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1 **Carbon balance of tropical peat forests at different fire history and implications**
2 **for carbon emissions**

3

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16

17 **Abstract**

18 Accurate assessment of tropical peat forest carbon stocks and impact of fires on carbon pools
19 is required to determine the magnitude of emissions to the atmosphere and to support
20 emissions reduction policies. We assessed total aboveground carbon (AGC) in biomass pools
21 including trees, shrubs, deadwood, litter and char, and peat carbon to develop empirical
22 estimates of peat swamp forest carbon stocks in response to fire and disturbance. In contrast
23 to the common assumption that peat fires combust all AGC, we observed that about half of
24 undisturbed forest AGC, equivalent to about 70 Mg C ha⁻¹, remains after one or two recent
25 fires – mainly in dead trees, woody debris and pyrogenic carbon. Both recently burnt and
26 repeatedly burnt peat forests store similar amounts of carbon in the top 10 cm of peat when
27 compared with undisturbed forests (70 Mg C ha⁻¹), mainly due to increased peat bulk density
28 after fires that compensates for their lower peat C%.

29
30 The proportion of fuel mass consumed in fire, or combustion factor (CF), is required to make
31 accurate estimates of peat fire emissions for both AGC and peat carbon. This study estimated
32 a CF for AGC (CF_{AGC}) of 0.56, comparable to the default value of the Intergovernmental
33 Panel on Climate Change (IPCC). This study estimated a varying CF for peat (CF_{PEAT}) that
34 ranged from 0.4 to 0.68 as depth of burn increased. This revised CF_{PEAT} is one third to one
35 half of the IPCC default value of 1.0. The current assumption of complete combustion of peat
36 (CF=1.0) is widely acknowledged in the literature as oversimplification and is not supported
37 by our field observation or data. This study provides novel empirical data to improve
38 estimates of peat forests carbon stocks and emissions from tropical peat fires.

39

40 *Keywords:* Indonesia, peat swamp forests, pyrogenic carbon, fire emissions, CWD,
41 deadwood, repeated fires

42 **Introduction**

43 Tropical peat forests are areas of high carbon (C) density and play an important role in global
44 terrestrial carbon balance. With an estimated C pool of 57 Gt, or 65% of the global total,
45 Indonesia has by far the largest share of global tropical peat forests (Page *et al.* 2011).

46 Continued drainage of peatlands for agriculture and plantation development, coupled with
47 global warming causes drying of peat forest over extensive areas, making them susceptible to
48 fires. Regional droughts in Indonesia in the 1990's and throughout the early 21st century
49 resulted in an unprecedented increase in peat fires, affecting both natural forests and forested
50 lands undergoing conversion to other land uses, with smoke and pollution affecting not only
51 Indonesia but all Southeast Asia (Khan *et al.* 2020). Improving the knowledge base of peat
52 carbon balance and reducing emissions from peatlands is an international priority of the
53 United Nations (FAO and Wetlands International 2012). However, despite strong
54 international commitment to reduce emissions from peatlands, there has been limited
55 progress towards improving the knowledge base of tropical peat forest carbon balance for
56 reducing uncertainty in peat fire emissions estimates (Volkova *et al.* 2021).

57

58 It has been estimated that peat fires of 1997 El Nino events released an equivalent of 13–40%
59 of the mean annual global carbon emissions from fossil fuels (Page *et al.* 2002). Current
60 emissions from drained or burnt Indonesian peatlands are highly uncertain and claimed to be
61 as high as 2 Gt CO₂ per year, or about 5% of all emissions caused by human activity (UN
62 2017), yet these estimates are based on many assumptions. Our comprehensive literature
63 review revealed major gaps in knowledge of the parameters required for peat emissions
64 estimates, with most of the field measurements collected about 20 years ago (Volkova *et al.*
65 2021). For instance, combustion factor (CF), the proportion of pre-fire fuel mass consumed
66 (IPCC 2006), directly influences emissions estimates and is required for both aboveground

67 fuels and peat, yet this parameter is rarely measured in the field and often assumed 0.5 for
68 aboveground fuels for the first fire, with no data provided for subsequent and repeated fires.
69 In the absence of country or region specific data, the IPCC (IPCC 2014) sets the default CF to
70 1.0 for organic soils (i.e. 100% combustion of peat), despite limited supporting evidence. In
71 the absence of direct measurements, the initial assumption that all peat carbon exposed to
72 combustion is converted to gas, is unlikely to be true in practice in all cases. Complete
73 combustion requires homogeneous and sustained high temperatures throughout the fuel bed
74 until it is fully consumed. Heterogeneous spatial patterns of combustion are also to be
75 expected, inevitable if the bed is not completely burnt. The evidence for a peat CF=1 in field
76 situations is limited or non-existent (see Volkova *et al.* 2021). While the CF of 1.0 is only
77 recommended for the Tier 1 level (i.e. where the estimate of peat emission is based on default
78 parameters), most published peat fire emissions estimates (Page *et al.* 2002; Gaveau *et al.*
79 2014; Hooijer *et al.* 2014; Konecny *et al.* 2016; Saragi-Sasmito *et al.* 2019) adopt the CF
80 value of 1.0 while also acknowledging that it is an oversimplification (Hooijer *et al.* 2014;
81 Konecny *et al.* 2016). Therefore the IPCC (2014) guidance recommends that country-specific
82 combustion factors be developed and applied to improve the accuracy of emission estimates
83 for organic soils. Moreover it suggests accounting for differences in the bulk density and
84 carbon concentration of peat according to depth of burn and even region of occurrence within
85 a country (IPCC 2014). Despite these IPCC recommendations, no country or regional level
86 combustion factors have been developed for organic soils, or at least we were not able to find
87 supporting literature (see also Volkova *et al.* (2021), resulting in a continued high level of
88 uncertainty in emissions estimates.

