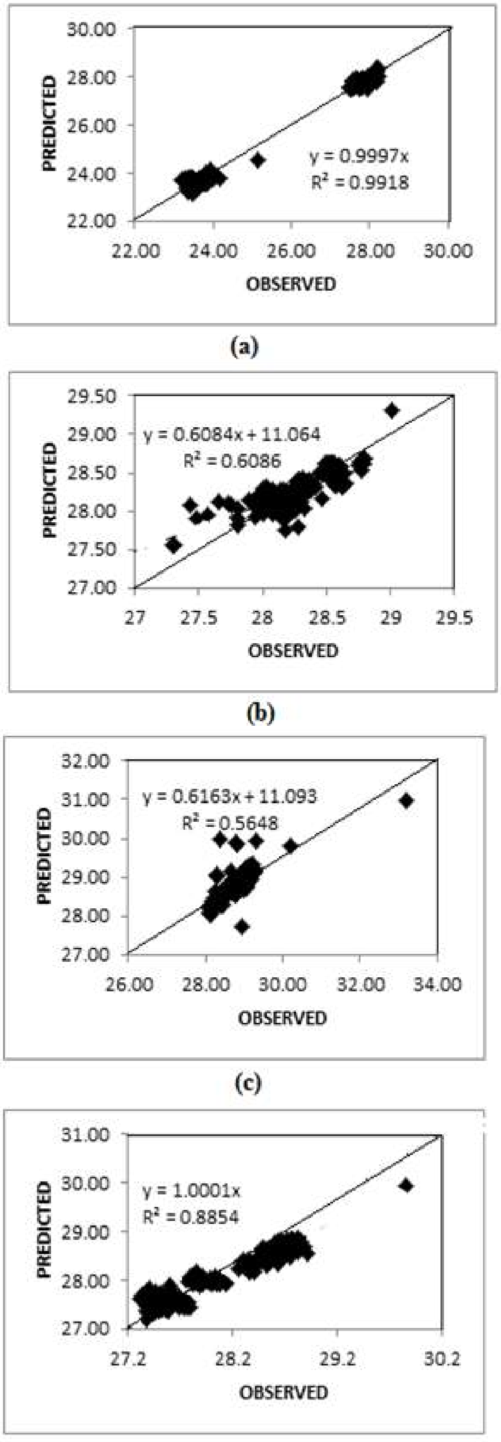


Figure 4: Comparison of the Observed and Predicted Soil Moisture at 70 cm for the Study Plots. a) 2000, b) 2002, c) 2006, and d) 2010



(d)

Figure 5: Comparison of the Observed and Predicted Soil Temperature at 70 cm for the Study Plots. a) 2000, b) 2002, c) 2006, and d) 2010

3.4 STATISTICAL ANALYSIS

Pearson's measures of correlation were used in investigating the strengths of association between rainfall and soil temperature at both depths. The result showed a negative significant difference (P<0.01, n = 178) between rainfall and soil temperature, a result indicating percolating rainfall cools the soil temperature both at the surface and at the deep layers. This explains the reasons behind the downwards trends in the soil temperature at both depths with high storm events. There is also a strong Pearson's correlation coefficient between soil temperature at 5 cm and soil temperature at 70 cm depth ranging from 0.719 – 0.813 (P<0.01, n = 178).

Positive significant correlation between water table depths and all other parameters like soil moisture and soil temperature at 5 cm and 70 cm, and rainfall (P<0.01, n = 178, ANOVA), except surface air temperature (SAT) was observed in plot '2000'. All other study plots, however, showed positive correlation (P<0.01, n = 178, ANOVA) between rainfall and water table depths. It further revealed that rainfall and SAT are significantly correlated with soil surface temperature and soil moisture at 70 cm in all the plots (P<0.01, n = 178, ANOVA). This, therefore, implies that surface air temperature, SAT could serve as a proxy of the soil temperature beneath the soil surface. However, Water table depth shows statistical significance with all the parameters (P<0.01, n = 178, ANOVA), except with SAT at both 2000 and 2002 study plots.

