Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat organic chemistry, physical properties and C stocks

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Abstract

Ecosystem services provided by tropical peat swamp forests, such as C storage and water regulation, are under threat due to encroachment and replacement of these natural forests by drainage-based agriculture, commonly palm oil. This study aims to quantify how the chemical and physical properties of peat change during land conversion to oil palm. This will be addressed by comparing four separate stages of conversion; namely, secondary peat swamp forests, recently deeply drained secondary forests, cleared and ~~deforested areas (with~~ recently planted ~~new~~ oil palm~~ plantation)~~, and mature oil palm plantation in the vicinity of North Selangor Peat Swamp Forest, Malaysia. Results indicate accelerated peat decomposition in surface peats of oil palm plantations due to the lowered water table and altered litter inputs associated with this land-use change. ~~This reduced s~~Surface organic matter content and peat C stocks ~~from 1000 Mg ha^{-1} in intact~~ at secondary forest sites than ~~to 500 Mg ha^{-1}~~ at mature oil palm sites (C stocks were 1000 and 500 Mg ha^{-1} at secondary forest and mature oil palm sites, respectively). Land conversion altered peat physical properties such as shear strength, bulk density and porosity, with mirrored changes above and below the water table. Our findings suggest close links between the degree of decomposition and peat physical properties through the entire depth of the peat profile. We have demonstrated that conversion from secondary peat swamp forest to mature oil palm plantation may seriously compromise C storage and, through its impact on peat physical properties, the water holding capacity in these peatlands.

Keyword: land use change; carbon stocks; oil palm; organic chemistry; peat decomposition; soil physical properties; tropical peat swamp forest

1. Introduction

Ombrotrophic tropical peat swamp forests are unique ecosystems covering 247 778 km^2 in SE Asia and 441 025 km^2 globally (Page et al., 2011). ~~covering an estimated 2 to 2.5 million~~ perched on rich deposits of preserved organic matter are made possible by substantial rainfall, coupled with suitable topography and geology, which results in waterlogging. The anoxic and acidic conditions retard microbial decay (Andriesse, 1988; Page *et al,* 2006; Yule and Gomez, 2009) resulting in peat accumulation as inputs of litter from the vegetation are greater than decomposition rates (Jauhiainen *et al.*, 2008).

These unique systems are valuable resources, contributing a multitude of ecosystem services. Above ground, tropical rainforests maintain areas of high biodiversity by providing habitats for a variety of species, many of which are endemic (Posa et al. 2011; Keddy *et al.,* 2009). Below ground, the sequestration of atmospheric carbon is interwoven into the fabric of the ecosystem (Jauhiainen *et al.,* 2008). An estimated 42,000 megatons of ancient carbon is stored in 12% of the total land area of Southeast Asia alone, making this one of the largest stores of terrestrial carbon on Earth (Wetlands International, 2014). Peat soil structure is responsible for ecosystem processes by controlling hydrology, which regulates hydrological features within the catchment. For example, its high organic matter content and low bulk density allows peat to acts as a water reservoir, mitigating extreme conditions such as floods and droughts (Huat *et al.,* 2011; Wösten *et al.,* 2008).

Land use change over the past century has been a key driver of peatland degradation, with conversion to agriculture and forestry, and peat extraction sites, leading to artificially lowered water tables (Haddaway *et al.,* 2014). Limitations in understanding how peatland systems function has led to land degradation, which, for example has caused uncontrollable burning of over a million hectares of Indonesian peat during 1996, resulting from excessive land use change by the Mega Rice Project (Page *et al.,* 2002). Land conversion to agricultural oil palm plantation represents one of the primary threats to Malaysia's peat swamp forests (Koh *et al.* 2011). However, knowledge of the impact of the different land conversion stages involved in the establishment of oil palm plantations, in terms of decomposition, C stocks and peat physical properties, is extremely limited as most previous work has focused on binary comparison of intact forest and mature oil palm plantations.

Drainage of peat swamp forests to support oil palm production intensifies peat degradation as the thickness of the oxygenated zone of decay (acrotelm) is increased. This enhances rapid aerobic microbial decay compared to anaerobic decomposition which predominates within the anoxic zone below the water table (Anshari *et al.,* 2010). In addition to lowered water tables, deforestation removes complex vegetation structures and replaces them with a monoculture of oil palm trees, which deposit far less biomass, limiting organic matter inputs (Anshari *et al.,* 2010). The combination of decreased biomass input and reduced preservation of deposited biomass has caused large-scale peat degradation resulting in high atmospheric CO_2 emissions (Hooijer *et al.*, 2010; Couwenberg *et al.,* 2010).

A greater degree of peat decomposition results in loss of structure as fresh litter is first broken down to fibrous hemic peat, and then, following sustained decomposition, to sapric peat (Wüst *et al.,* 2003). The progressing decomposition process alters the organic components and chemistry due to loss of carbon and conversion of readily decomposable materials, such as polysaccharides, celluloses and hemicelluloses, with only more recalcitrant compounds such as lignin and humic substances remaining (Andriesse, 1988; Broder *et al.,* 2012; Kuhry and Vitt, 1996; Yonebayashi *et al.,* 1994). Degradation of physical properties occurs through subsidence as the open pore structure created by the fibrous, woody material collapses due to oxidation, shrinkage and compression, reducing total porosity and increasing bulk density as more solid material is concentrated per unit volume (Wösten *et al.,* 1997; Quinton *et al.,* 2000). As a consequence of degradation, percolation of water down the peat profile slows, decreasing hydraulic conductivity (Firdaus *et al.*, 2010). Water storage characteristics are also altered by decomposition as the water holding capacity is lowered and water retention increases, with implications for both the water content and gas flux rates within the peatlands (Boelter, 1964).

Knowledge on peat chemical and physical properties, as affected by the stages of land conversion for oil palm cultivation, is necessary to develop effective peatland management, and in the instance of degraded peatlands, restoration plans (Jauhianen *et al.*, 2008; GEC, 2014), thus conserving valuable ecosystem services. Land-use change in tropical peatlands is commonly discussed from the perspective of carbon emissions, with a very limited literature associated with peatland properties, and even fewer studies associated with multiple stages of conversion. This study determines how peat chemical and physical properties are altered during land conversion to oil palm. To achieve this we tested the following hypothesis: Land-use change of secondary peat swamp forests by drainage, clearance of forest and planting of oil palm, and finally establishment of mature oil palm plantations, which involve lowering of the water table and altered litter inputs, will accelerate peat decomposition and reduce C storage in tropical peatlands. As a consequence of land-use change to oil palm plantation, we predict greater peat humification and loss of carbohydrates and carboxyl compounds relative to recalcitrant aromatic structures reflecting enhanced microbial decomposition in drained surface peat layers. We expect this enhanced decomposition to result in (i) peat subsidence and lower C stocks in mature oil palm plantations compared to secondary forest sites and areas under the initial stages of conversion and (ii) highest shear strength and bulk densities, but the lowest porosity at oil palm sites.