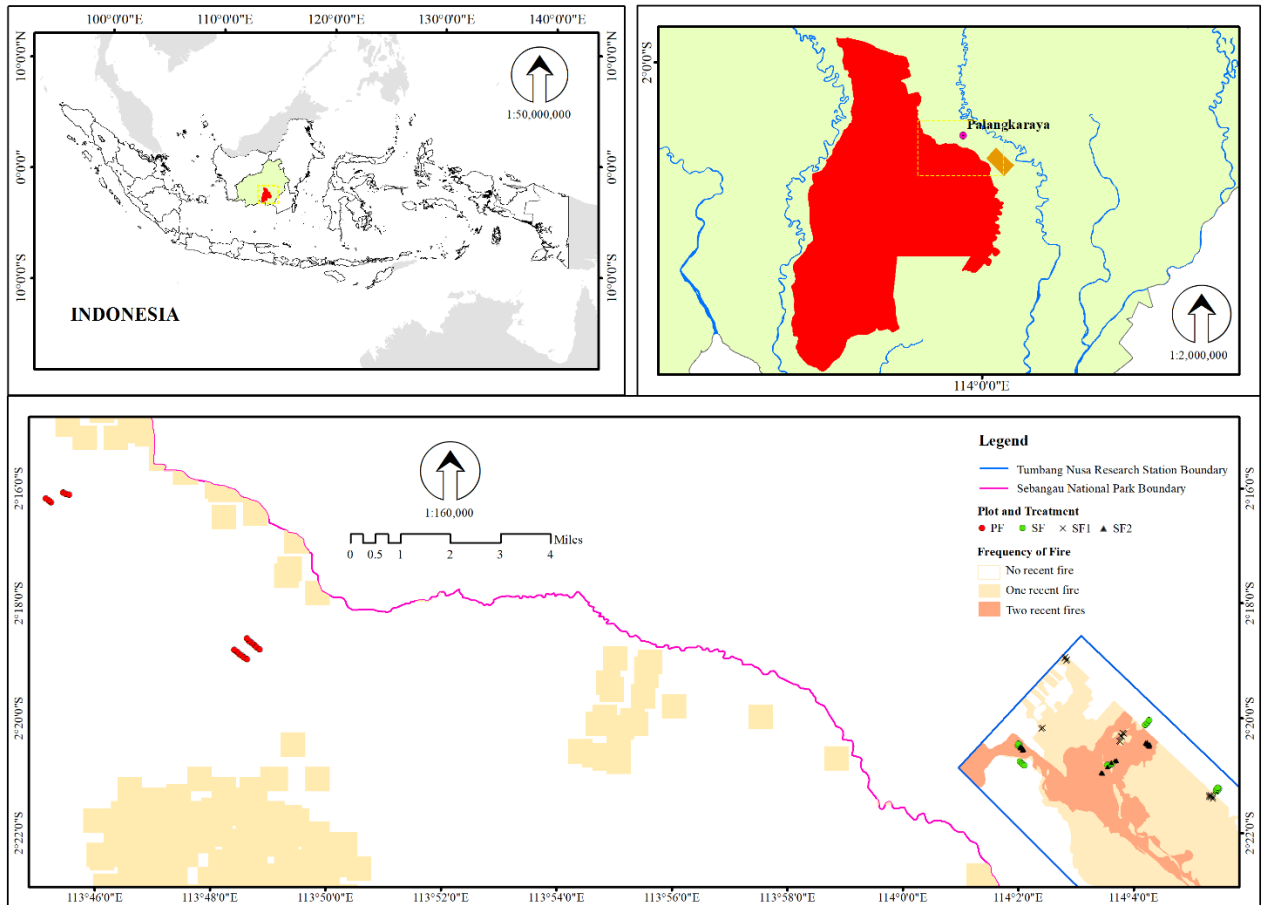
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90 With this background in mind the primary objectives of this study were to measure carbon
91 pools of tropical peat forests following recent and repeated fires as a basis for developing
92 more accurate parameters for peat carbon balance and peat fire emissions estimates.

93 **Materials and Methods**

94 *Study sites, chrono-sequence approach to establishing treatments and biomass sampling*
95 *design*

96 Peat swamp forest areas within the Sebangau National Park (NP) and a former Mega Rice
97 project within Tumbang Nusa Research Forest of Central Kalimantan, Indonesia were
98 selected for the study (Fig.1). For estimating the impact of peat fires on carbon pools and
99 combustion factors we applied a chrono-sequence approach rather than direct comparison of
100 mass before and after a fire in a forest stand. While sampling before and immediately after
101 fires is preferable it is difficult to achieve in practice as predicting where peat fires start is
102 almost impossible. Additionally, the sampling of these forests ahead of peat fires is
103 dangerous due to significant health risks from toxic smoke and the danger of falling trees.
104 Peat swamp forests are known to be inherently spatially variable in terms of carbon stocks
105 due to both position on the peat dome and prior disturbance history. For our chrono-sequence
106 approach we grouped sites according to similarity in disturbance histories, all sites were of
107 similar biotic and abiotic conditions (Foster and Tilman 2000) and had similar peat depth. We
108 applied the findings from our earlier pilot study and power analysis (Volkova *et al.* 2021)
109 indicating that at least 12 plots per treatment would be a sufficient replication to observe 30%
110 difference in the key carbon pools between disturbed and undisturbed forests with at least
111 80% probability.



112

113 *Figure 1. Study site location*

114 Throughout 2019 and early 2020, 18 plots per treatment or a total of 72 plots (4 treatments x
 115 3 blocks x 6 plots) were sampled for aboveground biomass and peat. Disturbance history and
 116 site accessibility were key factors in choosing sampling sites. The treatments reflect
 117 disturbance history ranging from relatively undisturbed forests in the Sebangau NP to forest
 118 regrowth following clear-fell logging that has subsequently burnt once or multiple times
 119 (Table 1, Fig. 2). An area of Sebangau NP - unburnt, relatively undisturbed by human
 120 activities, located in Core Zone/Wilderness Zone (Figs 1 and 2) was considered primary
 121 forest (PF) – and was chosen here as a reference forest to identify the impact of fires on peat
 122 forest carbon balance. The peat swamp forests disturbed more than eighteen years ago were

123 considered long undisturbed secondary forests (SF). Secondary peat swamp forests burnt in
 124 one (SF1) and two recent fires (SF2) were classified as heavily disturbed forests (Table 1).
 125

126 *Table 1 Characteristics of the peat swamp forest treatments.*

Treatment	Description	Disturbance history	Number of plots	Shape of the plot for tree measuring
PF	Primary Forests	Relatively undisturbed. Declared National Park in 2004	18	Circular plot, R=10 m (subplot r=3 m)
SF	Secondary Forests long undisturbed	Fire 1997 or 2003	18	Circular plot, R=10 m (subplot r=3 m)
SF1	Secondary Forests one recent fire	Fire 1997, 2015	18	A 50 m line transect, 12 subplots of r=2 m
SF2	Secondary Forests two recent fires	Fire 1997, 2014, 2015 Fire 2003, 2010, 2014	12 6	Centre - point method

