



THE UNIVERSITY *of* EDINBURGH

## Edinburgh Research Explorer

# Tropical peatlands and their contribution to the global carbon cycle and climate change

### Citation for published version:

Ribeiro, K, Pacheco, FS, Ferreira, JW, Sousa-neto, ER, Hastie, A, Krieger Filho, GC, Alvalá, PC, Forti, MC & Ometto, JP 2021, 'Tropical peatlands and their contribution to the global carbon cycle and climate change', *Global Change Biology*, vol. 27, no. 3, pp. 489-505. <https://doi.org/10.1111/gcb.15408>, <https://doi.org/10.1111/gcb.v27.3>

### Digital Object Identifier (DOI):

[10.1111/gcb.15408](https://doi.org/10.1111/gcb.15408)  
[10.1111/gcb.v27.3](https://doi.org/10.1111/gcb.v27.3)

### Link:

[Link to publication record in Edinburgh Research Explorer](#)

### Document Version:

Peer reviewed version

### Published In:

Global Change Biology

### General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

### Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact [openaccess@ed.ac.uk](mailto:openaccess@ed.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.



1 **Title: Tropical peatlands and their contribution to the global carbon cycle and climate**  
2 **change**

3 **Running Title: Tropical peatlands, carbon cycle and climate**

4

5 Kelly Ribeiro<sup>1</sup>, Felipe Siqueira Pacheco<sup>1</sup>, José Willian Ferreira<sup>1</sup>, Eráclito Rodrigues de Sousa-  
6 Neto<sup>1</sup>, Adam Hastie<sup>2</sup>, Guenther Carlos Krieger Filho<sup>3</sup>, Plínio Carlos Alvalá<sup>1</sup>, Maria Cristina  
7 Forti<sup>1</sup>, Jean Pierre Ometto<sup>1</sup>

8

9 1 – Earth System Science Center (CCST), National Institute for Space Research (INPE), Av.  
10 Astronautas, 1758, São José dos Campos, São Paulo, 12227-000, Brazil.

11 2 - School of GeoSciences, University of Edinburgh, EH9 3FF, Edinburgh, Scotland, UK

12 3- Laboratory of Thermal and Environmental Engineering, Polytechnic School of the  
13 University of São Paulo, Av. Prof. Mello Moraes, 2231, São Paulo 05508-030, Brazil

14

15 Contact Information:

16 Kelly Ribeiro, Earth System Science Center (CCST),

17 São José dos Campos, Brazil

18 Email: [kelly.ribeiro@inpe.br](mailto:kelly.ribeiro@inpe.br)

19 Tel: +55 12 32087926

20

21

22

23

24

25

**26 Abstract**

27

28 Peatlands are carbon-rich ecosystems that cover 185-423 million hectares of the earth's  
29 surface. The majority of the world's peatlands are in temperate and boreal zones, whereas  
30 tropical ones cover only a total area of 90-170 million hectares. However, there are still  
31 considerable uncertainties in C stock estimates as well as a lack of information about depth,  
32 bulk density and carbon accumulation rates. The incomplete data is notable especially in  
33 tropical peatlands located in South America, which are estimated to have the largest area of  
34 peatlands in the tropical zone. This paper displays the current state of knowledge surrounding  
35 tropical peatlands and their biophysical characteristics, distribution and carbon stock, role in  
36 the global climate, the impacts of direct human disturbances on carbon accumulation rates and  
37 greenhouse gas emissions. Based on the new peat extension and depth data, we estimate that  
38 tropical peatlands store 152-288 GtC, or about half of the global peatland emitted carbon. We  
39 discuss the knowledge gaps in research on distribution, depth, C stock and fluxes in these  
40 ecosystems which play an important role in the global carbon cycle and risk releasing large  
41 quantities of greenhouse gases into the atmosphere (CO<sub>2</sub> and CH<sub>4</sub>) when subjected to  
42 anthropogenic interferences (e.g. drainage and deforestation). Recent studies show that  
43 although climate change has an impact on the carbon fluxes of these ecosystems, the direct  
44 anthropogenic disturbance may play a greater role. The future of these systems as carbon sinks  
45 will depend on advancing current scientific knowledge and incorporating local understanding  
46 to support policies geared toward managing and conserving peatlands in vulnerable regions,  
47 such as the Amazon where recent records show increased forest fires and deforestation.

