

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

3 Amanda J. Tonks^{1,3}, Paul Aplin², Darren J. Beriro⁴, Hannah Cooper^{1,3}, Stephanie Evers³,
4 Christopher H. Vane⁴ and Sofie Sjögersten^{1*}

5

6 ¹The University of Nottingham, School of Biosciences, Division of Agricultural and
7 Environmental Science, Sutton Bonington Campus, Loughborough, LE12 5RD, United
8 Kingdom

9

10 ²Edge Hill University, St Helens Road, Ormskirk, Lancashire, L39 4QP, United Kingdom

11

12 ³The University of Nottingham Malaysia Campus, School of Biosciences, Semenyih,
13 Selangor Darul Ehsan 43500, Malaysia

14

15 ⁴British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12
16 5GG, United Kingdom

17

18 *Corresponding author: S. Sjögersten

19 E-mail: Sofie.Sjogersten@nottingham.ac.uk

20 Phone: +44 (0)7772993691

21

22 **Abstract**

23

24 Ecosystem services provided by tropical peat swamp forests, such as C storage and water
25 regulation, are under threat due to encroachment and replacement of these natural forests by
26 drainage-based agriculture, commonly palm oil. This study aims to quantify how the
27 chemical and physical properties of peat change during land conversion to oil palm. This will
28 be addressed by comparing four separate stages of conversion; namely, secondary peat
29 swamp forests, recently drained forests, cleared and deforested areas (with new oil palm
30 plantation), and mature oil palm plantation in the vicinity of North Selangor Peat Swamp
31 Forest, Malaysia. Results indicate accelerated peat decomposition in surface peats of oil palm
32 plantations due to the lowered water table associated with this land-use change. This reduced
33 surface organic matter content and peat C stocks from 1000 Mg ha⁻¹ in intact forest sites to
34 500 Mg ha⁻¹ at mature oil palm sites. Land conversion altered peat physical properties such as
35 shear strength, bulk density and porosity, with mirrored changes above and below the water
36 table. Our findings suggest close links between the degree of decomposition and peat
37 physical properties through the entire depth of the peat profile. We have demonstrated that
38 conversion from secondary peat swamp forest to oil palm plantation may seriously
39 compromise C storage and, through its impact on peat physical properties, the water holding
40 capacity in these peatlands.

41

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

44

45 **1. Introduction**

46 Ombrotrophic tropical peat swamp forests are unique ecosystems covering an estimated 2 to
47 2.5 million hectares of the total land area of Malaysia (Firdaus *et al.*, 2010). Areas of diverse
48 tropical rainforest perched on rich deposits of preserved organic matter are made possible by
49 substantial rainfall, coupled with suitable topography and geology, which results in
50 waterlogging. The anoxic and acidic conditions retard microbial decay (Andriessse, 1988;
51 Page *et al.*, 2006; Yule and Gomez, 2009) resulting in peat accumulation as inputs of litter
52 from the vegetation are greater than decomposition rates (Jauhiainen *et al.*, 2008).

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

64 Land use change over the past century has been a key driver of peatland degradation, with
65 conversion to agriculture and forestry, and peat extraction sites, leading to artificially lowered
66 water tables (Haddaway *et al.*, 2014). Limitations in understanding how peatland systems
67 function has led to land degradation, which, for example has caused uncontrollable burning
68 of over a million hectares of Indonesian peat during 1996, resulting from excessive land use

69 change by the Mega Rice Project (Page *et al.*, 2002). Land conversion to agricultural oil palm
70 plantation represents one of the primary threats to Malaysia's peat swamp forests (Koh *et al.*
71 2011). However, knowledge of the impact of the different land conversion stages involved in
72 the establishment of oil palm plantations, in terms of decomposition, C stocks and peat
73 physical properties, is extremely limited as most previous work has focused on binary
74 comparison of intact forest and mature oil palm plantations.

75 Drainage of peat swamp forests to support oil palm production intensifies peat degradation as
76 the thickness of the oxygenated zone of decay (acrotelm) is increased. This enhances rapid
77 aerobic microbial decay compared to anaerobic decomposition which predominates within
78 the anoxic zone below the water table (Anshari *et al.*, 2010). In addition to lowered water
79 tables, deforestation removes complex vegetation structures and replaces them with a
80 monoculture of oil palm trees, which deposit far less biomass, limiting organic matter inputs
81 (Anshari *et al.*, 2010). The combination of decreased biomass input and reduced preservation
82 of deposited biomass has caused large-scale peat degradation resulting in high atmospheric
83 CO₂ emissions (Hooijer *et al.*, 2010; Couwenberg *et al.*, 2010).

84 A greater degree of peat decomposition results in loss of structure as fresh litter is first broken
85 down to fibrous hemic peat, and then, following sustained decomposition, to sapric peat
86 (Wüst *et al.*, 2003). The progressing decomposition process alters the organic components
87 and chemistry due to loss of carbon and conversion of readily decomposable materials, such
88 as polysaccharides, celluloses and hemicelluloses, with only more recalcitrant compounds
89 such as lignin and humic substances remaining (Andriess, 1988; Broder *et al.*, 2012; Kuhry
90 and Vitt, 1996; Yonebayashi *et al.*, 1994). Degradation of physical properties occurs through
91 subsidence as the open pore structure created by the fibrous, woody material collapses due to
92 oxidation, shrinkage and compression, reducing total porosity and increasing bulk density as
93 more solid material is concentrated per unit volume (Wösten *et al.*, 1997; Quinton *et al.*,

94 2000). As a consequence of degradation, percolation of water down the peat profile slows,
95 decreasing hydraulic conductivity (Firdaus *et al.*, 2010). Water storage characteristics are also
96 altered by decomposition as the water holding capacity is lowered and water retention
97 increases, with implications for both the water content and gas flux rates within the peatlands
98 (Boelter, 1964).

99 Knowledge on peat chemical and physical properties, as affected by the stages of land
100 conversion for oil palm cultivation, is necessary to develop effective peatland management,
101 and in the instance of degraded peatlands, restoration plans (Jauhianen *et al.*, 2008; GEC,
102 2014), thus conserving valuable ecosystem services. Land-use change in tropical peatlands is
103 commonly discussed from the perspective of carbon emissions, with a very limited literature
104 associated with peatland properties, and even fewer studies associated with multiple stages of
105 conversion. This study determines how peat chemical and physical properties are altered
106 during land conversion to oil palm. To achieve this we tested the following hypothesis: Land-
107 use change of secondary peat swamp forests by drainage, clearance of forest, and
108 establishment of mature oil palm plantations, which involve lowering of the water table and
109 altered litter inputs, will accelerate peat decomposition and reduce C storage in tropical
110 peatlands. As a consequence of land-use change to oil palm plantation, we predict greater
111 peat humification and loss of carbohydrates and carboxyl compounds relative to recalcitrant
112 aromatic structures reflecting enhanced microbial decomposition in drained surface peat
113 layers. We expect this enhanced decomposition to result in (i) peat subsidence and lower C
114 stocks in mature oil palm plantations compared to secondary forest sites and areas under the
115 initial stages of conversion and (ii) highest shear strength and bulk densities, but the lowest
116 porosity at oil palm sites.

117

118 **2. Study sites**

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

129 Stage 1. Forest sites – prior to conversion, intact secondary peat swamp forests.

130 Stage 2. Drained sites – extensive drainage of peat swamp forests where large drainage
131 ditches have been dug every few hundred meters in order to lower the water table, but
132 trees and dense shrubs are left relatively intact. In this case ditches were constructed *c.* 6
133 months prior to fieldwork.

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

137 Stage 4. Oil palm sites – fully mature oil palm plantations, in which drainage,
138 deforestation, and establishment of oil palm trees for more than five years has occurred
139 (age range of the sampling sites was estimated to between *c.* 5 and 12 years based on
140 height of the oil palms).