127



128

129 *Figure 2 Photographs of the peat swamp forest treatments.*

130

131 Blocks were located at least 1 km, and up to 7 km, from each other; the first plot in each
 132 block was located randomly and the following plots located according to a grid method, with
 133 at least 60 meters between plots. Sampling design is described in detail in Volkova *et al.*
 134 (2021) and depending on the treatment, either a circular plot, a line transect plot or a nearest
 135 neighbour sampling method (i.e. a centre-point method) was chosen to measure live and dead
 136 trees (Table 1, Fig S1). For the SF and PF treatments the circular plot radius was set up to
 137 capture an average 10-20 trees per plot, as per the Guidelines for measuring aboveground
 138 carbon in peat swamp forests (Kauffman *et al.* 2016). Coarse woody debris (CWD), defined
 139 as detached woody material with diameter ≥ 2.5 cm lying on the forest floor, was measured
 140 along a 50-m transect extending through the plot following the methodology of Van Wagner
 141 (1968). The diameter of CWD intersected by the transect was measured at the point of
 142 intersection with the transect, and placed into one of three decay classes: sound, rotten (signs
 143 of decomposition extended to heartwood) or charred (heavily charred wood). Two samples of
 144 each decay class per plot were collected for density and carbon content analysis. Ground
 145 cover comprising grasses and small shrubs to 0.5 m high, and litter made up of leaves, tree

146 fruits, decomposed organic matter and twigs with $d < 2.5$ cm, were sampled from within a 0.1
147 m^2 metal frame placed on the forest floor at four locations per plot.

148 The thermochemically altered biomass that is created from the pyrolysis and incomplete
149 combustion of organic matter (Bird *et al.* 2015; Surawski *et al.* 2020), referred to here as
150 pyrogenic carbon (PyC), was collected from 0.1 m^2 metal frames randomly located on the
151 peat surface, at four locations near each plot boundary, and percent cover of PyC was visually
152 assessed following the Braun-Blanquet (1932) cover-abundance scale. Visually identifiable
153 PyC pieces were collected from the peat surface into plastic zip bags for mass and carbon
154 concentration determination.

155 *Estimating aboveground carbon*

156 Live tree biomass was calculated using an allometric equation derived for mixed species of
157 Indonesian peat swamp forests (Manuri *et al.* 2014). Dead tree biomass was adjusted for the
158 absence of leaves and branches by either reducing biomass by 2.5% (for a minor defoliation)
159 or 20% (where no leaves, branches or tops were present) (Kauffman *et al.* 2016).

160 CWD, ground cover, litter and PyC were oven-dried at 60°C for about two weeks to a
161 constant weight in the laboratory of FORDA, Bogor, Indonesia. All measurements are given
162 on a dry-weight basis. Wood density of CWD was estimated using a volumetric water
163 displacement method.

164 The total aboveground carbon (AGC) was estimated as the sum of carbon in live trees,
165 ground cover, dead trees, CWD, litter and PyC (noting that the PyC carbon pool is not
166 included in the current IPCC methodology, IPCC 2019).

167 *Peat*

168 Peat was sampled for bulk density and carbon content from near the centre point of each plot
169 to a depth of 1 m, beyond this depth the auger was turned into the peat until mineral soil was

170 detected in the auger head. The top 10 cm of peat was sampled with a metal cylinder of 7.3
 171 cm diameter driven and twisted into the peat surface by hand. For deeper peat the Edelman
 172 auger fitted with a half cylinder peat sampler (Eijkelkamp peat sampler;
 173 <https://en.eijkelkamp.com>) was used to sample 10-50 cm and 50-100 cm depths. At each of
 174 these depth intervals a 10 cm length sample was collected from the 4.9 cm diameter probe
 175 head at the mid-point; either 20-30 cm or 70-80 cm and analysed for mass and carbon
 176 content. The depth of peat was estimated from the length of the peat auger (6 m extension
 177 rods plus sampler) inserted to the mineral soil surface. When peat depth exceeded length of
 178 the extension rod, one meter was added to the measured depth.

179 Peat was oven-dried at 105°C until dry mass was recorded constant (about 2-5 days) for bulk
 180 density estimates and at 60°C for carbon analysis following the protocol of Kauffman *et al.*
 181 (2016).

182 Acknowledging that peat carbon is the biggest carbon pool in peat swamp forests, the impact
 183 of fires on peat carbon was estimated only to the first 1 m depth. Peat mass (M_{PEAT}) in Mg C
 184 ha⁻¹ was estimated by two methods: 1) A fixed depth method also called the IPCC good
 185 practice (IPCC 2003):

$$186 \quad M_{PEAT_h} = BD_h \cdot h \cdot C_{org} \quad \text{Eq. (1)}$$

187 Where: BD is peat bulk density at depth h , g cm⁻³, h is the sampled depth, cm, C_{org} is peat
 188 organic carbon content at the sampled depth, %.

189 2) An equivalent mass method, not sensitive to bulk density (Wendt and Hauser 2013):

$$190 \quad M_{PEAT_h} = \text{Mass of sample}_h / (\pi \cdot r^2) \cdot C_{org} \cdot 100 \quad \text{Eq. (2)}$$

191 Where: Mass of sample_h is the mass of peat sample at depth h , g, r is the inside radius of
 192 the sampling probe, mm, C_{org} is peat organic carbon content at the sampled depth, %. To
 193 account that only a 10 cm peat sample was taken from the depths 10-50 cm and 50-100 cm, a
 194 mass of sample was scaled up to either 40 cm or 50 cm.

195 Peat carbon to 1 m depth (PeatC_{1m}) was estimated as the sum of peat mass for each of
 196 sampled depth (0-10 cm, 10-50 cm, 50-100 cm).
 197 Collected samples of CWD, PyC and peat were analysed for carbon content at the facilities of
 198 the Centre for Agricultural Land Resource Research and Development using a loss on
 199 ignition method (LoI). For each sample, 1–2 g sub-samples were combusted at 550°C in a
 200 muffle furnace for at least 6 h and the residues weighed. Peat carbon content, C_{org} was
 201 estimated as organic matter divided by the conversion factor of 1.922 (Agus *et al.* 2011).
 202 The carbon content of trees was assumed to be 0.47 (IPCC 2006). Total peat forest carbon
 203 was calculated as the sum of AGC and PeatC_{1m}.