2. Study sites

~~The study site of North Selangor Peat Swamp Forest (NSPSF) is situated on a flat coastal plain about 10 km inland on the west coast of Peninsular Malaysia (Figure 1), (Yule and Gomez, 2009). This tropical ombrotrophic peat swamp covers 73,592 ha and includes 50,106 ha of the Sungai Karang Forest Reserve to the north and 23,486 ha of the Raja Musa Forest Reserve to the south (Ahmed, 2014). The main tree species found in the areas are:~~ ~~*Macaranga pruinosa, Campnospermacoriaceum, Blumeodendron tokbrai, Shorea platycarpa, Parartocarpus venenosus, Ixora grandiflora, Pternandra galeata, Crytostachys sp., and Pandanus atrocarpus*~~ ~~(Yule and Gomez 2009). Four land conversion classes were selected, with five replicate sites for each, to represent the stages involved in the process of conversion (ranging from intact forest to mature oil palm):~~

During the early Holocene, the area was likely colonised by extensive mangrove systems, but these diminished after the last Holocene interglacial marine incursion when the fresh water peatland vegetation started to take hold, resulting in the deposition of acidic peat up to 5 m deep, overlaying grey marine clay (Yule and Gomez, 2009). The area receives an average rainfall of over 2000 mm per year, with the driest month in June measuring 76 to 191 mm and the wettest month in November measuring 185 to 414 mm (Sim and Balamurugam, 1990; Yusop, 2002). Average shaded air temperature recorded was 28.5 °C, with an average monthly relative humidity of 77.2% (Hahn-Schilling, 1994).

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Stage 1. Shallowly drained ~~F~~forest sites – prior to conversion, ~~intact~~ secondary peat swamp forests were water tables are close to or at the surface for a large part of the year, maximum water table draw down was ca. 0.5-0.6 in areas away from drainage ditches (GEC 2014).

Stage 2. Recently deeply ~~D~~drained forest sites – extensive drainage of peat swamp forests where large drainage ditches (2-3 meters wide and ca. 2 m deep) have been dug every few hundred meters in order to lower the water table, but trees and ~~dense~~understory vegetation ~~shrubs are left relatively intact~~have not been removed. In this case ditches were constructed *c.* 6 months prior to fieldwork.

Stage 3. ~~Cleared~~Recently planted young oil palm sites – areas in which both drainage and deforestation has occurred, which subsequently is planted with oil palm seedlings (also *c.* 6 months prior to sampling).

Stage 4. Mature ~~O~~oil palm sites – fully mature oil palm plantations, in which drainage, deforestation, and establishment of oil palm trees for 10-15 years has occurred (age range of the sampling sites was estimated based on height of the oil palms). All the oil palm sites are first generation of oil palm . Water table monitoring within the NSPSF indicate maximum water table draw down to ca. 1.5 m below the surface during periods of low rainfall with water tables generally being below 0.5 m below the surface (GEC 2014).

3. Materials and Methods

3.1.Field sampling

Within each of the land conversion classes, five ~~census~~ plots with areas of 900 m^2 were marked out during November and December of 2014. The broad site selection was based on areal images and maps (GEC 2014). Forest sites were selected to be spatially distributed over NSPSF taking accessibility into account. Recently deeply-drained forest and recently plant oil palm plantations site were constrained to two areas of subject to this land use. Within these areas plots were selected randomly (see below). Mature oil palm areas were chosen to be as spatially distributed as possible but also site access. Random number tables were used to determine the direction and distance to the south west corner of the plot, ensuring random selection of the plot within the broader site. GPS coordinates were recorded for each corner; locations for each plot are in Supplementary information 1.

In each of the census plots, a 1 dm^3 block of surface peat and an entire peat core from surface to underlying grey marine clay were collected. The 10x10x10 cm peat blocks were measured with a ruler and carefully cut and lifted from the peat using a household bread knife and trowel, before sealing in large zipper storage bags. Peat cores were extracted using a side-filling Russian Peat Corer (Van Walt, UK) with a 50 cm long sampling chamber, allowing for the recovery of deep, uncompressed peat cores. Peat depth was determined at every site, recording the distance from the peat surface to the underlying clay layer. Immediately following extraction, peat samples were divided into 10 cm segments in the field. Samples were bagged and sealed to avoid moisture loss.

Surface peat volumetric water content was quantified at nine random locations within each plot using a ML2X ThetaProbe Soil Moisture Sensor with HH2 Moisture Meter Readout Unit (Delta-T Devices Ltd). Peat surface shear strength was gauged at the same nine locations using a 33 mm Shear Vane.

Commented [SS2]: Data was used as a covariate to the shear strength data

Water table height was measured with a measuring tape, either from the peat surface to the water surface if positive, or from the surface down to the water table depth using the borehole left by the Russian Peat Corer if negative.

3.2.Laboratory analysis

3.2.1. Methods to determine peat chemical properties

For total carbon (C) and nitrogen (N) determination, peat samples were first oven dried at 105 °C for 48 hours and then ball milled for homogenisation using a Planetary Ball Mill (Retsch-PM400, Castleford, UK). Analysis of C and N concentrations in the peat samples was performed using a total element analyzer (Thermo Flash EA 1112, CE Instruments, Wigan, UK).

The degree of decomposition was quantified using ~~two methods. First, the 10-point scale of von Post (1922) was used to indicate peat structure by ranking the state of decay of organic matter from H_1, very fibrous with little humification, to H_{10}, very few fibres with a high humification degree. The higher the number in the von Post scale, the higher the degree of humification (Huat *et al.*, 2011; Verry *et al.*, 2011; von Post, 1922). This was determined by squeezing a small sample of field-wet peat and assessing the proportion of peat which extruded through the fingers, the proportion left in the hand, and the colour and turbidity of the free liquid (Verry *et al.*, 2011). The proportions of each fraction that determine the H value has been translated from von Post (1922) into English and can be found in Stanek and~~

~~Silc (1977). H values were assessed for the surface peat blocks and through the entire peat~~ spectroscopy was used to: (i) determine the organic composition of surface peat, and (ii) assess if its organic chemistry was altered by land conversion by comparing the relative abundance of carbohydrates and carboxyls compounds to the abundance of aromatics. Specifically we calculated the 3340/1630 and 1710/1630 ratios, where the wavenumbers correspond to carbohydrates (3340), carboxyls (1710) and aromatics (1630) (Cocozza *et al.*, 2003; Artz *et al.*, 2008),~~.~~ these are subsequently denoted carbohydrates/aromatic ratio and carboxyl/aromatic ratio, respectively. In this instance, the higher the ratio, the higher the proportion of readily decomposable compounds to aromatics, and the lower the degree of decomposition.