141 The tropical peat swamp forest sites were chosen in areas with as little anthropogenic impact
142 as possible in order to represent natural peat swamp systems. Prior to gaining reserve status in
143 1990 (Kumari, 1996), NSPSF was a stateland forest, subject to uncontrolled deforestation. As
144 a result forest cover varies in quality and *c.*500 km of drainage ditches originally cut for
145 timber transport remain as a legacy. However, the sites chosen for this study had not been
146 targeted for logging in approximately 40 years and as such are in areas of relatively high
147 canopy density (GEC, 2014). In addition, drainage schemes implemented for irrigation of
148 Tanjung Karang rice paddies near the coast have further contributed to the alteration of
149 peatland hydrology. As such, water storage and retention in NSPSF has been found to be
150 severely diminished (Rahim & Yusop 1999). Together, these disturbances have resulted in
151 secondary mixed swamp forests. It is also important to note that some degraded areas of the
152 NSPSF are being restored under a new integrated management plan (GEC, 2014) aiming to
153 restore ecosystem services by raising water tables through drain blocking, fire management
154 and replanting with native tree species.

155 During the early Holocene, the area was likely colonised by extensive mangrove systems, but
156 these diminished after the last Holocene interglacial marine incursion when the fresh water
157 peatland vegetation started to take hold, resulting in the deposition of acidic peat up to 5 m
158 deep, overlaying grey marine clay (Yule and Gomez, 2009). The area receives an average
159 rainfall of over 2000 mm per year, with the driest month in June measuring 76 to 191 mm
160 and the wettest month in November measuring 185 to 414 mm (Sim and Balamurugam,
161 1990; Yusop, 2002). Average shaded air temperature recorded was 28.5 °C, with an average
162 monthly relative humidity of 77.2% (Hahn-Schilling, 1994).

163

164 **3. Materials and Methods**

165 ***3.1. Field sampling***

166 Within each of the land conversion classes, five census plots with areas of 900 m² were
167 marked out during November and December of 2014. Random number tables were used to
168 determine the direction and distance to the south west corner of the plot, ensuring random
169 selection of the plot within the broader site. GPS coordinates were recorded for each corner;
170 locations for each plot are in Supplementary information 1.

171 In each of the census plots, a 1 dm³ block of surface peat and an entire peat core from surface
172 to underlying grey marine clay were collected. The 10x10x10 cm peat blocks were measured
173 with a ruler and carefully cut and lifted from the peat using a household bread knife and
174 trowel, before sealing in large zipper storage bags. Peat cores were extracted using a side-
175 filling Russian Peat Corer (Van Walt, UK) with a 50 cm long sampling chamber, allowing for
176 the recovery of deep, uncompressed peat cores. Peat depth was determined at every site,
177 recording the distance from the peat surface to the underlying clay layer. Immediately
178 following extraction, peat samples were divided into 10 cm segments in the field. Samples
179 were bagged and sealed to avoid moisture loss.

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

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

187 ***3.2. Laboratory analysis***

188 3.2.1. *Methods to determine peat chemical properties*

189 For total carbon (C) and nitrogen (N) determination, peat samples were first oven dried at 105
190 °C for 48 hours and then ball milled for homogenisation using a Planetary Ball Mill (Retsch-
191 PM400, Castleford, UK). Analysis of C and N concentrations in the peat samples was
192 performed using a total element analyzer (Thermo Flash EA 1112, CE Instruments, Wigan,
193 UK).

194 The degree of decomposition was quantified using two methods. First, the 10-point scale of
195 von Post (1922) was used to indicate peat structure by ranking the state of decay of organic
196 matter from H₁, very fibrous with little humification, to H₁₀, very few fibres with a high
197 humification degree. The higher the number in the von Post scale, the higher the degree of
198 humification (Huat *et al.*, 2011; Verry *et al.*, 2011; von Post, 1922). This was determined by
199 squeezing a small sample of field-wet peat and assessing the proportion of peat which
200 extruded through the fingers, the proportion left in the hand, and the colour and turbidity of
201 the free liquid (Verry *et al.*, 2011). The proportions of each fraction that determine the H
202 value has been translated from von Post (1922) into English and can be found in Stanek and
203 Silc (1977). H values were assessed for the surface peat blocks and through the entire peat
204 profile at 10 cm intervals.

205 Second, diffuse Reflectance Infrared Fourier Transform (DRIFT) spectroscopy was used to:
206 (i) determine the organic composition of surface peat, and (ii) assess if its organic chemistry
207 was altered by land conversion by comparing the relative abundance of carbohydrates and
208 carboxyls compounds to the abundance of aromatics. Specifically we calculated the
209 3340/1630 and 1710/1630 ratios, where the wavenumbers correspond to carbohydrates
210 (3340), carboxyls (1710) and aromatics (1630) (Cocozza *et al.*, 2003; Artz *et al.*, 2008). In

211 this instance, the higher the ratio, the higher the proportion of readily decomposable
212 compounds to aromatics, and the lower the degree of decomposition.

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

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

227 *3.2.2. Methods to determine peat physical properties*

228 Peat water content, bulk density, total porosity, and organic matter content were determined
229 for all surface peat blocks and entire peat columns at 10 cm intervals. Gravimetric water
230 content was assessed by oven drying the peat at 105°C for 48 hours. The peat mass was
231 recorded before and after oven drying and applied to Equation (1). Bulk density was
232 determined using the oven dried mass and known volumes, as in Equation (2). Total porosity
233 was derived from bulk density using Equation (3) and an average particle density for peat of
234 1.4 g cm^{-3} (Rowell, 1994). Organic matter contents were quantified using the loss on ignition

235 method. 5 g of oven dried, ball milled peat were weighed into porcelain crucibles, before
236 placing in a Carbolite AAF muffle furnace (Carbolite Ltd.) at 550 °C for 4 hours. The weight
237 of ash left after ignition was recorded and Equation (4) was used to determine the percentages
238 of organic matter.

239

$$240 \quad \Theta = \frac{M_w - M_d}{M_d} \times 100 \quad (1)$$

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

243

$$244 \quad \rho_{\text{bulk}} = \frac{M_d}{V} \quad (2)$$

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

247

$$248 \quad \phi = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{particle}}} \times 100 \quad (3)$$

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

251

252

$$253 \quad \text{OM} = \frac{M_1 - M_2}{M_1} \times 100 \quad (4)$$

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

256 *3.2.3 Estimating C stocks*

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

263 *3.3. Statistical analysis*

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

271 One-way analysis of variance (ANOVA) was used to determine significant differences in the
272 3340/1630 and 1710/1630 ratios among land conversion class. Two way ANOVAs were used
273 to analyse significant differences between land conversion class, depth, and their interaction,
274 allowing the incorporation of more than one discrete variable into the model. Continuous
275 profiles of data for von Post H values, gravimetric water content, bulk density, porosity, ash
276 and organic matter content with depth were categorised into three distinct groups in order to

277 run the two way ANOVA: surface peat, peat just below the water table, and the deepest peat
278 horizon which was above the clay layer (subsequently denoted “deep peat”).

279

280 **4. Results**

281 ***4.1. Peat chemical properties***

282 Peat pH values ranged from 3.4 to 3.7 at forest sites, rising to 3.7 to 4.1 at oil palm
283 plantations.

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

289 Surface peats (0-30 cm depth) from the oil palm plantations were more humified, i.e. had
290 higher H values on the van Post scale, than the other land conversion classes (Figure 2d), as
291 these were the only sapric surface peats whereas the others were classed as hemic (Wüst *et*
292 *al.*, 2003). Furthermore, drained, cleared and oil palm sites all had lower H values below the
293 water table than in the surface peat, with the largest H value reduction of up to 4 categories
294 within oil palm sites, before increasing with depth, indicating enhanced humification for
295 surface peats following onset of conversion. There was no difference in the degree of
296 decomposition between the first two depths of the forest sites but the extent of humification
297 increased with depth and was generally high throughout the profiles (Supplementary
298 information 2).

299 The DRIFT spectra showed that all peat samples had similar organic functional groups (Figure
300 3). Broad peaks were observed at approximately 3340 cm^{-1} which are associated with O–H
301 stretching of hydrogen in bonded O–H groups, specific to cellulose and other polysaccharides
302 (Vane, 2003). Two sharp peaks observed at 2920 and 2850 cm^{-1} were due to asymmetric and
303 symmetric C–H stretching of $-\text{CH}_2-$ groups from aliphatic compounds such as fats, waxes,
304 and lipids. Shoulders were observed at approximately 1710 cm^{-1} on the side of 1630 cm^{-1}
305 peaks, associated with C=O stretching of $-\text{COOH}$ or $-\text{COOR}$ groups present in carboxyl
306 compounds. Broader peaks at 1630 cm^{-1} were assigned to aromatic C=C stretching and
307 asymmetric $-\text{COO}-$ stretching of lignin and other aromatics. The distinct peak at 1510 cm^{-1}
308 were assigned to aromatic C=C stretching vibrations in lignins (Vane, 2003). Three peaks of
309 similar height and width were observed at 1450 , 1420 , and 1370 cm^{-1} , indicating O–H and C–
310 H deformations in aliphatic and phenolic structures (Artz *et al.*, 2008; Gandois *et al.*, 2013;
311 Vane, 2003).