204 *Estimating combustion factors*

205 A combustion factor for aboveground carbon (CF_{AGC}) was estimated as the difference in
 206 AGC before and after fires divided by pre-fire AGC. Because AGC in the SF1 and SF2
 207 treatments was not sampled immediately after fires, regeneration of small trees
 208 (DBH<10cm), ground cover and litter re-accumulation were excluded from AGC estimates in
 209 SF1-SF2 treatments.

210 Combustion factor for peat (CF_{PEAT}) was estimated as the difference in peat mass before and
 211 after fires (Eq. 3) using the peat mass calculated by the equivalent mass method (Eq. 2).
 212 Combustion factors were estimated for a range of increments over the depth range 10 cm - 40
 213 cm, as the literature suggests that between 7 cm and 33 cm of peat is burnt in fires (e.g.
 214 Ballhorn *et al.* 2009).

$$215 \quad CF_{PEAT} = (M_{PEAT_{BF}} - M_{PEAT_{AF}}) / M_{PEAT_{BF}} \quad \text{Eq. (3)}$$

216 Where: $M_{PEAT_{BF}}$ is mass of peat before fire calculated to 100 cm depth, Mg C ha⁻¹, $M_{PEAT_{AF}}$
 217 is mass of peat after fire calculated for peat loss equivalent to the top 10 cm, and then in
 218 10cm intervals up to 50 cm peat depth burnt, Mg C ha⁻¹.

$$219 \quad M_{PEAT_{BF\ 0-100cm}} = M_{PEAT\ 0-10cm} + M_{PEAT\ 10-50cm} + M_{PEAT\ 50-100cm} \quad \text{(Eq.4)}$$

220 For example, $CF_{Peat\ 10cm\ burnt}$:

$$221 M_{PEAT_{AF}} = M_{PEAT\ 10-50cm} + M_{PEAT\ 50-100cm} \quad (\text{Eq. 5})$$

222 *Statistical analysis*

223 A linear mixed - effects model (lme) was applied to test the effect of disturbance on each of
224 measured carbon pools. The fixed factor was ‘treatment’ (PF, SF, SF1, SF2) and ‘block’ was
225 used as the random part of the model. For peat, fixed factors were “treatment”, “depth” and
226 their interactions. The differences were considered significant at 5% level. For each analysis,
227 normality and heterogeneity of variance was assessed using histograms of residuals and fitted
228 value plots. For those variables where residues were not equally distributed and the
229 homogeneity of variance assumption was violated, the variance correction (varIdent) was
230 incorporated following the method described in Zuur *et al.* (2009). The best fit model was
231 selected based on weighing and the lowest Akaike information criterion (AIC, see
232 Supplementary examples and Fig S2). Statistical differences among treatments were
233 estimated using the emmeans package (Lenth 2020) based on unadjusted P-values
234 (Supplementary, Table S3). The analyses were conducted in the R statistical environment
235 version 3.6.0 (R Core Team 2020).

236 **Results**

237 *Aboveground carbon – live and dead pools*

238 Disturbance history had a significant effect on AGC stocks of peat swamp forests. Primary
239 forests and long undisturbed secondary forests stored a similar mass in live trees (about 109
240 Mg C ha⁻¹) significantly higher than the 3.4 to 12.7 Mg C ha⁻¹ of recently burnt forests (Table
241 2). Conversely primary forests stored less carbon in ground vegetation than fire-disturbed
242 forests, with the size of this AGC pool similar to the litter C pool. Carbon stored in dead
243 standing trees was similar among all treatments ($P=0.1$), yet recently burnt forests had almost

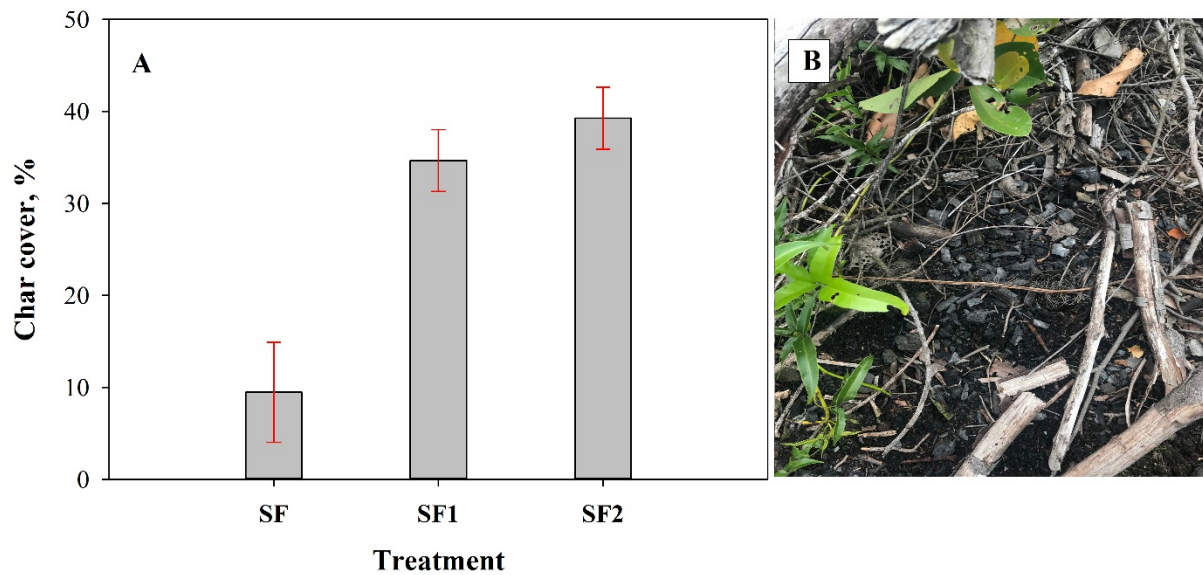
244 three times more carbon in CWD. This significant difference was driven by the presence of
 245 charred CWD in twice burnt forests (mean 11 Mg C ha⁻¹, Table 2). The presence of charred
 246 CWD in the SF treatment, burnt most recently in 2003, demonstrates the persistence of this C
 247 pool in disturbed forests. The mass of forest floor litter was highest in the PF and SF sites
 248 with a closed canopy cover, and lowest in recently burnt forests (SF1 and SF2) where
 249 regenerating trees were yet to close canopy. PyC, char fragments on the peat surface, was
 250 present in secondary forests burnt in 2003 and was highest in recently burnt forests (Table 2).
 251 PyC covered about 30% of the peat surface in recently burnt forests, regardless of fire
 252 frequency, and about 10% in secondary forests (SF) burnt in 2003 (Fig. 3). Carbon content in
 253 CWD was highest in charred CWD at 65%, followed by sound category at 50.9% and rotten
 254 at 47.9% (Table S1). Density of CWD was highest in charred class and lowest in rotten CWD
 255 (Table S2). Overall, the primary and long undisturbed secondary forests (PF, SF) stored
 256 almost twice more carbon aboveground than recently burnt forests. Forests burnt in two
 257 recent fires (SF2) stored a comparable amount in AGC as forest burnt in one recent fire (SF1)
 258 (Table 2, Fig 3).