4 DISCUSSION

In this study, it was observed that soil moisture and soil temperature at 5 cm below the peat surface experienced much fluctuation compared to the observed values at 70 cm. Fluctuations experienced by soil moisture at the surface could be attributed to the environmental effect, water holding capacity of the soil at oil palm root zones (Hökkä et al., 2013) or the moisture accumulation at the root zones which is dependent of storm events and soil bulk density. On the other hand, fluctuations experienced by soil temperature at peat surface could be due to precipitation and varying surface air temperature which has little or no effects on deep soil temperature (Feng and Hu, 2005). Soil temperature at the surface has been observed to be the source of deep (terrestrial) temperature (Feng and Hu, 2005). The seasonality of soil moisture and temperature was therefore enhanced by their correlation with precipitation (Feng and Hu, 2005; Dong et al., 2007; Cong and Brady, 2012) and some other factors like SAT, rainfall intensity, soil physical properties and groundwater levels which is consistent with Schlosser and Milly (2002) and Carretero and Kruse (2012).

The positive significant correlation between soil moisture and soil temperature at 5 cm and 70 cm with water table depths and rainfall means that water table depth is influenced by storm events with significant effects on soil moisture and temperature at both depths (Moore et al., 2012; Yi et al., 2015). Also the strong significance change in rainfall (P < 0.05, n = 178) with water table level means the rise in water table level in the study areas was largely as a result of primary maximum rainfall that occurred between October and November,

2014. Mean water table depth of 90.80 cm below the peat surface was observed in April as against 27.16 cm below the peat surface in December which largely reflects the influence of storm events on water table depth.

The positive correlation between rainfall and water table depths could also be attributed to the contribution of baseflow to the groundwater recharge in the event of rainfall which is consistent with Brixel (2010). In other words, higher soil moisture recorded at 70 cm in all the study plots could be due to the nearness to groundwater table. However, the decline in soil temperature at both depths with increased rainfall (Feng and Hu, 2005; Cong and Brady, 2012) could largely be attributed to the cooling effects as a result of advent of storm events which cools the soil temperature both at the surface and at the deep layers.

This study establishes linear relationships between soil moisture and soil temperature at 70 cm (predicted and observed) using in-situ measurements of soil moisture and soil temperature at 5 cm with meteorological data; rainfall and surface air temperature. The use of these linear relationships in all the study plots for prediction gives a better prediction capability of soil moisture and temperature as coefficients of determination, R2, is mostly above 0.5 and the agreements are within 0.05 – 0.1 of each other (i.e 95% and 99% confidence intervals). A conclusion should review the main points of the paper and should state concisely the most important propositions of the paper. It should state the author's views of the practical implications of the results.in addition to the deductions that can be made from the results. Do not replicate the abstract as the conclusion. A conclusion might also elaborate on the importance of the work or suggest applications and extensions.

5 CONCLUSION

The relationship between soil moisture, soil temperature, rainfall and water table depth in a drained tropical peatland in Southeast Asia was evaluated. Seasonal variation in soil moisture and soil temperature was observed. The two soil properties, irrespective of depth, were observed to be correlated significantly with rainfall. Negative significant correlation between soil temperature and soil moisture in the two depths examined was also observed. In other words, inverse relationships were observed between soil moisture and soil temperature at both depths considered which means following a rainfall event, increase in soil moisture results in decrease in soil temperature. The soil moisture and soil temperature at the surface (0-5 cm) were observed to be influenced by storm events which also explain why there are fluctuations in the surface soil moisture and soil temperature. Rainfall percolating into the soil was also observed to influence both the surface and deep soil temperature.

In conclusion, peatland soil moisture and temperature have been observed to be seasonal which majorly are influenced by storm events. Linear relationships between them at 70 cm below peat surface have also been observed. These linear relationships, which predict the estimation of both the soil moisture and soil temperature at 70 cm yields good results and give better prediction capacities for their estimation irrespective of soil depth.