Spectra were obtained using a Bio-Rad FTX3000MX series FTIR (Digilab Div., Bio-Rad Laboratories, Cambridge, MA) and a diffuse reflectance auto sampler attachment (Pike Technologies Inc. Madison, WI), using a similar method to that described by Vane (2003). Each acquisition measured wavenumbers 4000 to 400 cm^{-1} with 4 cm^{-1} spectral resolution and 40 scans. Samples were rotated 90° before repeating the analysis, allowing elimination of any variation due to an uneven surface. Sample spectra were referenced against a powdered potassium bromide matrix at the same instrument settings to produce a background spectra; which was used to eradicate the interference of carbon dioxide and water vapour in the air. All spectra were baseline corrected and the peak heights specific to readily decomposable organic compounds were divided by peak heights specific to recalcitrant aromatic compounds to generate decomposition indexes.

Surface peat pH was determined by diluting 5 cm^3 of field-wet peat in 12.5 cm^3 of distilled water in oakridge centrifuge tubes and leaving on a rotary shaker overnight, before measuring with a pH 209 benchtop pH meter (Hanna Instruments Ltd.) and combination pH electrode.

3.2.2. Methods to determine peat physical properties

Peat water content, bulk density, total porosity, and organic matter content were determined for all surface peat blocks and entire peat columns at 10 cm intervals. Gravimetric water content was assessed by oven drying the peat at 105°C for 48 hours. The peat mass was recorded before and after oven drying and applied to Equation (1). Bulk density was determined using the oven dried mass and known volumes, as in Equation (2). Total porosity was derived from bulk density using Equation (3) and an average particle density for peat of 1.4 g cm^{-3} (Rowell, 1994). Organic matter contents were quantified using the loss on ignition method. 5 g of oven dried, ball milled peat were weighed into porcelain crucibles, before placing in a Carbolite AAF muffle furnace (Carbolite Ltd.) at 550 °C for 4 hours. The weight of ash left after ignition was recorded and Equation (4) was used to determine the percentages of organic matter.

$$\Theta = \frac{M_w - M_d}{M_d} \times 100 \qquad \textbf{(1)}$$

Where Θ is the gravimetric water content, dry weight basis (%); M_w is the mass of wet peat (g); and M_d is the mass of oven dry peat (g).

$$\rho_{bulk} = \frac{M_d}{V} \qquad \textbf{(2)}$$

Where ρ_{bulk} is the bulk density, dry weight basis (g cm^{-3}); M_d is the mass of oven dry peat (g); and V is the volume of the peat core (cm^3).

$$\phi = 1 - \frac{\rho_{bulk}}{\rho_{particle}} \times 100 \qquad \textbf{(3)}$$

Where ϕ is the total porosity (%); ρ_{bulk} is the bulk density, dry weight basis (g cm^{-3}); and $\rho_{particle}$ is the particle density (g cm^{-3}).

$$\mathrm{OM} = \frac{\mathrm{M_1} - \mathrm{M_2}}{\mathrm{M_1}} \times 100 \qquad \textbf{(4)}$$

Where OM is the organic matter content (%); M_1 is the mass of oven-dry peat (g); and M_2 is the mass of ash left after ignition (g).

3.2.3 Estimating C stocks

We calculated C stocks at each site by predicting C concentration throughout the entire peat profile using a transfer function between C content (which was analysed for 168 selected peat samples) and LOI which was analysed for each 10 cm peat section. The C density in each 10 cm sample was then calculated using bulk density and summed over the entire peat profiles to generate C stocks. Comparisons among land conversion stages were done using the stock difference method (Hergoualc'h and Verchot 2011).

3.3.Statistical analysis

GenStat 17th edition statistical analysis software was used to evaluate all data generated from this project. Shear strengths were analysed using linear mixed models with restricted maximum likelihood (REML) to compare between land conversion classes by allowing the incorporation of both fixed and random effects into the model accounting for environmental variation between sites. Volumetric water content was added as a covariate when analysing for differences between land conversion classes for shear strength as this variable accounted for a high proportion of between-site variation.

One-way analysis of variance (ANOVA) was used to determine significant differences in the ~~3340~~carbohydrate/~~1630~~ aromatic and ~~1710~~carboxyl/~~1630~~ aromatic ratios among land conversion class. Two way ANOVAs were used to analyse significant differences between land conversion class, depth, and their interaction, allowing the incorporation of more than one discrete variable into the model. Continuous profiles of data for ~~von Post H values,~~ gravimetric water content, bulk density, porosity, ash and organic matter content with depth were categorised into three distinct groups in order to run the two way ANOVA: surface peat, peat just below the water table, and the deepest peat horizon within each core which was above the clay layer (subsequently denoted "deep peat"), for the ANOVA three sub samples from each layer from all cores were used.~~.~~

4. Results

4.1.Peat chemical properties

Peat pH values increased with conversion ($F_{3,19}$ –=4.37, $P < 0.05$) specifically pH ranged from 3.4 ± 0.06, 3.7 ± 0.06, 3.7 ± 0.08, to 3.9~~7~~ ± 0.08 at forest sites, deeply drained sites, recently planted and mature ooil palm sites, respectively ~~rising to 3.7 to 4.1 at oil palm plantations~~.

The peat C content did not differ significantly with either depth or among the land conversion classes (Figure 2a) while the N content was highest in the surface peat and in the recently drained forest area (Figure 2b). Consequently the C/N ratios were considerably higher in the two deeper peat layers but did not differ overall among sites (Figure 2c). C, N and C/N ratios through the individual peat profiles are shown in Supplementary information 3.

~~Surface peats (0-30 cm depth) from the oil palm plantations were more humified, i.e. had~~ 3). Broad peaks were observed at approximately 3340 cm^{-1} which are associated with O–H stretching of hydrogen in bonded O–H groups, specific to cellulose and other polysaccharides (Vane, 2003). Two sharp peaks observed at 2920 and 2850 cm^{-1} were due to asymmetric and symmetric C–H stretching of $–CH_2–$ groups from aliphatic compounds such as fats, waxes, and lipids. Shoulders were observed at approximately 1710 cm^{-1} on the side of 1630 cm^{-1} peaks, associated with C=O stretching of –COOH or –COOR groups present in carboxyl compounds. Broader peaks at 1630 cm^{-1} were assigned to aromatic C=C stretching and asymmetric –COO– stretching of lignin and other aromatics. The distinct peak at 1510 cm^{-1} were assigned to aromatic C=C stretching vibrations in lignins (Vane, 2003). Three peaks of similar height and width were observed at 1450, 1420, and 1370 cm^{-1}, indicating O–H and C–H deformations in aliphatic and phenolic structures (Artz *et al.*, 2008; Gandois *et al.*, 2013; Vane, 2003).