259 *Table 2. Aboveground carbon pools of peat swamp forest treatments in Mg C ha⁻¹.*

Carbon pool	Treatment			
	PF	SF	SF1	SF2
Live trees	115.6 (105.5, 125.7) ^a	103.4 (79.9, 126.9) ^a	12.7 (-3.7, 29.2) ^b	3.4 (1.6, 5.2) ^b
Ground cover	0.58 (0.38, 0.78) ^a	2.34 (1.74, 2.94) ^b	3.45 (2.91, 3.99) ^c	2.99 (2.47, 3.51) ^{bc}
Dead trees	22.7 (17.2, 28.4) ^a	19.3 (14.2, 24.5) ^a	10.6 (1.4, 19.8) ^a	24.1 (12.7, 35.5) ^a

CWD total	15.7 (10.3, 21.1) ^a	16.3 (11.5, 21.1) ^a	47.5 (32.7, 62.3)	33.3 (22.9, 43.6) ^b
			b	
sound	10.2 (5.43, 15.0) ^a	8.7 (4.9, 12.4) ^a	21.2 (11.9, 30.4)	10.4 (5.2, 15.5) ^a
			b	
rotten	5.4 (3.1, 7.8) ^a	7.5 (4.0, 10.9) ^{ac}	20.5 (12.9, 28.1)	11.5 (8.2, 14.9) ^c
			b	
charred	0.0 ^a	0.11 (-4.4, 4.6) ^a	5.8 (1.26, 10.3) ^b	11.4 (6.8, 15.9) ^c
Litter	4.83 (4.24, 5.42) ^a	3.98 (2.68, 5.29) ^{ab}	3.26 (2.33, 4.18)	2.50 (1.91, 3.09) ^b
			b	
PyC	--	0.62 (-0.9, 2.2) ^a	5.46 (3.92, 7.00)	6.31 (4.77, 7.85) ^b
			b	
Total AGC	159.4 (147.8, 171.0) ^a	146 (120.8, 171.1) ^a	82.9 (52.7, 113.2) ^b	72.6 (55.1, 90.2) ^b

260 Values are the predicted means, n=18, values in brackets are 95% CI. Superscript letters
261 indicate the significant difference between the treatments at <0.05 level for each carbon pool.
262
263



264

265 *Figure 3. A) Percent cover of PyC at the secondary peat swamp forest treatments. B)*

266 *Photograph showing PyC on the peat surface in SF2 forests four years after fires. Where SF*

267 *is secondary forests long unburnt, SF1 forests burnt in one recent fire, SF2 forests burnt in*

268 *two recent fires.*

269 *Peat carbon*

270 The carbon content of peat ($C_{org}\%$) at each sampled depth was higher by about 6-8% in

271 primary forest (PF; 46-50%) compared with other treatments (35-43%; Table 3). The bulk

272 density of peat was lowest in the surface (0-10 cm; $0.14-0.18 \text{ g cm}^{-3}$) compared to sub-

273 surface peat ($0.21-0.29 \text{ g cm}^{-3}$) for all treatments. Bulk density in 0-10 cm was comparable

274 between PF and SF treatments ($0.13-0.14 \text{ cm}^{-3}$) but was significantly higher in recently burnt

275 forests (0.18 g cm^{-3} ; Table 3).

276

277 *Table 3 Peat characteristics*

Treatment	Peat carbon content, C _{org} , %			Peat Bulk density g cm ⁻³		
	0-10 cm	10-50 cm	50-100 cm	0-10 cm	10-50 cm	50-100 cm
PF	50.96±0.4	46.35±0.7	46.61±0.7	0.14±0.0	0.25±0.0	0.29±0.0
	17 ^a	30 ^a	92 ^a	01 ^a	1 ^a	1 ^a
SF	43.12±1.6	36.64±2.6	34.77±2.5	0.13±0.0	0.24±0.0	0.24±0.0
	88 ^b	76 ^b	92 ^b	01 ^a	1 ^a	2 ^b
SF1	39.66±3.0	39.30±2.5	40.72±1.1	0.18±0.0	0.22±0.0	0.21±0.0
	12 ^b	04 ^b	39 ^b	01 ^b	1 ^{ab}	1 ^{bc}
SF2	43.25±1.3	40.81±1.4	38.52±0.9	0.18±0.0	0.21±0.0	0.19±0.0
	13 ^b	86 ^b	86 ^b	01 ^b	1 ^b	1 ^c

278 Values are the means, ± se, n=18. Superscript letters indicate the significant difference
279 between the treatments at <0.05 level for C_{org}, % and for Bulk density g cm⁻³ within each peat
280 depth category. Where PF is primary forests, SF – secondary forests long unburnt, SF1
281 forests burnt in one recent fire, SF2 forests burnt in two recent fires.