312 The decomposition indexes, i.e. the $3340/1630$ (carbohydrate/aromatics) and $1710/1630$
313 (carboxyl/aromatics) ratios, in the surface peat differed significantly between land conversion
314 classes (Figures 4a and 4b). Specifically, the $3340/1630$ ratio were significantly higher in
315 forest and cleared sites (12.3 ± 1.2 and 16.4 ± 3.2 respectively), relative to drained and oil palm
316 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
317 aromatic structures relative to carbohydrates in drained and oil palm acrotelms (Figure 4a).
318 $1710/1630$ ratios were significantly higher in the surface peats of cleared sites (1.8 ± 0.2),
319 relative to other sites with ratios between 1.0 and 1.1 ± 0.1 ($F_{(3,16)}=5.62$, $P=0.008$, $r^2=0.51$),
320 which suggests higher proportions of carboxyl groups relative to aromatic compounds within
321 acrotelms at cleared sites (Figure 4b).

322 ***4.2 Peat depth and C stocks***

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

331 ***4.3 Peat physical properties***

332 The position of the water table at the time the peat cores were collected was 6.0 ± 22 , $-14 \pm$
333 23 , -39 ± 15 , and -21 ± 18 cm at the forest, drained, cleared, and oil palm sites, respectively,
334 with positive values indicating the water surface being above the peat ($F_{(3,44)}=5.45$, $P<0.05$).
335 The position of the water table was reflected in the volumetric surface moisture content
336 which was 82.3 ± 28 , 46.3 ± 22 , 33.3 ± 9 , and 56.56 ± 21 % at the forest, drained, cleared,
337 and oil palm sites, respectively. Shear strength was significantly different among land
338 conversion classes ($F_{(3,20)}=3.49$, $P=0.035$, $SED=0.959$ using volumetric water content as a
339 covariate), with higher values found at the oil palm plantations (9.7 ± 0.6 kPa) than the other
340 land conversion classes (8.4 ± 0.6 , 6.8 ± 0.9 , and 7.8 ± 0.6 kPa for forest, drained and recently
341 cleared sites, respectively).

342 Surface organic matter content was highest at forest sites ($94.1 \pm 1.5\%$) and lowest in oil palm
343 plantations ($77.3 \pm 5.9\%$) (Figure 6a). In line with the field measurements of volumetric soil
344 moisture content, forest sites had significantly higher water content (627 ± 90) in the surface
345 layer than oil palm sites (440 ± 42) (Figure 6b; Supplementary information 5). Peat at drained
346 and cleared sites had higher moisture content below the water table, than at the mature oil

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

354

355 5. Discussion

356 5.1. Changes in peat organic chemistry, humification, and C stocks following land use 357 change

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

371 The higher degrees of humification (higher H values on the von Post scale, Figure 2d) and
372 lower organic matter contents (Figure 6a) in the drained surface layer at the drained, cleared
373 and oil palm sites provides further evidence that the conversion process stimulated
374 decomposition. However, the enhanced decomposition following drainage was only evident
375 when comparing forest to mature oil palm plantation, which suggests that C loss from
376 oxidative decay is controlled in part by exposure time to air, as well as being influenced by
377 fertiliser inputs, which also enhance decomposition (Wösten *et al.*, 1997; Anshari *et al.*,
378 2010; Corley *et al.*, 2003). The greater degree of humification in surface peats relative to the
379 deeper peat layers of drained and cleared forest, and oil palm indicates loss of structure and

380 enhanced decomposition rates in surface peats (Figure 2d). This contrasts to the forested sites
381 with water tables close to or at the peat surface, where the greatest decomposition degree was
382 found in the deepest layers of peat (Kuhry and Vitt, 1996).

383 Although the H values were highest at the surface of the oil palm sites, the high degree of
384 decomposition (H values ranging from about 7 to 10) found throughout the entire forest peat
385 profiles (Appendix: Figure 1a) are intriguing as they contrast to studies of temperate and
386 boreal peatlands where surface peat tends to have much lower H values (Kuhry and Vitt,
387 1996; Frohking *et al.*, 2001). The DRIFT spectra presented in Figure 3 display the majority of
388 peaks corresponding to temperate peatlands (Artz *et al.*, 2008; Coccozza *et al.*, 2003).

389 However, the latter usually show an additional broad peak between 1080 and 1030 cm^{-1}
390 which is not prominent here. This peak is assigned to C–O stretching and O–H deformation
391 within polysaccharides (Artz *et al.*, 2008) and its low intensity in all surface peats, including
392 forest sites, suggests rapid decomposition of polysaccharides in line with the high H values.
393 This could be due to impacts of historical logging activities prior to the 1980s or to vegetation
394 structure and litter inputs. Furthermore, peat swamp forests have both increased aeration
395 associated with large tree roots (Hoyos-Santillan *et al.*, 2016), and an open pore structure
396 provided by the fibrous wood input (in contrast to the shallow rooted, less fibrous sphagnum
397 moss that dominates northern peatlands (Wüst *et al.*, 2003)), which together may contribute
398 to aerobic microbial decay throughout the rhizosphere. The early decay of polysaccharides
399 observed here as compared to temperate peatlands may also be enhanced by the higher
400 ambient air temperatures in Malaysia. For example, fungal decay studies have shown that
401 aerobic oxidative degradation of polysaccharides by white and soft rot fungi (the most
402 vigorous of all wood-decay microbes) is optimal at temperatures between 20 to 40°C (Vane,
403 2003; Vane *et al.*, 2001). Similarly, a study of carbon cycling in tropical mangroves showed
404 that arboreal termites cause extensive polysaccharide decay in leaf and wood litter due to

405 symbiotic bacteria; this suggests that in tropical environments, litter may undergo extensive
406 multi-phase (insectivorous and microbial) alteration prior to burial (Vane *et al.*, 2011).

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

424

425 The large reductions in peat depth, of up to 2 m after 25 years of oil palm cultivation on
426 drained peatland, demonstrated by Hooijer *et al.* (2012) further support the notion of dramatic
427 C losses due to peat oxidation following drainage. Although the original peat depths at the oil
428 palm sites are not known, peat depths in adjacent peatland areas (ca. 1-2 km away from the

429 oil palm sites) are ca. 4 m (unpublished data not included in this study, Sofie Sjogersten)
430 indicating that rapid peat subsidence and C losses have occurred during the establishment of
431 mature oil palm plantations. Importantly, C loss rates measured in our study were higher than
432 those reported for Central Kalimantan, Indonesia of $10.8 \pm 3.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ (Hergoualc'h
433 and Verchot 2011) and the loss rates of $1400 \text{ Mg C ha}^{-1}$ over 100 years predicted by
434 modelling studies by Kurinanto *et al.* (2015) indicating that substantial C loss can occur
435 quickly following conversion of peat swamp forests to oil palm plantations. Our findings
436 contrasts starkly to the minor changes in C stocks in mineral soil following conversion of
437 forest to oil palm plantation in Indonesia (53.63 ± 5.98 and $51.85 \pm 18.95 \text{ Mg C ha}^{-1}$ in forest
438 and oil palm plantations, respectively; Khasanah *et al.*, 2015). Indeed, our peatland study
439 strongly refutes the concept of C neutral oil palm plantations, as suggested for mineral soil
440 systems by Khasanah *et al.* (2015). The large C losses from the peat shown in our study,
441 together with losses of the large tree biomass held in intact peat swamp forests (ranging
442 between 125 to 160 Mg C ha^{-1} assuming a 50% C content in the vegetation; Kauffman *et al.*,
443 2011; Kornseder *et al.*, 2012; Toriyama *et al.*, 2014; Schlund *et al.*, 2015), is nowhere near
444 replaced by oil palm vegetation, which has an estimated life span above ground biomass of
445 $30 \pm 10 \text{ Mg C ha}^{-1}$ (Germer and Sauerborn 2008). Indeed, this investigation points towards a
446 substantial C footprint of oil palm plantations on tropical peatlands.