The decomposition indexes, i.e. the ~~3340/1630 (~~carbohydrate/aromatics~~)~~ and ~~1710/1630 (~~carboxyl/aromatics~~)~~ ratios, in the surface peat differed significantly between land conversion classes (Figures 4a and 4b). Specifically, the 3340/1630 ratio were significantly higher in forest and cleared sites (12.3±1.2 and 16.4±3.2 respectively), relative to drained and oil palm sites (8.5±0.5 and 8.5±0.8), ($F_{(3,16)}$=5.64, P=0.008, r^2=0.51), indicating higher proportions of aromatic structures relative to carbohydrates in drained and oil palm acrotelms (Figure 4a). 1710/1630 ratios were significantly higher in the surface peats of cleared sites (1.8±0.2), relative to other sites with ratios between 1.0 and 1.1±0.1 ($F_{(3,16)}$=5.62, P=0.008, r^2=0.51), which suggests higher proportions of carboxyl groups relative to aromatic compounds within acrotelms at cleared sites (Figure 4b).

4.2 Peat depth and C stocks

Peat depths ranged between 125 and 273 cm with the greatest accumulation of peat found at the recently drained forest sites and the shallowest at the oil palm plantations (near significant effect, Figure 5a). In contrast, C stocks were highest at the forest sites at~~ *ca.*~~ ~~1000 ~~975 ± 151 Mg ha^{-1} and lowest at the oil palm sites at ~~*ca*, 500 ~~497 ± 157 Mg ha^{-1}, which suggests oil yield half the C stocks of those found at the forest sites (Figure 5b). Peat depth was a reasonable predictor of C stocks ($R^2 = 0.55$) (Figure 5c), however, the discrepancy between peat depth and C stocks among the different land conversion classes shows that bulk density and C concentrations impact the C stocks.

4.3 Peat physical properties

The position of the water table at the time the peat cores were collected was 6.0 ± 22, -14 ± 23, -39 ± 15, and -21 ± 18 cm at the forest, drained, cleared, and oil palm sites, respectively, with positive values indicating the water surface being above the peat ($F_{(3,44)}=5.45$, $P<0.05$). The position of the water table was reflected in the volumetric surface moisture content which was 82.3 ± 28, 46.3 ± 22, 33.3 ± 9, and 56.56 ± 21 % at the forest, drained, cleared, and oil palm sites, respectively. Shear strength was significantly different among land conversion classes ($F_{(3,20)}=3.49$, $P=0.035$, $SED=0.959$ using volumetric water content as a covariate), with higher values found at the oil palm plantations (9.7±0.6 kPa) than the other land conversion classes (8.4±0.6, 6.8±0.9, and 7.8±0.6 kPa for forest, drained and recently cleared sites, respectively).

Surface organic matter content was highest at forest sites (94.1±1.5%) and lowest in oil palm plantations (77.3±5.9%) (Figure 6a). ~~In line with the field measurements of volumetric soil moisture content, f~~Forest sites had significantly higher water content (627±90%) in the surface layer than oil palm sites (440±42%) (Figure 6b; Supplementary information ~~5~~4). Peat at drained and cleared sites had higher moisture content below the water table, than at the mature oil palm plantations. Bulk density was ~~displayed the opposite trend with~~ lowest at the a bulk density of 0.07 g cm^{-3}~~;~~, ~~while surface~~and the other land conversion classes having ~~were slightly higher at~~between 0.10-0.12 g cm^{-3} for ~~the other land conversion classes~~ (Figure oil palm plantations both at the surface and at the two deeper layers.

Surface porosity was high for all land-use classes with the highest porosity observed at drained sites (95.2±0.4%) (Figure ~~6c~~6d). Porosity then dropped as land conversion progressed to cleared and mature oil palm plantations across the peat profile. ~~Bulk density displayed the opposite trend with lowest surface bulk density of 0.07 g cm^{-3} at drained sites, while surface bulk densities were slightly higher at 0.10-0.12 g cm^{-3} for the other land conversion classes (Figure 6d). The peat then became denser at cleared and mature oil palm plantations both at the surface and at the two deeper layers.~~

5. Discussion

5.1. Changes in peat organic chemistry~~, humification, and C stocks~~ following land use change

The higher carbohydrate/aromatic ratio~~3340/1630 ratio~~ (Figure 4a) found in forest and cleared surface layers suggests greater abundance of fresh litter inputs as a high ratio indicates a relatively high proportion of cellulose to aromatic compounds, which is typical of poorly decomposed peat (Cocozza *et al.*, 2003). Although continual, natural levels of litter inputs occurred both in forest and drained sites, only forest sites were observed to have the high water tables capable of preserving the cellulose-rich organic matter. The lower carbohydrate/aromatic ~~3340/1630~~ ratio at oil palm sites therefore indicates enhanced peat decomposition at this site. The fact that the carbohydrate/aromatic~~3340/1630~~ ratio was highest at the cleared site was unexpected. We speculate this is due to incorporation of carbohydrate rich woody debris (observed during sampling), from the recent deforestation into the top peat horizon during soil preparation (Andriesse, 1988). Indeed, the high proportion of carboxyl structures relative to aromatics, indicated by the ~~1710/1630~~carboxyl/aromatic ratios in surface peat at cleared sites (Figure 4b), indicate productions of carboxyls from the decomposition of recently deposited plant tissues in the surface peat (Cocozza *et al.*, 2003).

The ~~higher degrees of humification (higher H values on the von Post scale, Figure 2d) and~~ lower organic matter contents (Figure 6a) in the drained surface layer at the drained, cleared and oil palm sites provides further evidence that the conversion process stimulated decomposition. However, the enhanced decomposition following drainage was only evident when comparing forest to mature oil palm plantation, which suggests that C loss from oxidative decay is controlled in part by exposure time to air, as well as being influenced by fertiliser inputs, which also enhance decomposition (Wösten *et al.*, 1997; Anshari *et al.*, 2010; Corley *et al.*, 2003). ~~The greater degree of humification in surface peats relative to the deeper peat layers of drained and cleared forest, and oil palm indicates loss of structure and enhanced decomposition rates in surface peats (Figure 2d). This contrasts to the forested sites with water tables close to or at the peat surface, where the greatest decomposition degree was found in the deepest layers of peat (Kuhry and Vitt, 1996).~~