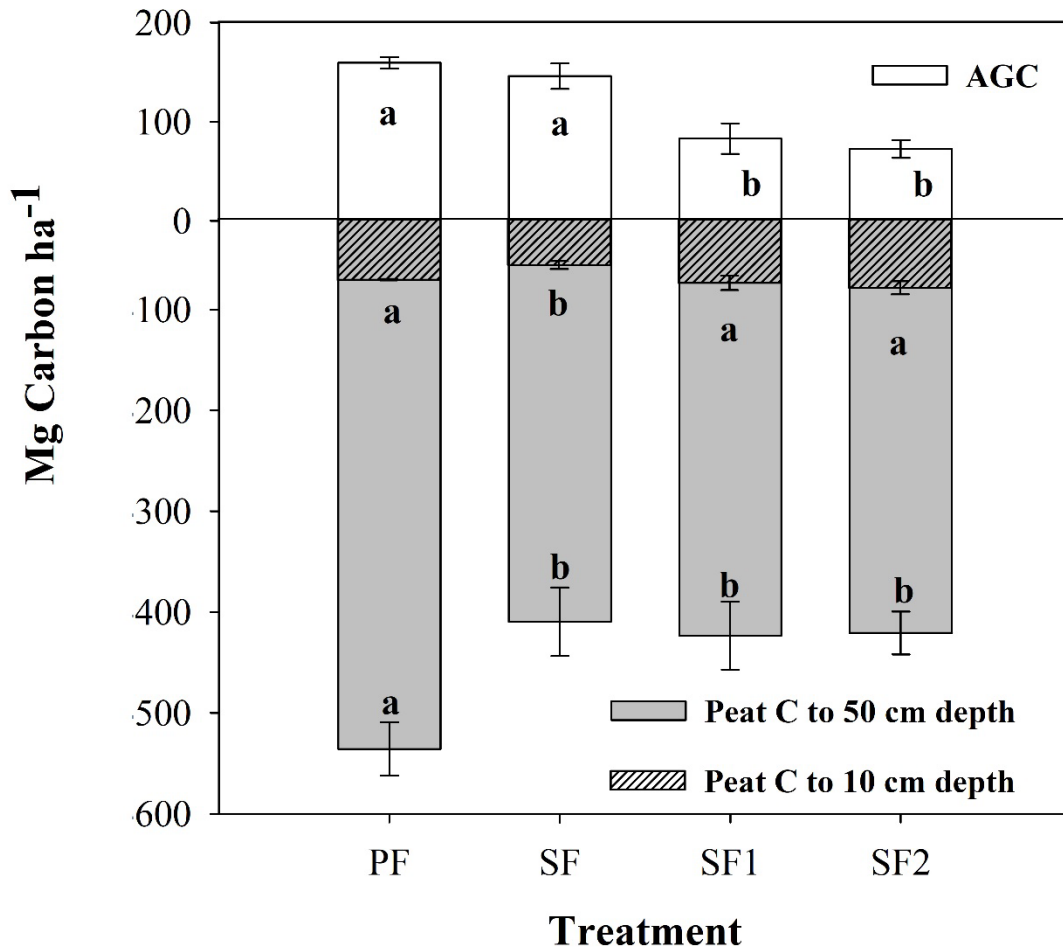
282
283 In estimating the mass of peat carbon, the IPCC ‘good practice’ method and the equivalent
284 soil mass method produced comparable results (Table 4); for simplicity in describing the
285 results we report here the more widely adopted IPCC method. About 70 Mg C ha⁻¹ was stored
286 in the top 10 cm of peat layer and it was comparable between primary and recently burnt
287 forests (Table 4, Fig. 4). Peat carbon to 50 cm depth was highest in primary forests at 535±26
288 Mg C ha⁻¹ and similar among secondary forest treatments at just over 400 Mg C ha⁻¹ (Fig. 4).
289 Consequently, primary forests stored almost 30% more carbon to 1 m depth than secondary
290 forests. Peat depth averaged from 3.5 m to 5 m (Table 4).

291 *Table 4. Mass of peat carbon in Mg C ha⁻¹ using two different methods with peat bulk density*
 292 *(BD) and equivalent mass method.*

Treatment	Peat Mass estimates based on BD			Equivalent soil mass method (independent from BD)			Peat depth, m
	PeatC_10cm	PeatC_50cm	PeatC_1m	PeatC_10cm	PeatC_50cm	PeatC_1m	
PF	70.2±0.63 ^a	535±26 ^a	1225±67.6 ^a	77.2±0.69 ^a	547±27 ^a	1237±67.7 ^a	4.7
SF	55.7±3.9 ^b	409±33 ^b	804.7±67.6 ^b	61.3±4.48 ^b	415±33 ^b	810±67.7 ^b	3.8
SF1	73.4±7.1 ^a	423±33 ^b	844.6±67.6 ^b	86.1±7.20 ^a	428±21 ^b	796±67.7 ^b	4.6
SF2	78.3±6.6 ^a	420±21 ^b	789.1±67.6 ^b	80.7±7.8 ^a	430±34 ^b	852±67.7 ^b	3.9
P values	0.002	<0.0001	<0.0001	0.0019	<0.001	<0.001	

293 Values are the means, ± se, n=18. Superscript letters indicate the significant difference
 294 between the treatments at <0.05 level for each peat depth category. Where PF is primary
 295 forests, SF – secondary forests long unburnt, SF1 forests burnt in one recent fire, SF2 forests
 296 burnt in two recent fires.

297



298

299

300 *Figure 4. Total Forest Carbon to 50 cm peat depth. Letters indicate significant difference at*
 301 *<0.0001 level within one carbon pool (AGC only; Peat C to 50 cm only and Peat C to 10 cm*
 302 *depth only). Where PF is primary forests, SF – secondary forests long unburnt, SF1 forests*
 303 *burnt in one recent fire, SF2 forests burnt in two recent fires.*

304 *Total peat forest carbon to 1m peat depth*

305 The total carbon mass of peat swamp forests to 1 m depth was greatest at 1385 ± 66 Mg C ha⁻¹
 306 for primary forests, and comparable among secondary forests; 950 ± 66 Mg C ha⁻¹ (long
 307 unburnt), 919 ± 66 Mg C ha⁻¹ (one recent fire) and 861 ± 66 Mg C ha⁻¹ for forests burnt in two
 308 recent fires (Table 4).

309 *Combustion Factors*

310 Because the PF and SF forests stored a similar amount of aboveground carbon, a combustion
 311 factor for AGC (CF_{AGC}) was estimated as the difference between the average AGC of PF and
 312 SF (pre-fire) and the average AGC of SF1 and SF2 (post-fire). CF_{AGC} was averaged at 0.564.
 313 Combustion factor for peat (CF_{PEAT}) was estimated as the peat mass difference between PF to
 314 1 m depth (pre-fire) and an average of SF1 and SF2 forests (post-fire) calculated for between
 315 10 and 50 cm depth of peat loss. CF_{PEAT} gradually increased with the depth of peat burnt,
 316 from 0.399 at 10 cm peat depth burnt, to 0.540 at 30 cm peat depth burnt. Increasing the
 317 depth of peat burnt to 50 cm increased peat combustion factor by 26% to 0.681 (Table 5).

318 *Table 5 Combustion factors for aboveground and peat biomass*

Combustion Factor	This study	IPCC default
CF_{AGC}^*	0.564	0.50
$CF_{PEAT-10cm}$	0.399	1.0
$CF_{PEAT-20cm}$	0.469	1.0
$CF_{PEAT-30cm}$	0.540	1.0
$CF_{PEAT-40cm}$	0.610	1.0
$CF_{PEAT-50cm}$	0.681	1.0

319 *assuming that there is no live trees, shrubs or litter remain immediately after fires. i.e. AGC
 320 is estimated as the sum of Dead trees +CWD +PyC.