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TABLE 2: PREDICTION OF SOIL MOISTURE @ 70 CM USING SOIL PROPERTIES AND METEOROLOGICAL DATA (X0=TEMP@5CM; X1=TEMP@70CM; X2=SOILMOIST@5CM; X3=RAINFALL; X4=WATERTABLE; X5= SAT)

Equation Nos	Study Plot	Dependent Variables (y)	Independent Variables (x)	R^2	Equations of prediction	n
1	2000	Soil moisture @ 70 cm	WaterTableLev; Rainfall; Temp@5cm; Temp@70cm; WaterTab@5cm	0.999**	$y= 3.067 - (0.105 * x0) + (0.00850 * x1) + (0.900 * x2) - (0.000322 * x3) - (0.00268 * x4) - (0.00409 * x5)$	178
2	2002	Soil moisture @ 70 cm	WaterTableLev; Rainfall; Temp@5cm; Temp@70cm; WaterTab@5cm	0.0848**	$y = 3.910 + (0.0104 * x0) - (0.139 * x1) - (0.477 * x2) - (0.000352 * x3) + (0.000379 * x4) + (0.0111 * x5)$	178
3	2006	Soil moisture @ 70 cm	WaterTableLev; Rainfall; Temp@5cm; Temp@70cm; WaterTab@5cm	0.772**	$y = -0.566 + (0.00213 * x0) + (0.0186 * x1) + (1.011 * x2) + (0.0000545 * x3) + (0.000489 * x4) + (0.00104 * x5)$	174
4	2010	Soil moisture @ 70 cm	WaterTableLev; Rainfall; Temp@5cm; Temp@70cm; WaterTab@5cm	0.331**	$y = 0.279 - (0.00421 * x0) + (0.00797 * x1) + (0.344 * x2) - (0.000139 * x3) - (0.000144 * x4) - (0.000379 * x5)$	178

*** significant at 0.05% level of probability

TABLE 3: PREDICTION OF SOIL TEMPERATURE @ 70 CM USING SOIL PROPERTIES AND METEOROLOGICAL DATA (X0=TEMP@5CM; X1=SOILMOIST@5CM; X2=SOILMOIST@70CM; X3=RAINFALL; X4=WATERTABLE; X5=SAT)

Equation Nos	**Study Plot**	**Dependent Variables (y)**	**Independent Variables (x)**	**R^2**	**Equations of prediction**	**n**
1	2000	Soil Temp.@ 70 cm	Temp@5cm; MoisContent@5cm, MoisContent@70cm; Rainfall; WatTab	0.992**	$y= 12.996 + (0.536 * x0) - (0.543 * x1) + (0.0620 * x2) + (0.000916 * x3) - (0.00462 * x4) + (0.0268 * x5)$	178
2	2002	Soil Temp.@ 70 cm	WaterTableLev; Rainfall; WaterTab @5cm;Temp@70cm; WaterTab@70cm	0.608**	$y = 31.870 + (0.114 * x0) - (14.636 * x1) - (0.297 * x2) - (0.000704 * x3) + (0.00132 * x4) + (0.00571 * x5)$	178
3	2006	Soil Temp.@ 70 cm	WaterTableLev; Rainfall; WaterTab @5cm;Temp@70cm; WaterTab@70cm	0.661**	$y = 25.458 + (0.166 * x0) - (3.762 * x1) + (1.117 * x2) + (0.00238 * x3) - (0.00767 * x4) - (0.00288 * x5)$	174
4	2010	Soil Temp.@ 5 cm	WaterTableLev; Rainfall; WaterTab @5cm;Temp@70cm; WaterTab@70cm	0.897**	$y = 26.802 + (0.192 * x0) - (6.761 * x1) + (1.084 * x2) + (0.00131 * x3) - (0.00337 * x4) - (0.0346 * x5)$	178

*** significant at 0.05% level of probability