48

49

50 Keywords: tropical peatlands, carbon cycling, greenhouse gas emissions, climate change, land  
51 use change

52

53

54

## 55 **Introduction**

56 Peatlands are a type of wetland that form when waterlogged anoxic conditions limit the  
57 decomposition and respiration of organic matter (Vitt, 2013) and creates an accumulation of  
58 peat. Like most wetlands, peatlands can have dense vegetation cover with lacustrine  
59 characteristics (presence of the water plants), sometimes influenced by river seasonality and  
60 dynamics (Lähteenoja, Flores, & Nelson, 2013), as well as seasonal or annual floods with  
61 geomorphological features where water is retained (Finlayson & Milton, 2018; Kelly et al.,  
62 2013; Warner & Rubec, 1997). Whilst there is no absolute consensus on what defines peat,  
63 most studies have settled on two criteria: soils that have both an organic matter content of at  
64 least 30% (Reiche, Gleixner, & Küsel, 2010; Sorensen, 1993), though typically with a higher  
65 threshold of 50% (Gumbrecht et al., 2017) or 65% (e.g. (Dargie et al., 2017), and a minimum  
66 depth of 30cm to 40cm (Dargie et al., 2017; Page et al., 2011; Page & Baird, 2016; Dargie et  
67 al., 2017; Page et al., 2011; Page & Baird; 2016) .

68 These ecosystems provide unique ecosystem services, such as water storage by regulating  
69 the river's discharge, thereby benefiting ecosystems and human communities (Harenda,  
70 Lamentowicz, Samson, & Chojnicki, 2018), along with regulating water flow in hydrographic  
71 basins, including buffering floods (Joseph, 2005). Moreover, they are fertile fields for  
72 agricultural and horticultural production (Rieley et al., 2008), play an important role in  
73 sediment, nutrient and carbon (C) retention (Rieley et al., 2008), and are home to a unique  
74 biodiversity that includes a variety of endemic species (Wilson, Griffiths, & Anielski, 2001).

75 Peatlands cover a total area of about 185-423 million hectares throughout the world (1.2-  
76 2.8% of the earth's total land area) (Xu, Morris, Liu, & Holden, 2018). In the tropical area,  
77 zones covered by peat range from 90-170 million hectares and are located mainly in South  
78 America, Southeast Asia and Central Africa (Gumbrecht et al., 2017). These system store large  
79 amounts of C (469-694 Giga tonnes of C) (Lähteenoja et al., 2012; Leifeld & Menichetti, 2018;

80 Page et al., 2011; Yu et al., 2010) and act as net sinks of atmospheric carbon dioxide (CO<sub>2</sub>).  
81 However, they can also act as major sources of greenhouse gas (GHG) emissions, such as CO<sub>2</sub>  
82 and methane (CH<sub>4</sub>), into the atmosphere (Leifeld & Menichetti, 2018; Roulet, 2012), due to  
83 either natural processes such as changes in autotrophic and heterotrophic respiration rates,  
84 changes in river paths, droughts and natural fires, or anthropogenic interferences including  
85 logging, drainage, deforestation, fires, and land use and land cover (LULC) changes (Hooijer  
86 et al., 2010; Leng, Ahmed, & Jalloh, 2019; Yule, Lim, & Lim, 2016).

87 Changes to the gross C uptake and/or release of these ecosystems can reverse whole-  
88 peatlands carbon budget and significantly alter the current and future global climate (Worrall  
89 et al., 2011; Wu & Roulet, 2014). In recent years, tropical peatlands have been receiving more  
90 attention not only because of their contribution to the global carbon budget and climate change,  
91 but also because of new estimates of larger peatland areas in the tropics (Dargie et al., 2017;  
92 Draper et al., 2014; Gumbrecht et al., 2017; Page et al., 2011; Xu et al., 2018). To understand  
93 how tropical peatlands contribute to global climate change, it is important to understand their  
94 geographical coverage, capacity to store and sequester carbon, and the main factors that drive  
95 their degradation (Yu, 2011).

96 In contrast to temperate peatlands, in which the relationship between climate, ecosystem  
97 dynamics and carbon (C) accumulation is well studied, the body of literature on tropical  
98 peatlands is mainly concentrated on Southeast Asia (S E Page, Rieley, Shotyk, & Weiss, 1999;  
99 San José et al., 2013), Peru in South America (Kelly et al., 2017; Lähteenoja et al., 2012;  
100 Roucoux et al., 2017; Sorribas et al., 2016) and, to a lesser degree, the Cuvette Centrale basin  
101 in Africa (Dargie et al., 2019, 2017). This paper presents an extensive review about tropical  
102 peatlands in terms of their biophysical conditions that promotes peat formation (e.g.  
103 temperature, rainfall, ground water, nutrient pool and substrate quality), spatial distribution and  
104 carbon stock, as well as how these ecosystems are affected under different disturbance regimes.