321 **Discussion**

322 *Aboveground and peat carbon*

323 Our field measurements show that the primary peat swamp forest stored about 30% more
 324 carbon belowground to 1 m depth relative to the group of secondary forests. However, the

325 aboveground carbon was comparable between primary and long unburnt secondary forest
326 (SF), demonstrating a rapid rate of biomass recovery after disturbance. In making this
327 observation we acknowledge that the relatively undisturbed and protected forests of the
328 Sebangau NP are a new baseline for carbon stock estimates, despite their earlier history of
329 human disturbance. Our plot size for PF and SF treatments was big enough to incorporate an
330 average 33 trees per plot (range 24 to 57), supporting the recommendation for peat swamp
331 forests inventories that ‘a plot radius that captures an average of 10-20 trees per plot should
332 be sufficient to adequately describe the tree mass of peat forests’ (Kauffman *et al.* 2016).

333

334 Our study has shown that in secondary forests more than 70 Mg C ha⁻¹ remains aboveground
335 mainly in dead trees and as charred CWD and PyC after first and second consecutive fires
336 (Table 2). This finding is in contrast to the assumption that emission from consecutive fires is
337 a result of peat combustion only (Konecny *et al.* 2016; MoEF 2016). Furthermore, the AGC
338 that remains after the first fire is mainly redistributed aboveground after a second fire,
339 reducing the loss impact of assumed carbon emission. Rather than AGC pools being mainly
340 combusted in second and subsequent fires, due to the large piece size of residues, much of the
341 AGC, such as sound CWD is transformed to charred CWD of much greater C concentration
342 and wood density (Tables S1-2). Consequently a proportion of residues remaining after the
343 second or subsequent fires is more resistant to decomposition, thereby acting more as a
344 carbon sink than as a readily decomposable C source.

345

346 PyC is not included in the current IPCC definition of carbon pools (IPCC 2019), yet a
347 growing body of literature suggests its importance in the global carbon cycle, especially in
348 ecosystems subjected to fires (Santin *et al.* 2016; Landry and Matthews 2017). In our study
349 PyC was present on the peat surface seventeen years after a single fire, and in recently burnt

350 forests it covered one third of the surface (Fig.3). In recently and recurrently burnt forests
351 PyC becomes an important carbon pool accounting for up to 8% of the AGC, equivalent to
352 the mass of carbon stored in regenerating trees and ground cover. With residence times of up
353 to 10 000 years (Swift 2001), PyC is a potential source of long-term carbon sequestration
354 when stored in soils or sediments (Preston and Schmidt 2006). Not accounting for fire
355 produced PyC in carbon mass balance will lead to overestimation of atmospheric emissions
356 by between 2% and 27% according to recent studies (Surawski *et al.* 2016; Santin *et al.*
357 2020).

358

359 In agreement with many other studies (Ali *et al.* 2006; Hooijer *et al.* 2012; Sinclair *et al.*
360 2020), we observed an increase in peat BD in the top layer (0-10cm) with fire frequency due
361 to drainage and heat related compaction of the peat surface. Recently burnt forests stored a
362 similar amount of carbon in the top 10 cm of peat as primary forests, which was a result of
363 greater BD compensating for a loss of C_{org} with disturbance (from 51% to 43%). Even
364 though the fixed depth method has been shown to introduce substantial errors when soil BD
365 differs between the treatments (Wendt and Hauser 2013), in our case the two methods for
366 calculating peat C mass produced remarkably similar results (Table 4), indicating that for
367 peat, both methods are comparable. Peat BD is also influenced by peat maturity with younger
368 (fibric) peat having lower BD than more mature, hemic or fibric, peats (Agus *et al.* 2012). In
369 our case, every effort was taken to sample from more mature peat by visually assessing peat
370 structure in the field following the nationally adopted guidelines (Agus *et al.* 2011). Peat C %
371 (C_{org}) varied with depth and degree of forest disturbance (Table 3) and our values, even for
372 primary forests in the top layer ($51 \pm 0.4\%$), were lower than reported in the literature e.g.
373 global average for peats of $56 \pm 3\%$ (Page *et al.* 2011), 55.3% (at 20 cm depth) by Konecny *et*
374 *al.* (2016) or 58% used in 1997 peat fire emission estimates (Page *et al.* 2002). The difference

375 can be attributed to the analytical technique to quantify peat carbon content, with loss on
376 ignition (LoI) yielding somewhat lower estimates than elemental analysis (Farmer *et al.*
377 2014). In our case, the LoI method with a coefficient of 1.922 was applied to convert organic
378 matter to C_{org} following the national guidelines (Agus *et al.* 2011). A study by Farmer *et al.*
379 (2014), based on a limited number of samples, showed that using 1.922 may
380 underestimate C_{org} by around 3.4% (Farmer *et al.* 2014). Accounting for the difference in the
381 analytical methods, our results still would be on the lower range of C_{org} values reported in
382 the literature.

383

384 Average peat depth in our plots was 4.23 m (Table 4), slightly below the 5.5 m depth range
385 reported by Page *et al.* (2011). Peat depth varied among the treatments and was more a
386 reflection of the position of our forest plots on the peat dome rather than a treatment impact,
387 as has been reported in other studies (Page *et al.* 1999; Silvestri *et al.* 2019). For this reason,
388 we estimated forest carbon down to 1 m depth to allow for direct comparison among
389 treatments, and for the calculation of combustion factors that are discussed below.

390 *Aboveground and peat combustion factors (CF)*

391 Field measurements of all aboveground carbon pools, including PyC, in primary and
392 secondary forests allowed for the calculation of a CF_{AGC} of 0.56, comparable to the default
393 IPCC value of 0.5 (IPCC 2006) for disturbed and repeatedly burnt forests. Our CF for the
394 AGC purely reflected the fire related losses of AGC, rather than previous disturbance history
395 or biological decomposition, as long unburnt but logged forests stored a similar amount of
396 carbon as primary forests (Table 2).