447 ***5.2.Changes in peat physical properties following land use change***

448 The peat porosity and bulk density at forest sites were comparable to those found in tropical
449 peatlands in Malaysia and elsewhere. For example, Firdaus *et al.* (2010) found porosities and
450 bulk densities of $91.5 \pm 1.8\%$ and $0.112 \pm 0.004 \text{ g cm}^{-3}$, respectively, in forest surface peats.
451 Other tropical peat studies have found bulk densities ranging from 0.02 to 0.21 g cm^{-3} ,
452 correlating with this study (Page *et al.*, 2004; Rieley and Page, 2008; Wösten *et al.*, 2008;
453 Page *et al.*, 2011). Decomposition decreases the proportion of coarse, hollow fibres in peat as

454 organic particle size and organic matter content (Figure 6a) is reduced with land conversion,
455 and is expected to form a dense, closed soil structure (Huat *et al.*, 2011). In this study,
456 enhanced decomposition, potentially in combination with compaction from machinery,
457 following land conversion resulted in greater shear strength and lower soil moisture content
458 in the surface peat layer at oil palm sites. The lack of a linear response of porosity and bulk
459 density as land conversion progressed from intact peat swamp forest, through forest drainage
460 and clearance, to mature oil palm (Figures 6c and 6d), may be linked to initial subsidence of
461 the drained peat layers below the surface network of roots resulting in high porosity and low
462 bulk density. We speculate that the subsequent decreased porosity and increased bulk density
463 at the cleared and oil palm sites are due to the removal of lignified root biomass during the
464 ground preparation, together with greater decomposition rates, resulting in denser peats over
465 time (Huat *et al.*, 2011; Quinton *et al.*, 2000). It is also worth noting that the gradual
466 reduction in peat gravimetric moisture content and porosity moving from drained to oil palm
467 sites, is also evident below the water table, which may be linked to peat subsidence following
468 drainage (Wösten *et al.*, 1997).

469 These findings demonstrate that land conversion for oil palm plantations changed peat
470 physical properties over time through a combination of physical collapse of the peat structure
471 following drainage, and enhanced decomposition in the drained surface peats. It is likely that
472 such changes in peat physical properties are irreversible, particularly in the instance of
473 changes caused by enhanced decomposition. This has important implications for land
474 management policies, as some ecosystem services linked to the peat physical properties, e.g.
475 water holding capacity (Abdul Rahim & Yusop 1999), may be permanently, and negatively,
476 affected by land conversion for oil palm plantation. Indeed, peatland restoration, which is
477 currently implemented at degraded peatland sites across SE Asia (e.g. Jauhianen *et al.*, 2008)
478 and specifically within this study catchment (GEC 2014), may recover the biodiversity, fire

479 regulation and C sink capacity of peatlands, however, this may not be the case for the water
480 regulation services as these closely link to peat organic matter content, structure, density and
481 porosity (Firdaus *et al.*, 2010).

482

483 **Acknowledgements**

484 We thank the Royal Geographical Society (with IBG) for funding this project through the
485 Ralph Brown expedition award (to PA), with additional support from the University of
486 Nottingham. We are very grateful to the Selangor State Forestry Department for granting
487 forest reserve access and in providing field ranger support (including Mr Mohd Rosli B. Md
488 Kadim (Rosli), Mr Sabaruddin Mohd Shahid (Din) and the rest of the team at Raja Musa and
489 Sungai Karang Forestry Offices) as a follow-up to the 2013 Biodiversity Expedition
490 organised in association with Malaysia Nature Society; and also to staff at the Global
491 Environment Centre, Selangor, ~~and especially Miss Hannah Cooper~~, for fieldwork assistance.
492 We also thank PKPS Agricultural Development Corporation for granting site access. We are
493 grateful to Mr James Verran, Mr Saul Vazquez Reina and Mr John Corrie for assistance in
494 the laboratory. CHV publishes with permission of the Executive Director, British Geological
495 Survey (NERC).

496

497 **References**

498 Abdul Rahim, N. & Yusop, Z., 1999. Hydrological impacts of forestry and land-use
499 activities: Malaysian and regional experience, 86-105. In: Water: forestry and land use
500 perspectives; Technical documents in hydrology; Vol.:70; 2004, Available at:
501 <http://unesdoc.unesco.org/images/0013/001379/137954e.pdf> [Accessed April 10, 2016]

502 Ahmad, N. (2014) *Guardians of the North Selangor Peat Swamp Forest* [online]. Peatlands
503 International, Issue 2.2014. Available at:
504 <https://peatlandsinternational.wordpress.com/2014/06/20/peatlands-international-2-2014/>>
505 [accessed 17 April 2015].

506 Andriesse, J. (1988) *Nature and management of tropical peat soils* [online]. FAO Soils
507 Bulletin 59. FAO - Food and Agriculture Organization of the United Nations, Rome.
508 Available at: <<http://www.fao.org/docrep/x5872e/x5872e00.htm#Contents>> [Accessed 16
509 October 2014].

510 Anshari, G., Afifudin, M., Nuriman, M., Gusmayanti, E., Arianie, L., Susana, R., Nusantara,
511 R., Sugardjito, J., and Rafiastanto, A. (2010) Drainage and land use impacts on changes in
512 selected peat properties and peat degradation in West Kalimantan Province, Indonesia.
513 *Biogeosciences*. Vol. 7, no. 11, pp. 3403-3419.

514 Artz, R., Chapman, S., Robertson, A., Potts, J., Laggoun-Défarage, F., Gogo, S., Comont, L.,
515 Disnar, J., and Francez, A. (2008) FTIR spectroscopy can be used as a screening tool for
516 organic matter quality in regenerating cutover peatlands. *Soil Biology and Biochemistry*.
517 Vol. 40, no. 2, pp. 515-527.

518 Boelter, D. (1964) Water storage characteristics of several peats in situ. *Soil Science Society*
519 *of America Journal*. Vol. 28, no. 3, pp. 433-435.

520 Broder, T., Blodau, C., Biester, H., and Knorr, K. (2012) Peat decomposition records in three
521 pristine ombrotrophic bogs in southern Patagonia. *Biogeosciences*. Vol. 9, no. 4, pp. 1479-
522 1491.

523 Corley, R. Hereward V., and Tinker, P. (2003) *The Oil Palm*. 4th edition. Blackwell Science
524 Ltd.

525 Coccozza, C., D'orazio, V., Miano, T., and Shotyk, W. (2003) Characterization of solid and
526 aqueous phases of a peat bog profile using molecular fluorescence spectroscopy, ESR and
527 FT-IR, and comparison with physical properties. *Organic Geochemistry*. Vol. 34, no. 1, pp.
528 49-60.

529 Douglas, I. (1996) The impact of land-use changes, especially logging, shifting cultivation,
530 mining and urbanization on sediment yields in humid tropical Southeast Asia: a review with
531 special reference to Borneo. *IAHS Publications-Series of Proceedings and Reports-Intern*
532 *Assoc Hydrological Sciences*. Vol. 236, pp. 463-472.

533 Firdaus, M., Gandaseca, S., Ahmed, O., and Majid, N. (2010) Effect of converting secondary
534 tropical peat swamp forest into oil palm plantation on selected peat soil physical
535 properties. *American Journal of Environmental Sciences*. Vol. 6, no. 4, pp. 402-405.

536 Frohking, S., Roulet, N., Moore, T., Richard, P., Lavoie, M., and Muller, S. (2001) Modeling
537 northern peatland decomposition and peat accumulation. *Ecosystems*. Vol. 4, no. 5, pp. 479-
538 498.

539 Gandois, L., Cobb, A., Hei, I., Lim, L., Salim, K., and Harvey, C. (2013) Impact of
540 deforestation on solid and dissolved organic matter characteristics of tropical peat forests:
541 implications for carbon release. *Biogeochemistry*. Vol. 114, no. 1-3, pp. 183-199.

542 GEC (Global Environment Centre), 2014. Integrated Management Plan for North Selangor
543 Peat Swamp Forest 2014-2023 for Selangor State Forestry Department. , (June), p.183.

544 Haddaway, N., Burden, A., Evans, C., Healey, J., Jones, D., Dalrymple, S., and Pullin, A.
545 (2014) Evaluating effects of land management on greenhouse gas fluxes and carbon balances
546 in boreo-temperate lowland peatland systems. *Environmental Evidence*. Vol. 3, no. 1, pp. 5.