105 Moreover, the paper identifies and discusses knowledge gaps surrounding this highly  
106 threatened, yet poorly understood ecosystem in several regions of the tropical area.

107

### 108 **Peat formation process and biophysical characteristics of tropical peatlands**

109 In general, peat is formed when the amount of photosynthetically produced organic matter  
110 exceeds the loss of organic matter through fire, decomposition and lateral loss (Hodgkins et al.,  
111 2018). Peat formation is led by several factors, such as hydrological dynamics (groundwater,  
112 seasonality and river dynamics), climatic characteristics (temperature and precipitation),  
113 underlying topography and geology of the area, nutrient pool, chemistry, and vegetation  
114 dynamics (Biancalani & Avagyan, 2014; Hapsari et al., 2017; Yu, 2012). Hydrological  
115 dynamics are among the main factors that regulate peatlands and control peat formation  
116 processes, predominant vegetation, nutrient content, carbon sequestration capacity, and  
117 decomposition processes (Blodau, 2002; Limpens et al., 2008). In certain peatlands, where  
118 water-saturated condition occurs all year around, peat soil profiles identified peat domes that  
119 reach depths up to 15 m (Gumbrecht et al., 2017).

120 In many tropical peatlands the soil is seasonally flooded mostly by large rivers with high  
121 nutrient content and intense sediment deposition. These factors associated to high precipitation  
122 patterns and temperatures favor the development of flooded peatlands concomitant of dense  
123 tree coverage, with high floristic diversity and high net primary productivity (NPP) (Gillman et  
124 al., 2015) and absence of mosses (Page et al., 1999). On the contrary, in many northern  
125 peatlands, the low temperature and low nutrient inputs favors the dominance of the bryophyte  
126 genus *Sphagnum* (Clymo, 1987) and a shrub layer is usually well developed with sparse  
127 occurrence of large trees (Vitt, 2013; Ingram, 1987).

128 The peatland vegetation cover described above, is an important characteristic that  
129 influences the composition and the process of peat formation. Peat in tropical peatlands is  
130 mainly formed by woody material and dead branches and roots (Dommain et al., 2015; Gallego-

131 Sala et al., 2018) whereas most of the peat in northern peatlands is formed of Sphagnum mosses  
132 and sedges. The woody material contains high C:N and lignin:N ratios that degrade slowly  
133 (Gandois et al., 2012; Gandois et al., 2014). This promotes the release of phenolic components  
134 that inhibit decomposition (H. Wang, Richardson, & Ho, 2015). These conditions increase the  
135 aromatic content in the soil and create a reduced oxidation state in which C remains and  
136 recalcitrance is high, despite high temperatures (Hodgkins et al., 2018). Divergent from the peat  
137 formation process in northern peatlands, the low soil temperatures, freezing and the acid  
138 characteristics of the cell wall of Sphagnum species favor the reduction of C oxidative processes  
139 even with abundant labile carbohydrates (Sphagnum) (Vitt, 2013; Clymo, Kramer, &  
140 Hammerton, 1984).

141 “In general, there are two types of peatlands: ombrotrophic and minerotrophic (Clymo,  
142 1987), being divided according to the origin of nutrient input in the system . Ombrotrophic  
143 peatlands are influenced exclusively by water from precipitation (no other sources)  
144 (Bourbonniere, 2009; Takada, Shimada, & Takahashi, 2016; Vitt, 2013) while minerotrophic  
145 peatlands are typically formed in depressions and floodplains and receive mineral nutrients with  
146 incoming surface or ground water (Bourbonniere, 2009; International Peatland Society (IPS),  
147 n.d.; Lahteenoja et al., 2009; Takada et al., 2016; Vitt, 2013).