397 In adopting peat C to 100 cm depth in primary forests as the “before” available fuel measure,
398 and peat C from 10-100 cm, 20-100 cm, 30-100 cm, 40-100 cm and 50-100 cm depths in SF1
399 and SF2 forests as the “after” measures, the resulting CF_{PEAT} ranged from 0.39 to 0.68, or two

400 to three times lower than the default IPCC value of 1.0. While the IPCC guidelines
401 recommend using a default value of 1.0 only for the Tier 1 peat fire emissions estimates (i.e.,
402 in the absence of more specific data), we were not able to find any published and reported
403 peat fire emission estimates using anything but a CF of 1 (see Volkova *et al.* 2021). There
404 appears to have been no attempt to define or improve estimates of peat combustion factors
405 since the release of the 2013 Wetland supplement to the 2006 IPCC Guidelines for National
406 GHG Inventories (IPCC 2014). Moreover, the IPCC also doesn't provide more specific
407 guidelines to calculate the peat combustion factor. A recent refinement of IPCC Guidelines
408 for National GHG Inventories (IPCC 2019) provides no change to methodologies or to
409 default parameters. There seems to be a great confusion in estimating fire-related peat carbon
410 loss in the literature. It is assumed that a CF is only to be used to estimate the amount of peat
411 burnt if the amount of peat 'available' for combustion is known (IPCC 2014), which is
412 difficult to know at the landscape scale. To calculate peat fire emissions many studies have
413 assumed that the mass of organic matter associated with changes in the pre-fire to post-fire
414 surface (i.e. the depth of the burn into the peat surface) is 100% combusted and emitted to the
415 atmosphere. Our field observations indicate that the organic matter burnt is made up of peat,
416 plant roots, organic residues from forest disturbance events and recently added litter from
417 aboveground plant components. Due to the high moisture content and heterogeneity of these
418 organic materials in surface peat, it is highly likely that only a proportion of the total is
419 transformed combusted and emitted to the atmosphere. Therefore, the assumption that all
420 organic matter burnt is (a) peat, and (b) completely combusted is unlikely, and does not
421 support the adoption of a CF of 1.0 (see Hooijer *et al.* 2014; Konecny *et al.* 2016). For these
422 reasons we have proposed a method for estimating peat combustion factors that allows for
423 incomplete combustion of peat and more realistically reflect fire related peat loss (Table 5).
424

425 The significantly lower CF_{PEAT} estimated in this study means that emissions from Indonesian
426 peatlands can be up to three times lower than was previously reported (e.g. Page *et al.* 2002).
427 For example, if all other parameters of the equation 2.8 of the IPCC (2014) except CF remain
428 constant, for one ha of peat burnt down to 10 cm, emissions would be about 30% of those
429 calculated with the default CF of 1.0 (Table 5, see Supplementary example for details of CO₂
430 emission calculations). For estimating CF_{PEAT} , we applied an equivalent soil mass method
431 that is not sensitive to treatment effect on soil bulk density (Wendt and Hauser 2013). The
432 selected depths for CF calculations are based on the range of 7 cm to 33 cm peat consumed in
433 fires, reported by other studies (Ballhorn *et al.* 2009; Hamada *et al.* 2012; Stockwell *et al.*
434 2016). While not perfect, the method for calculating CF_{PEAT} proposed in this study is based
435 on real field data and it is a transparent approach for reducing uncertainties and
436 misinterpretation in estimating emissions from peat fires. As discussed earlier, the default
437 value of 1.0 is not supported by field observations and is well acknowledged in the literature
438 as an oversimplification (Hooijer *et al.* 2014; Konecny *et al.* 2016). Because there was no
439 significant difference between peat parameters (BD, C_{org}) among the SF-SF1-SF2 treatments
440 (Table 3), it is reasonable to apply one CF value to a second and subsequent fires, so that
441 differences in emission estimates will be driven mainly by the depth of peat burnt (Table 6).
442 Typically there is greater consumption of peat in first fires: up to 33 cm was measured by
443 Konecny *et al.* (2016); Page *et al.* (2002) assumed 50 cm consumption, while repeated fires
444 burn to a fraction of that depth, with average of 7 cm (Konecny *et al.* 2016). The results of
445 this study reflect peat conditions of our study sites in Central Kalimantan and as
446 recommended by the IPCC, region-specific emission equation factors should be developed
447 for each of Indonesia's peat rich regions (Kalimantan, Sumatra and Papua). In the absence of
448 detailed assessments of the fate of organic matter burnt in a peat fire, we argue for the

449 application of the results of this study as an interim method to more realistically represent
 450 carbon loss and emissions from peat fires.

451 *Table 6. Estimated CO₂ emissions (Mg CO₂-e) from 1 ha of peat burnt down to 10 cm and 30*
 452 *cm depth using the IPCC default and study derived CF_{PEAT}.*

Peat depth burnt	Estimated CO ₂ emissions using the IPCC default CF	Estimated CO ₂ emissions using study derived CF _{PEAT}	Emission reduction per hector of peat burnt
10 cm	262	104	2.51
30 cm	1275	688	1.85

453

454 **Conclusion**

455 This comprehensive comparison of primary peat swamp forest with secondary forests of
 456 different fire-disturbance history shows that logged and burnt forests can retain up to 35% of
 457 the AGC as standing dead trees, CWD and PyC. The mass of carbon in surface peat to 10 cm
 458 was similar among primary forest and recently burnt secondary forests, reflecting increased
 459 peat compaction due to fires and increased drainage. Using the biomass data from the forests
 460 assessed here, the estimated CF_{AGC} of 0.56 is similar to the IPCC default value of 0.5, while
 461 the CF_{PEAT} is 0.4-0.7, or 30% to 60% lower than the IPCC default value of 1 that is currently
 462 used in the international reporting of peat fire emissions. A comparison of emissions from
 463 peat fire calculated using CF_{PEAT} 1 (default) and our study specific CF_{PEAT} (0.4-0.7) yield
 464 emission estimates that are 2-4 times lower than default. Findings from this study provide
 465 novel data that will reduce uncertainties in the peat fire emissions estimates.

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471 **Declaration of interest**

472 Authors declare no competing interests

473 **Authors contribution**

474 HK, CJW and LV designed the study, overseen its implementation and contributed to the
475 development of the manuscript idea. HK and LV have written the first draft of the
476 manuscript. LV has analysed the data and HK overseen logistic of the field campaign. WCA
477 led field sampling and sample analysis, collided the data and conducted data quality control.
478 RI led study sites selections and fire history analysis. Suyoko has overseen sampling in the
479 Sebangau NP. All authors did equal contributions, participated in field data collection,
480 contributed to data analysis, and writing of the manuscript.

481

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