547 Hahn-Schilling, B. (1994) Struktur, sukzessionale Entwicklung und Bewirksamkeit selektiv
548 genutzter Moorwälder in Malaysia. Göttinger Beiträge zur Land- und Forstwirtschaft in den
549 Tropen und Subtropen, Heft 94. Dissertation. Verlag Erich Goltze GmbH & Co. KG,
550 Göttingen.

551 Holden, J., Chapman, P., and Labadz, J. (2004) Artificial drainage of peatlands: hydrological
552 and hydrochemical process and wetland restoration. *Progress in Physical Geography*. Vol.
553 28, no. 1, pp. 95-123.

554 Huat, B., Kazemian, S., Prasad, A., and Barghchi, M. (2011) State of an art review of peat:
555 General perspective. *International Journal of the Physical Sciences*. Vol. 6, no. 8, pp. 1988-
556 1996.

557 Jauhiainen, J., Takahashi, H., Heikkinen, J., Martikainen, P., and Vasander, H. (2005) Carbon
558 fluxes from a tropical peat swamp forest floor. *Global Change Biology*. Vol. 11, no. 10, pp.
559 1788-1797.

560 Jauhiainen, J., Limin, S., Silvennoinen, H., and Vasander, H. (2008) Carbon dioxide and
561 methane fluxes in drained tropical peat before and after hydrological restoration. *Ecology*.
562 Vol. 89, no. 12, pp. 3503-3514.

563 Keddy, P., Fraser, L., Solomeshch, A., Junk, W., Campbell, D., Arroyo, M., and Alho, C.
564 (2009) Wet and wonderful: the world's largest wetlands are conservation priorities.
565 *BioScience*. Vol. 59, no. 1, pp. 39-51.

566

567 Koh, L.P., Miettinen, J., Liew, S.C., Ghazoul, J. (2011) Remotely sensed evidence of tropical
568 peatland conversion to oil palm. *Proceedings of the National Academy of Sciences of the*
569 *United States of America*, 108(12), pp.5127–32. Available at:

570 [http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3064377&tool=pmcentrez&rende](http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3064377&tool=pmcentrez&rendertype=abstract)
571 [rttype=abstract](http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3064377&tool=pmcentrez&rendertype=abstract) [Accessed April 6, 2016].

572 Kuhry, P., and Vitt, D. (1996) Fossil carbon/nitrogen ratios as a measure of peat
573 decomposition. *Ecology*. Vol. 77, no. 1, pp. 271-275.

574 Kumari, K. 1996. An application of the incremental cost framework to biodiversity
575 conservation: a wetland case study in Malaysia. Centre for Social and Economic Research on
576 the Global Environmental, 96-15.

577 Page, S., Siegert, F., Rieley, J., Böhm, H., Jaya, A., Limin, S. (2002) The amount of carbon
578 released from peat and forest fires in Indonesia in 1997. *Nature*. Vol. 420, no. 6911, pp. 61–
579 65.

580 Page, S., Wüst, R., Weiss, D., Rieley, J., Shotyk, W., and Limin, S. (2004) A record of Late
581 Pleistocene and Holocene Carbon accumulation and climate change from an equatorial peat
582 bog (Kalimantan, Indonesia): Implications for past, present and future carbon dynamics.
583 *Journal of Quaternary Science*. Vol. 19, no. 7, pp. 625–636.

584 Page, S., Rieley, J., and Wüst, R. (2006) Lowland tropical peatlands of Southeast Asia. In:
585 Martini, P., Martinez-Cortizas, A., and Chesworth, W. (editors), *Peatlands: basin evolution*
586 *and depository of records on global environmental and climatic changes*. Amsterdam
587 (Developments in Earth Surface Processes Series): Elsevier. pp. 145–72.

588 Posa, M., Wijedasa, L.S. and Corlett, R.T., 2011. Biodiversity and Conservation of Tropical
589 Peat Swamp Forests. *BioScience*, 61(49), pp.49–57.

590 Price, J., and Schlotzhauer, S. (1999) Importance of shrinkage and compression in
591 determining water storage changes in peat: the case of a mined peatland. *Hydrological*
592 *Processes*. Vol. 13, no. 16, pp. 2591-2601.

593 Quinton, W., Gray, D., and Marsh, P. (2000) Subsurface drainage from hummock-covered
594 hillslopes in the Arctic tundra. *Journal of Hydrology*. Vol. 237, no. 1, pp. 113-125.

595 Rieley, J. and Page, S. (2008) *Master Plan for the Rehabilitation and Revitalisation of the*
596 *Ex-Mega Rice Project Area in Central Kalimantan* [online]. CARBOPEAT Technical
597 Review No. 1. The Science of Tropical Peatlands and the Central Kalimantan Peatland
598 Development Area. Euroconsult Mott MacDonald/Defltares/Delft Hydraulics. Available at:
599 <http://www.geog.le.ac.uk/carbopeat/media/pdf/pub_technical_review%201-science.pdf>
600 [Accessed 30 April 2015].

601 Rowell, D. (1994) The arrangement of particles and pores: soil structure. In: Rowell, D.
602 (editor), *Soil Science: Methods and Applications*. Essex, England, Longman Scientific and
603 Technical, pp. 61.

604 Sim, L., and Balamurugam, G. (1990) Hydrological functions. In: Prentice, C. (editor),
605 *Environmental action plan for the North Selangor peat swamp forest*. AWB Publication,
606 Asian Wetland Bureau/WWF—Malaysia.

607 Stanek, W., and Silc, T. (1977) Comparisons of four methods for determination of degree of
608 peat humification (decomposition) with emphasis on the von Post method. *Canadian Journal*
609 *of Soil Science*. Vol. 57, no. 2, pp. 109-117.

610 Tipping, E., Smith, E., Lawlor, A., Hughes, S., and Stevens, P. (2003) Predicting the release
611 of metals from ombrotrophic peat due to drought-induced acidification. *Environmental*
612 *Pollution*. Vol. 123, no. 2, pp. 239-253.

613 Vane, C. (2003a) Monitoring decay of black gum wood (*Nyssa sylvatica*) during growth of
614 the shiitake mushroom (*Lentinula edodes*) using diffuse reflectance infrared
615 spectroscopy. *Applied spectroscopy*. Vol. 57, no. 5, pp. 514-517.

616 Vane, C. (2003b). The molecular composition of lignin in spruce decayed by white-rot fungi
617 (*Phanerochaete chrysosporium* and *Trametes versicolor*) using Pyrolysis–GC–MS and
618 Thermochemolysis with Tetramethylammonium Hydroxide. *International Biodeterioration*
619 *and Biodegradation*. Vol. 51, no 1, pp. 67-75.

620 Vane, C., Martin, S., Snape, C., Abbott, G.D. (2001) Degradation of lignin in wheat straw
621 during growth of the Oyster mushroom (*Pleurotus ostreatus*) using off-line
622 thermochemolysis with tetramethylammonium hydroxide and solid state ¹³C NMR. *Journal*
623 *of Agriculture and Food Chemistry*. Vol. 49, pp. 2709-2716.

624 Vane, C.H., Kim, A.W., Moss-Hayes V, Snape C.E, Castro-Diaz, M., Khan, N.S., Engelhart
625 S.E. and Horton, B.P. 2013. Mangrove tissue decay by arboreal termites (*Nasutitermes*
626 *acajutlae*) and their role in the mangrove C cycle (Puerto Rico): Chemical characterisation
627 and organic matter provenance using bulk $\delta^{13}\text{C}$, C/N, alkaline CuO oxidation-GC/MS and
628 solid-state ¹³C NMR. *Geochemistry, Geophysics, Geosystems* Vol. 14, no 8, pp. 3176-3191.

629 Verry, E., Boelter, D., Päivänen, J., Nichols, D., Malterer, T., and Gafni, A. (2011) Physical
630 Properties of Organic Soils. In: Kolka, R., Sebestyen, S., Verry, E., and Brooks, K. (editors),
631 *Peatland Biogeochemistry and Watershed Hydrology at the Marcell Experimental Forest*.
632 United States of America, CRC Press: Taylor and Francis Group, pp. 136 -137.