~~Although the H values were highest at the surface of the oil palm sites, the high degree of decomposition (H values ranging from about 7 to 10) found throughout the entire forest peat profiles (Appendix: Figure 1a) are intriguing as they contrast to studies of temperate and boreal peatlands where surface peat tends to have much lower H values (Kuhry and Vitt, 1996; Frolking *et al.*, 2001).~~ The DRIFT spectra presented in Figure 3 display the majority of peaks corresponding to temperate peatlands (Artz *et al.*, 2008; Cocozza *et al.*, 2003). However, the latter usually show an additional broad peak between 1080 and 1030 cm^{-1} which is not prominent here. This peak is assigned to C–O stretching and O–H deformation within polysaccharides (Artz *et al.*, 2008) and its low intensity in all surface peats, including forest sites, suggests rapid decomposition of polysaccharides~~ in line with the high H values~~. This could be due to impacts of historical logging activities prior to the 1980s or to vegetation structure and litter inputs. Furthermore, peat swamp forests have both increased aeration associated with large tree roots (Hoyos-Santillan *et al.*, 2016), and an open pore structure provided by the fibrous wood input (in contrast to the shallow rooted, less fibrous sphagnum moss that dominates northern peatlands (Wüst *et al.*, 2003)), which together may contribute to aerobic microbial decay throughout the rhizosphere. The early decay of polysaccharides observed here as compared to temperate peatlands may also be enhanced by the higher ambient air temperatures in Malaysia. For example, fungal decay studies have shown that aerobic oxidative degradation of polysaccharides by white and soft rot fungi (the most vigorous of all wood-decay microbes) is optimal at temperatures between 20 to 40°C (Vane, 2003; Vane *et al*., 2001). Similarly, a study of carbon cycling in tropical mangroves showed that arboreal termites cause extensive polysaccharide decay in leaf and wood litter due to symbiotic bacteria; this suggests that in tropical environments, litter may undergo extensive multi-phase (insectivorous and microbial) alteration prior to burial (Vane *et al*., 2011).

~~The forest C stocks were within the lower range of those reported from peat swamp forests in~~

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~~The large reductions in peat depth, of up to 2 m after 25 years of oil palm cultivation on drained peatland, demonstrated by Hooijer *et al.* (2012) further support the notion of dramatic C losses due to peat oxidation following drainage. Although the original peat depths at the oil palm sites are not known, peat depths in adjacent peatland areas (ca. 1-2 km away from the oil palm sites) are ca. 4 m (unpublished data not included in this study, Sofie Sjogersten) indicating that rapid peat subsidence and C losses have occurred during the establishment of mature oil palm plantations. Importantly, C loss rates measured in our study were higher than those reported for Central Kalimantan, Indonesia of 10.8 ± 3.5 Mg C ha^{-1} year^{-1} (Hergoualc'h and Verchot 2011) and the loss rates of 1400 Mg C ha^{-1} over 100 years predicted by modelling studies by Kurinanto *et al.* (2015) indicating that substantial C loss can occur quickly following conversion of peat swamp forests to oil palm plantations. Our findings contrasts starkly to the minor changes in C stocks in mineral soil following conversion of forest to oil palm plantation in Indonesia (53.63 ± 5.98 and 51.85 ± 18.95 Mg C ha^{-1} in forest and oil palm plantations, respectively; Khasanah *et al.*, 2015). Indeed, our peatland study strongly refutes the concept of C neutral oil palm plantations, as suggested for mineral soil systems by Khasanah *et al.* (2015). The large C losses from the peat shown in our study, together with losses of the large tree biomass held in intact peat swamp forests (ranging between 125 to 160 Mg C ha^{-1} assuming a 50% C content in the vegetation; Kauffman *et al.*, 2011; Kornseder *et al.*, 2012; Toriyama *et al.*, 2014; Schlund *et al.*, 2015), is nowhere near replaced by oil palm vegetation, which has an estimated life span above ground~~

~~biomass of 30 ± 10 Mg C ha^{-1} (Germer and Sauerborn 2008). Indeed, this investigation points~~

The peat porosity and bulk density at forest sites were comparable to those found in tropical peatlands in Malaysia and elsewhere. For example, Firdaus *et al.* (2010) found porosities and bulk densities of 91.5±1.8% and 0.112±0.004 g cm^{-3}, respectively, in forest surface peats. Other tropical peat studies have found bulk densities ranging from 0.02 to 0.21 g cm^{-3}, correlating with this study (Page *et al.*, 2004; Rieley and Page, 2008; Wösten *et al.*, 2008; Page *et al.*, 2011). Decomposition decreases the proportion of coarse, hollow fibres in peat as organic particle size and organic matter content (Figure 6a) is reduced with land conversion, and is expected to form a dense, closed soil structure (Huat *et al.*, 2011). In this study, enhanced decomposition, potentially in combination with compaction from machinery, following land conversion resulted in greater shear strength and lower soil moisture content in the surface peat layer at oil palm sites. The lack of a linear response of bulk density and porosity~~porosity and bulk density~~ as land conversion progressed from intact peat swamp forest, through forest drainage and clearance, to mature oil palm (Figures 6c and 6d), may be linked to initial subsidence of the drained peat layers below the surface network of roots resulting in high porosity and low bulk density. We speculate that the subsequent decreased porosity and increased bulk density at the cleared and oil palm sites are due to the removal of lignified root biomass during the ground preparation, together with greater decomposition rates, resulting in denser peats over time (Huat *et al.*, 2011; Quinton *et al.*, 2000). It is also worth noting that the gradual reduction in peat gravimetric moisture content and porosity moving from drained to oil palm sites, is also evident below the water table, which may be linked to peat subsidence following drainage (Wösten *et al.*, 1997).

5.3 Variation in peat depth and C stocks among land conversion classes

The peat C stocks in the forest were within the lower range of those reported from peat swamp forests in SE Asia (Warren *et al.*, 2012; Comas *et al.*, 2015; Farmer *et al.*, 2014) and the pan-tropics (Kauffman *et al.*, 2011; Lähteenoja *et al.*, 2012; Draper *et al.*, 2014). The comparatively low C stocks are due to the relatively shallow peat depths at the forest sites around the edges of the peatlands (Figure 1). As peat depth in the central areas (not used in this study) of the NSPSF are >4 m (GEC 2014), C stocks are therefore likely to be substantially higher in the interior parts of the peatland than our estimates. We expected that enhanced decomposition rates following conversion to oil palm plantations, would result in peat subsidence and reduced C stocks compared to forest sites. This prediction was supported by the shallower peat depths and C stocks found in oil palm plantations (51% reduction in C stocks; Figure 5) compared to other land conversion classes. These findings suggests that increased decomposition rates following drainage and establishment of mature oil palm plantations have dramatically and rapidly reduced peat swamp forest C stocks. Large reductions in C stocks are in line with Farmer *et al.* (2014) who found a 30% decrease in C stock on oil palm as compared to intact peat swamp forest in Sumatra, Indonesia.