633 von Post, L. (1922) Sveriges Geologiska Undersöknings torvinventering och några av dess
634 hittills vunna resultat. Svenska Mosskulturforeningens, Tidskrift. Vol. 1, pp. 1-27.

635 Wetlands International (2014) *Tropical Peat Swamp Forests* [online]. Wetlands International,
636 Netherlands. Available at:
637 <[http://www.wetlands.org/Whatarewetlands/Peatlands/Tropicalpeatswampforests/tabid/2739/](http://www.wetlands.org/Whatarewetlands/Peatlands/Tropicalpeatswampforests/tabid/2739/Default.aspx)
638 [Default.aspx](http://www.wetlands.org/Whatarewetlands/Peatlands/Tropicalpeatswampforests/tabid/2739/Default.aspx)> [Accessed 02 November 2014].

639 Wösten, J., Ismail, A., and Van Wijk, A. (1997) Peat subsidence and its practical
640 implications: a case study in Malaysia. *Geoderma*. Vol. 78, no. 1-2, pp. 25-36.

641 Wösten, J., Clymans, E., Page, S., Rieley, J., and Limin, S. (2008) Peat–water
642 interrelationships in a tropical peatland ecosystem in Southeast Asia. *Catena*. Vol. 73, no. 2,
643 pp. 212-224.

644 Wüst, R., Bustin, R., and Lavkulich, L. (2003) New classification systems for tropical
645 organic-rich deposits based on studies of the Tasek Bera Basin, Malaysia. *Catena*. Vol. 53,
646 no, 2, pp.133-163.

647 Yonebayashi, K., Pechayapisit, J., Vijarnsorn, P., Zahari, A., and Kyuma, K. (1994)
648 Chemical alterations of tropical peat soils determined by Waksman's proximate analysis and
649 properties of humic acids. *Soil Science and Plant Nutrition*. Vol. 40, no. 3, pp. 435-444.

650 Yule, C., and Gomez, L. (2009) Leaf litter decomposition in a tropical peat swamp forest in
651 Peninsular Malaysia. *Wetlands Ecology and Management*. Vol. 17, no. 3, pp. 231-241.

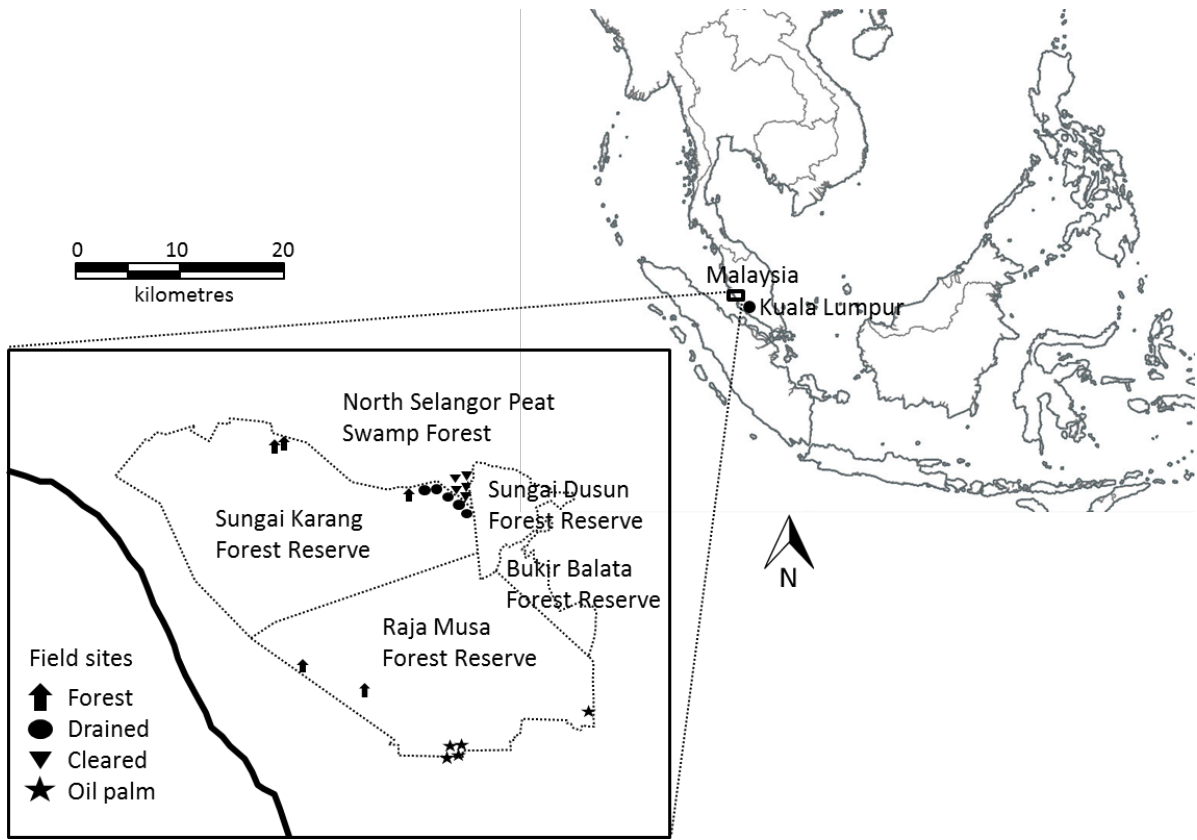
652 Yusop, Z. (2002) Hydrological attributes of a disturbed peat swamp forest. In: Parish, F.,
653 Padmanabhan, E., Lee, C., and Thang, H. (editors), *Prevention and control of fire in*
654 *peatlands*. Proceedings of workshop on prevention and control of fire in peatlands, 19–21
655 March 2002, Kuala Lumpur. Global Environment Centre and Forestry Department Peninsular
656 Malaysia. Cetaktama, Kuala Lumpur, pp. 51–56.

657 Zhang, R. (1997) Determination of soil sorptivity and hydraulic conductivity from the disk
658 infiltrometer. *Soil Science Society of America Journal*. Vol. 61, no. 4, pp. 1024-1030.