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The large reductions in peat depth, of up to 2 m after 25 years of oil palm cultivation on drained peatland, demonstrated by Hooijer *et al.* (2012) further support the notion of dramatic C losses due to peat oxidation following drainage. Although the original peat depths at the oil palm sites are not known, peat depths in adjacent peatland areas (ca. 1-2 km away from the oil palm sites) are ca. 4 m (unpublished data not included in this study, Sofie Sjogersten) indicating that rapid peat subsidence and C losses have occurred during the establishment of mature oil palm plantations. Importantly, C loss rates measured in our study were higher than those reported for Central Kalimantan, Indonesia of 10.8 ± 3.5 Mg C ha^{-1} year^{-1} (Hergoualc'h and Verchot 2011) and the loss rates of 1400 Mg C ha^{-1} over 100 years predicted by modelling studies by Kurinanto *et al.* (2015) indicating that substantial C loss can occur quickly following conversion of peat swamp forests to oil palm plantations. Our findings contrasts starkly to the minor changes in C stocks in mineral soil following conversion of forest to oil palm plantation in Indonesia (53.63 ± 5.98 and 51.85 ± 18.95 Mg C ha^{-1} in forest and oil palm plantations, respectively; Khasanah *et al.*, 2015). Indeed, our peatland study strongly refutes the concept of C neutral oil palm plantations, as suggested for mineral soil systems by Khasanah *et al.* (2015). The large C losses from the peat shown in our study, together with losses of the large tree biomass held in intact peat swamp forests (ranging between 125 to 160 Mg C ha^{-1} assuming a 50% C content in the vegetation; Kauffman *et al.*, 2011; Kornseder *et al.*, 2012; Toriyama *et al.*, 2014; Schlund *et al.*, 2015), is nowhere near replaced by oil palm vegetation, which has an estimated life span above ground biomass of 30 ± 10 Mg C ha^{-1} (Germer and Sauerborn 2008). Indeed, this investigation points towards a substantial C footprint of oil palm plantations on tropical peatlands.

These findings demonstrate that land conversion for oil palm plantations changed peat physical properties over time through a combination of physical collapse of the peat structure following drainage, and enhanced decomposition in the drained surface peats. It is likely that such changes in peat physical properties are irreversible, particularly in the instance of changes cause by enhanced decomposition. This has important implications for land management policies, as some ecosystem services linked to the peat physical properties, e.g. water holding capacity (Abdul Rahim & Yusop 1999), may be permanently, and negatively, affected by land conversion for oil palm plantation. Indeed, peatland restoration, which is currently implemented at degraded peatland sites across SE Asia (e.g. Jauhianen *et al.*, 2008) and specifically within this study catchment (GEC 2014), may recover the biodiversity, fire regulation and C sink capacity of peatlands, however, this may not be the case for the water regulation services as these closely link to peat organic matter content, structure, density and porosity (Firdaus *et al.*, 2010).

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Figures

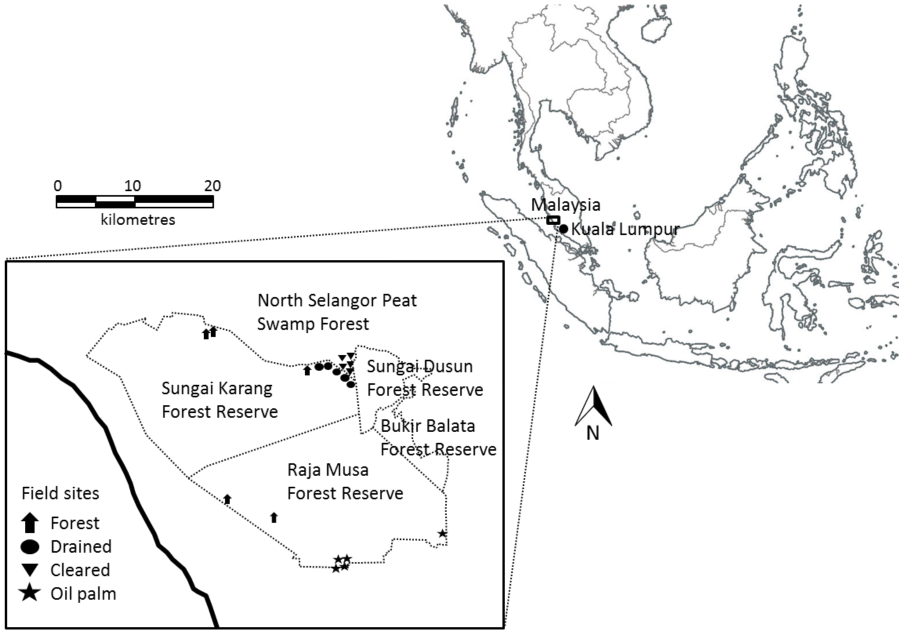

Figure 1: Location of North Selangor Peat Swamp Forest and field plots.

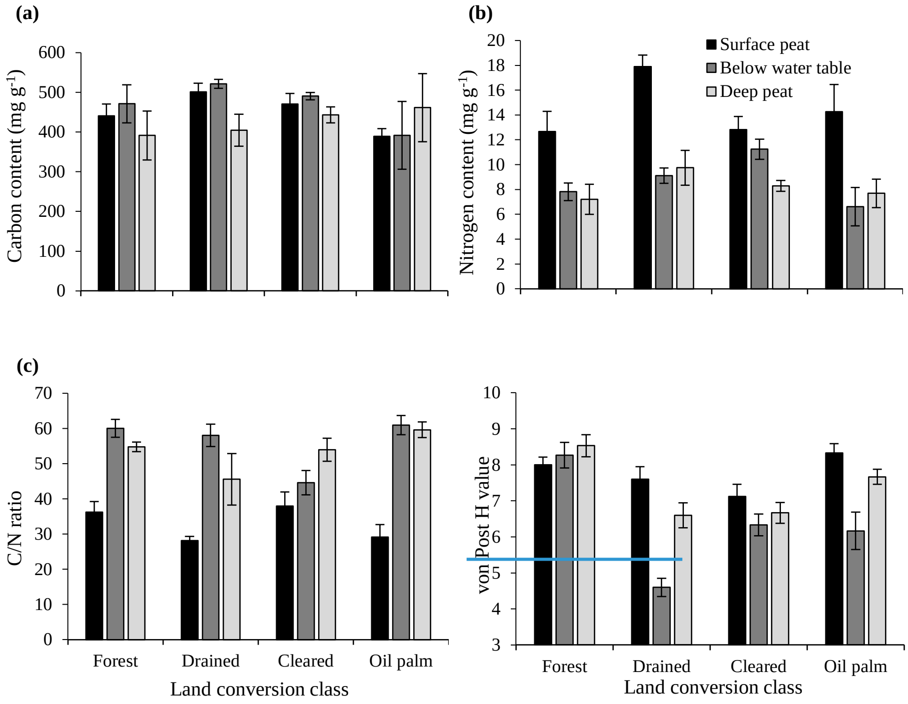

Figure 2: The difference in (a) carbon content; (b) nitrogen content; and (c) C/N ratio ~~between secondary peat, and (d) degree of decomposition indicated by the H-value~~ among secondary peat swamp forests, drained peat swamp forests, cleared peat swamp forests, and mature oil palm plantations at three different depths within the peat profiles: surface peat (black bar); below the water table (dark grey bar); and deep peat (light grey bar). Average values for land conversion classes and standard error bars are shown.