659

660 **Figures**

661



662

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

664

665

666

667

668

669

670

671

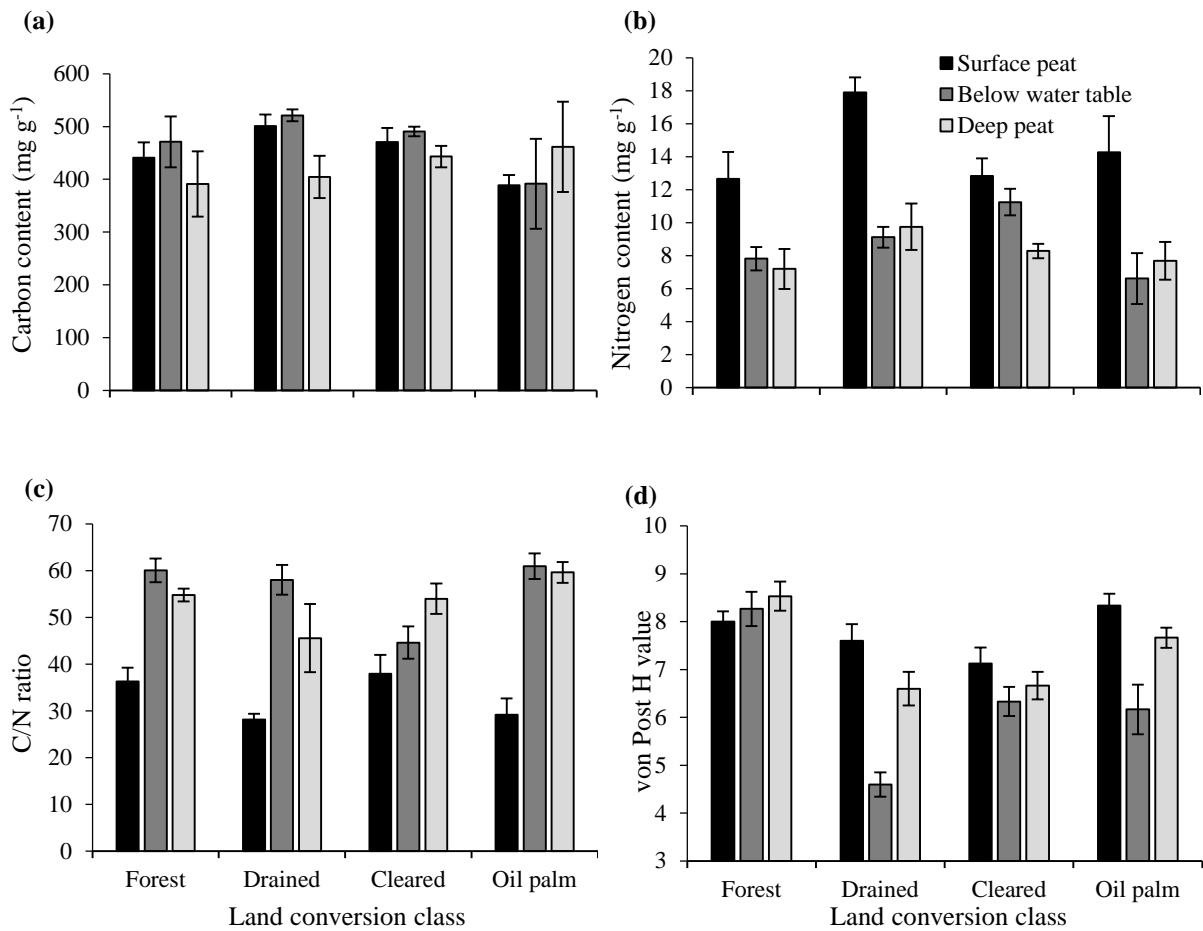
672

673

674

675

676



677

678

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

684 (a) Land conversion class: $F_{(3,44)}=1.97$, $P=0.133$; Depth: $F_{(2,44)}=2.26$, $P=0.116$; Interaction: $F_{(6,44)}=0.84$,
 685 $P=0.544$

686 (b) Land conversion class: $F_{(3,44)}=3.25$, $P=0.031$; Depth: $F_{(2,44)}=28.21$, $P<0.001$; Interaction: $F_{(6,44)}=1.61$,
 687 $P=0.166$

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

689

690 (d) Land conversion class: $F_{(3,269)}=56.77$, $P<0.001$; Depths: $F_{(2,269)}=92.87$, $P<0.001$; Interaction: $F_{(6,269)}=12.08$,
691 $P<0.001$

692

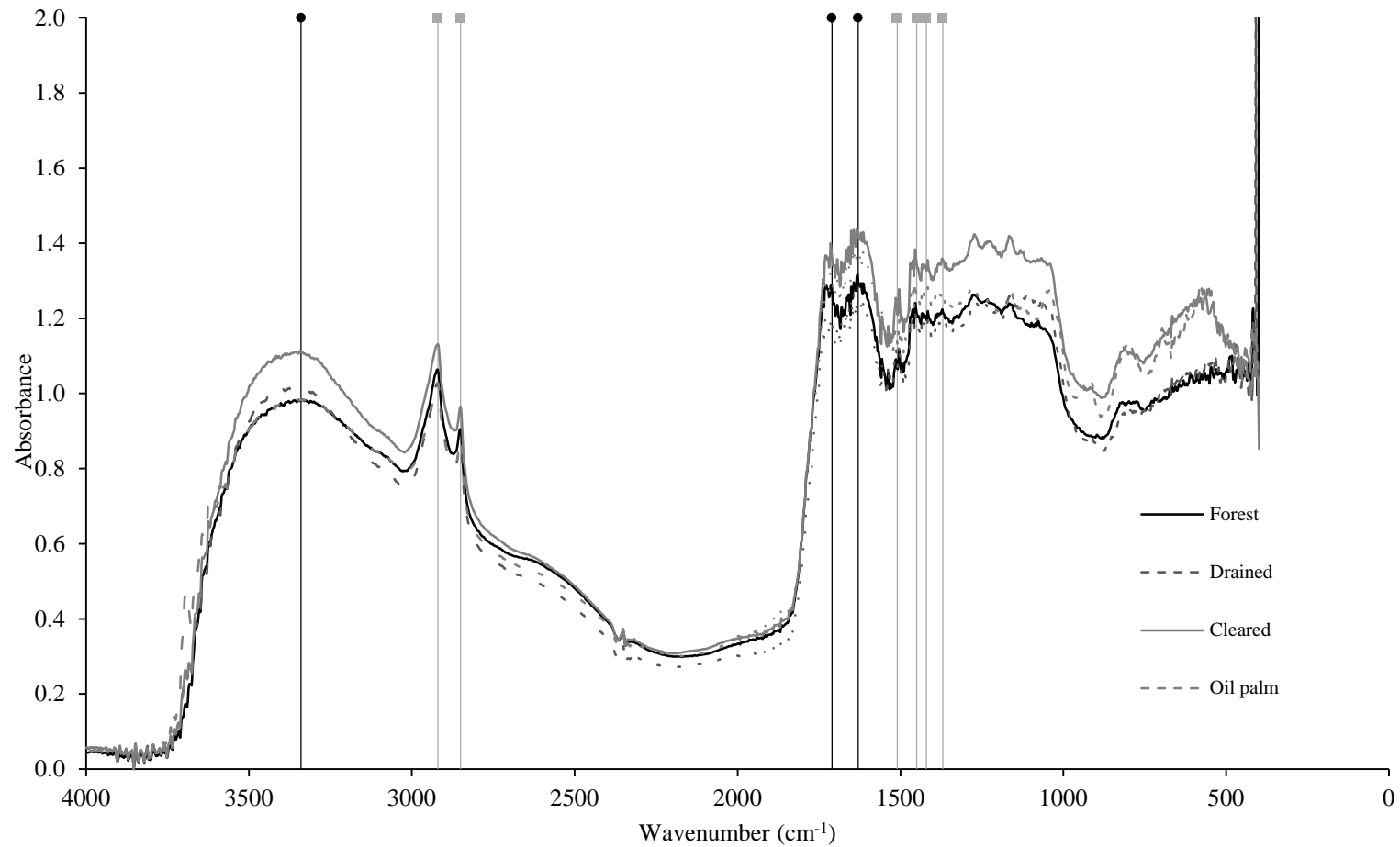


Figure3: DRIFT spectra of the average surface peat samples from 0-10 cm for: secondary peat swamp forests (black line), drained peat swamp forests (black dashed line), cleared peat swamp forests (grey line), and mature oil palm plantations (grey dashed line). Vertical black lines indicate the peaks at 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.

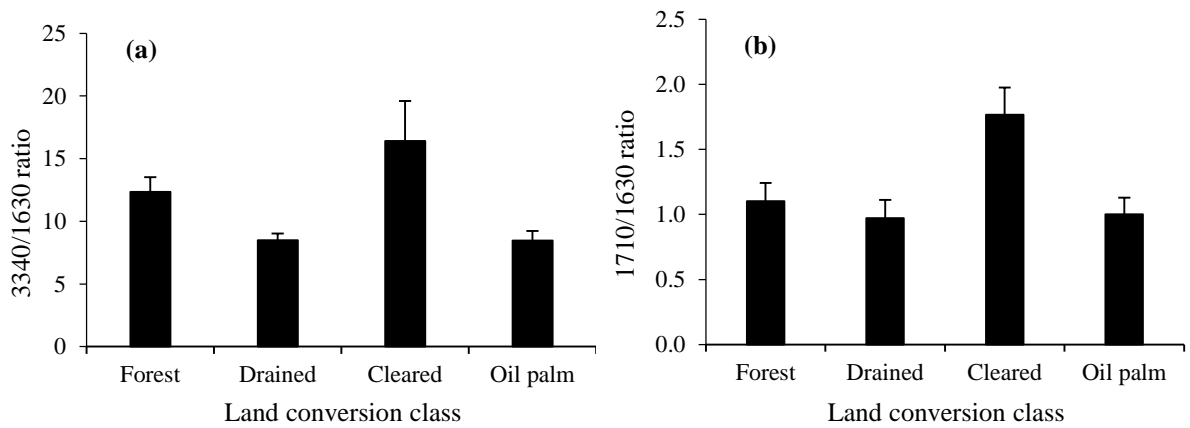


Figure 4: The difference in (a) 3340/1630 ratio or carbohydrate/aromatic ratio; and (b) 1710/1630 or carboxyl/aromatic ratio between secondary peat swamp forests, drained peat swamp forests, cleared peat swamp forests, and mature oil palm plantations in surface peat. Average values for land conversion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

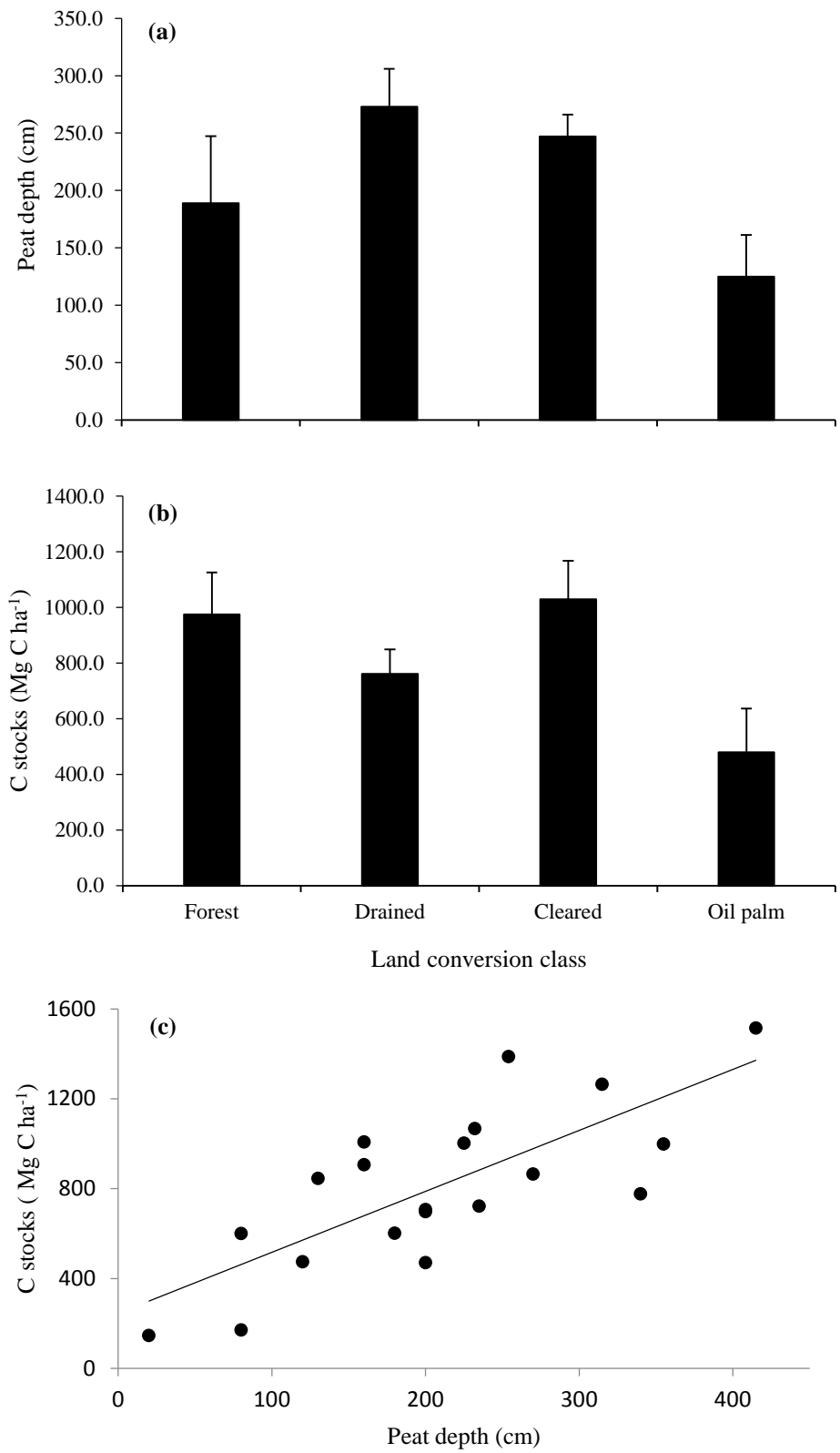


Figure 5: (a) Peat depth; and (b) C stocks at the different land conversion classes. Average values for land conversion classes and standard error bars are shown. Significant differences among land conversion classes: (a) $F_{(3,19)}=2.81$, $P = 0.07$; (b) $F_{(3,19)}=4.11$, $P=0.02$. (c) Relationship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

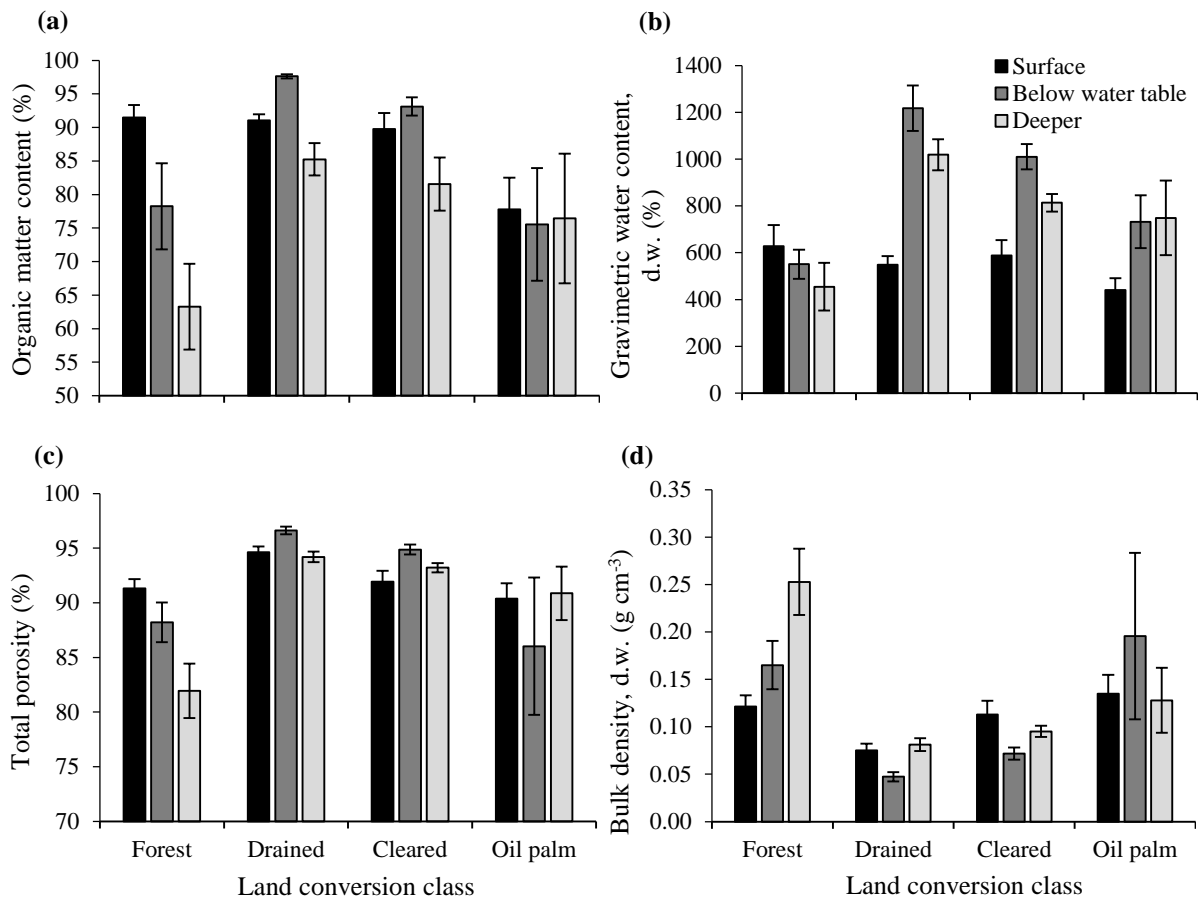


Figure 6: The difference in (a) organic matter content; (b) gravimetric water content (dry weight basis); (c) total porosity; and (d) bulk density (dry weight basis) between secondary peat swamp forests, drained peat swamp forests, cleared peat swamp forests, and mature oil palm plantations at three 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: $F_{(3,156)}=19.43$, $P<0.001$; Depth: $F_{(2,156)}=4.33$, $P=0.015$; Interaction: $F_{(6,156)}=2.21$, $P=0.044$
- (d) Land conversion class: $F_{(3,156)}=21.47$, $P<0.001$; Depth: $F_{(2,156)}=5.47$, $P=0.005$; Interaction: $F_{(6,156)}=2.22$, $P=0.044$