(a) Land conversion class: $F_{(3,44)}$=1.97, P=0.133; Depth: $F_{(2,44)}$=2.26, P=0.116; Interaction: $F_{(6,44)}$=0.84, P=0.544

(b) Land conversion class: $F_{(3,44)}$=3.25, P=0.031; Depth: $F_{(2,44)}$=28.21, P<0.001; Interaction: $F_{(6,44)}$=1.61, P=0.166

(c) Land conversion class: $F_{(3,44)}$=1.80, P=0.16; Depth: $F_{(2,44)}$=47.17, P<0.001; Interaction: $F_{(6,44)}$=3.25, P=0.01

~~(d) Land conversion class: $F_{(3,269)}$=56.77, P<0.001; Depths: $F_{(2,269)}$=92.87, P<0.001; Interaction: $F_{(6,269)}$=12.08, P<0.001~~

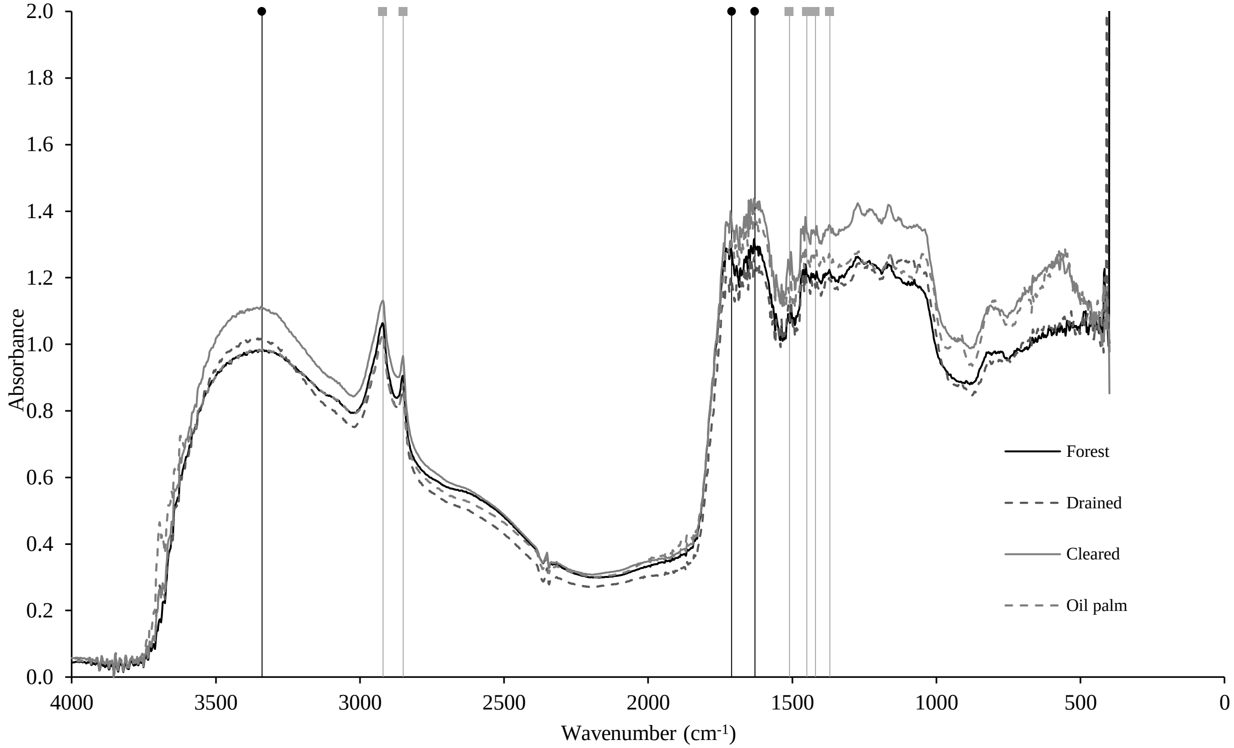

Figure3: DRIFT spectra of the average surface peat samples from 0-10 cm for: secondary peat swamp forests (black line), drained peat swamp forests (black dashed line), cleared peat swamp forests (grey line), and mature oil palm plantations (grey dashed line). Vertical black lines indicate the peaks at wavenumbers 3340, 1710, and 1630 cm^{-1} of which significantly different ratios were found between land conversion classes, and vertical grey lines indicate the peaks at wavenumbers 2920, 2850, 1510, 1450, 1420, and 1370 cm^{-1} common to tropical peats.

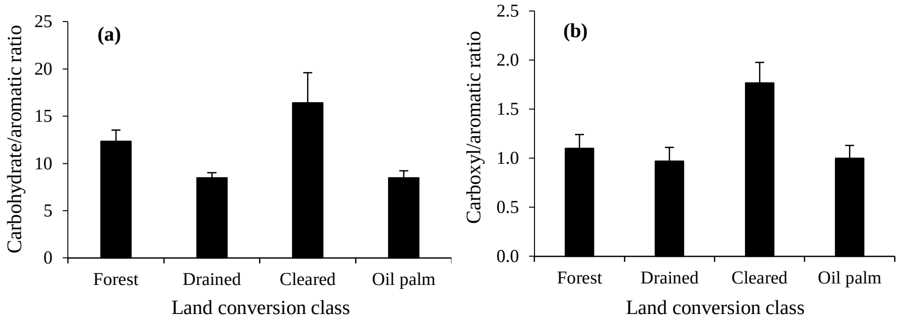

Figure 4: The difference in (a) ~~3340/1630 ratio or~~ carbohydrate/aromatic ratio i.e. 3340/1630 ratio or; and (b) ~~1710/1630 or~~ carboxyl/aromatic ratio i.e. 1710/1630 ratio ~~between~~ among secondary peat swamp forests, drained peat swamp forests, cleared peat swamp forests, and mature oil palm plantations in surface peat. Average values for land conversion classes and standard error bars are shown: (a) $F_{(3,16)}=5.64$, $P=0.008$; (b) $F_{(3,16)}=5.62$, $P=0.008$.

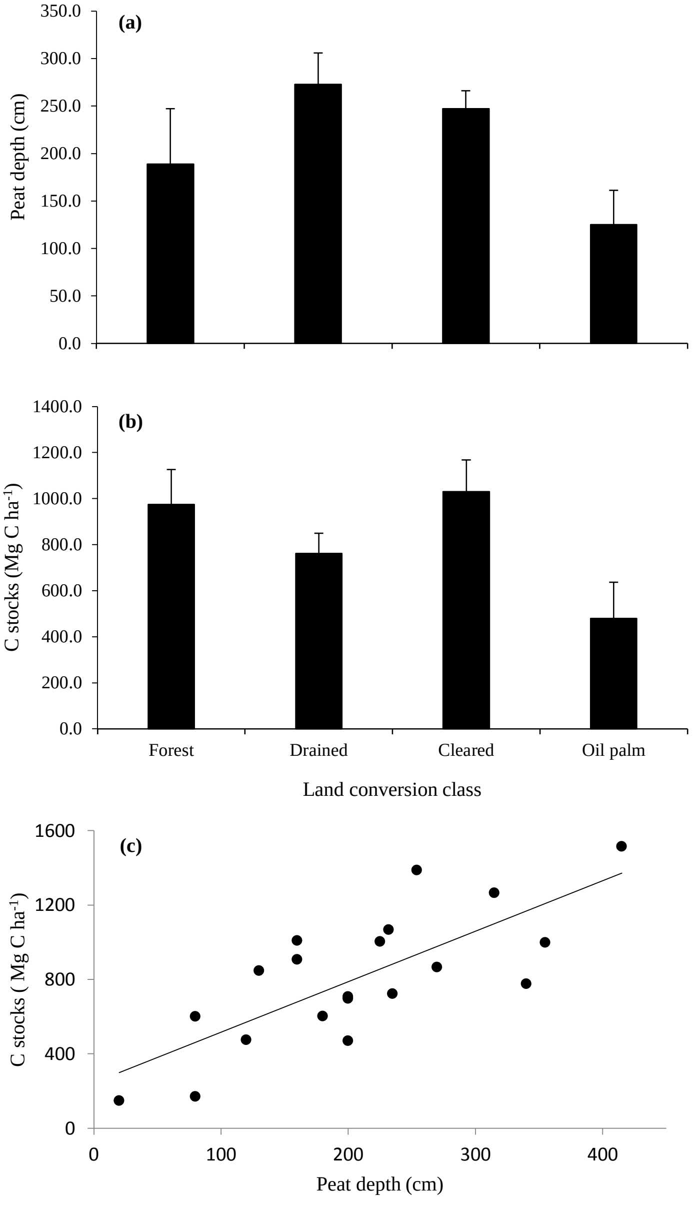

Figure 5: (a) Peat depth; and (b) C stocks at the different land conversion classes. Average values for land conversion classes and standard error bars are shown. Significant differences among land conversion classes: (a) $F_{(3,19)}=2.81$, $P = 0.07$; (b) $F_{(3,19)}=4.11$, $P=0.02$. (c) Relationship between peat depth and C stocks; $F_{(1,19)}=24.05$, $P < 0.001$, $R^2 = 0.55$.

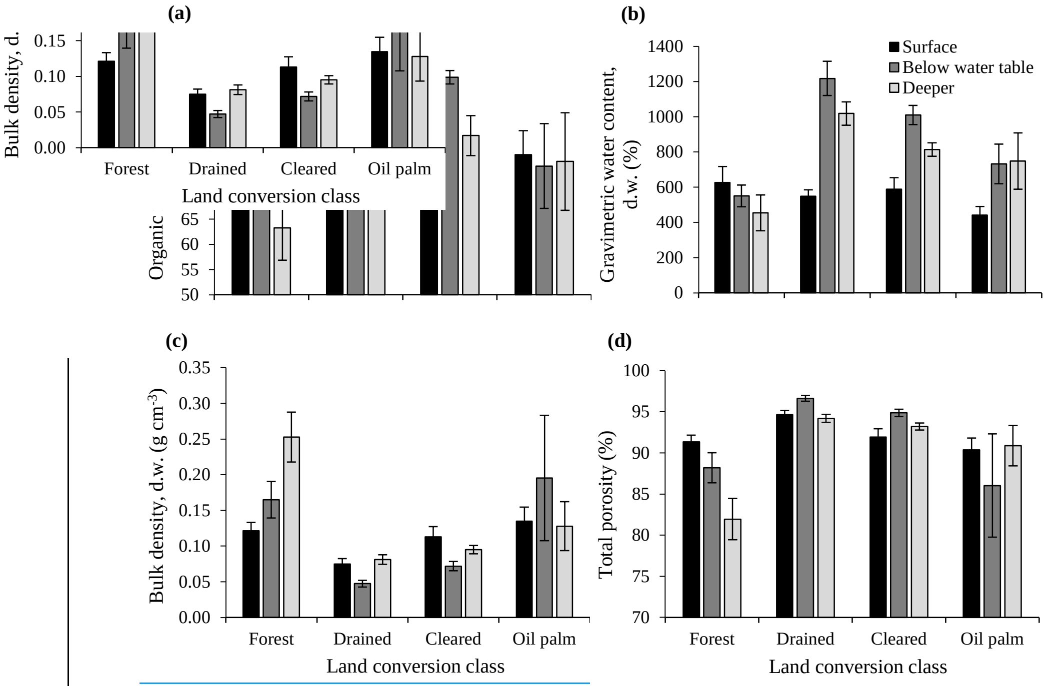

Figure 6: The difference in (a) organic matter content; (b) gravimetric water content (dry weight basis); (c) total porosity; and (d) bulk density (dry weight basis) between secondary peat swamp forests, drained peat swamp forests, cleared peat swamp forests, and mature oil palm plantations at three different depths within the peat profiles: surface peat (black bar); below the water table (dark grey bar); and deep peat (light grey bar). Average values for land conversion classes and standard error bars are shown.

(a) Land conversion class: $F_{(3,156)}$=5.44, P=0.001; Depth: $F_{(2,156)}$=9.19, P<0.001; Interaction: $F_{(6,156)}$=2.66, P=0.017

(b) Land conversion class: $F_{(3,156)}$=17.93, P<0.001; Depth: $F_{(2,156)}$=17.31, P<0.001; Interaction: $F_{(6,156)}$=5.31, P<0.001

(c) Land conversion class: $F_{(3,156)}$=21.47, P<0.001; Depth: $F_{(2,156)}$=5.47, P=0.005; Interaction: $F_{(6,156)}$=2.22, P=0.044

~~(b)~~

P=0.044

~~(c)~~(d) Land conversion class: $F_{(3,156)}$=19.43, P<0.001; Depth: $F_{(2,156)}$=4.33, P=0.015; Interaction: $F_{(6,156)}$=2.21, P=0.044

~~(d)(a) Land conversion class: $F_{(3,156)}$=21.47, P<0.001; Depth: $F_{(2,156)}$=5.47, P=0.005; Interaction: $F_{(6,156)}$=2.22, P=0.044~~