148 At the start of the peat formation, the peatland is initially minerotrophic (Clymo, 1987).  
149 As the peat layer grows in height, the dome becomes elevated and the peatland may no longer  
150 be affected by the river that feeds into it or by the entry of groundwater, thereby obtaining water  
151 exclusively from precipitation and becoming ombrotrophic. At this stage, nutrient and mineral  
152 deposits are mainly from atmospheric dry deposition or precipitation, but large amounts of  
153 nutrients can also come from dust and air pollution (Ponette-Gonzalez et al., 2016). For  
154 instance, according to Swindles et al. (2018), the oldest Peruvian tropical peatlands discovered  
155 to date were formed in three stages: first, peat was formed in an abandoned river channel with

156 open water and aquatic plants; then inundated forest swamp was formed; and finally the peat  
157 dome raised as the peat accumulated.

158 Many peatlands in tropical region are minerotrophic having been formed from the lateral  
159 migration of rivers (Lähteenoja et al., 2013, 2012; Lähteenoja et al., 2009; Schumann & Joosten,  
160 2008). Most of them are located in river deltas, floodplain areas, abandoned river channels and  
161 shallow oxbow lakes (dead arms) (Baker, 2014; C. B. T.-C. and R. W. Craft, 2016; Rieley et  
162 al., 2008; Rebelo, Finlayson, & Nagabhatla, 2009). However, there are examples of  
163 ombrotrophic peat bogs in the tropics in South America (S E Page et al., n.d.; Swindles et al.,  
164 2018), Southeast Asia (S E Page, Rieley, & Wüst, 2006; Wösten, Clymans, Page, Rieley, &  
165 Limin, 2008) and Africa (Dargie et al., 2017) reported in the literature. In Southeast Asia,  
166 different formation processes have been observed and most of the peat is currently  
167 ombrotrophic, with some related to ancient sea-level rise and an increase of Holocene  
168 precipitation (Dommain, Couwenberg, & Joosten, 2011). Thus, even at similar latitudes, the  
169 mechanisms of peat formation, regulation and carbon accumulation can differ between  
170 regions.”

171

## 172 **Distribution and carbon stock of tropical peatlands**

173 There is a lot of variation in the published data about the occurrence and distribution of  
174 tropical peatlands. Up to a few years ago, Southeast Asia (Indonesia, East Sumatra, Kalimantan,  
175 Papua New Guinea, Papua New Guinea, and Malaysia) was considered to have the largest  
176 peatland C reservoirs in the tropical area (Dargie et al., 2017; Joosten, 2009; Lähteenoja et al.,  
177 2009; Miettinen & Liew, 2010; Miettinen, Shi, & Liew, 2016; Page, Rieley, & Banks, 2011;  
178 Page et al., 2002), however large intact peatlands have recently been described in South  
179 America (Draper et al., 2014) and Africa (Dargie et al., 2017). For example, Dargie et al. (2017)  
180 used field measurements combined with remote sensing data to estimate the extent of a peat  
181 complex in the Cuvette Centrale region of the Congo Basin, the largest intact tropical peatland

182 to date at 14.6 (13.2-15.6) million hectares (Mha). As a result of these recent studies, estimates  
183 of tropical peatlands have been revised (see Gumbricht et al., 2017; Xu et al., 2018) and the  
184 total area of tropical peatlands is now considered to cover 90-170 Mha, (23% to 30% of the  
185 total area covered by peatlands throughout the world). This new estimate is two to three times  
186 larger than the 56 Mha that Page et al. (2011) reported and which led to new discussions on the  
187 physical and chemical factors that define wetlands and peatlands (Figure 1).

188 The new estimates of total peat cover in the tropics represent a volume of about 3,850-  
189 7,268 km<sup>3</sup> (estimated using area from Xu et al., 2018 and Gumbricht et al., 2017, and mean  
190 depth from Gumbricht et al., 2017), which is much higher than the previous estimate of 1,758  
191 km<sup>3</sup> (Page et al., 2011) (Figure 1). Considering these estimates, the largest reserves of peat are  
192 located in Brazil (area and volume of 23 Mha and 900 km<sup>3</sup>, respectively), Indonesia (14 Mha  
193 and 578 km<sup>3</sup>) and the Democratic Republic of the Congo (9 Mha and 445 km<sup>3</sup>, Figure 2). It is  
194 important to note that in Indonesia there is a longer history of fieldwork and, therefore, a  
195 relatively large database of ground-truthing points (Jaenicke et al., 2008), whereas to date there  
196 are relatively few published field data from the Congo Basin (Dargie et al., 2017), and even  
197 fewer from Brazil (Lähteenoja. 2013).

198 Based on the estimated volume of peat in the tropics and the average carbon content per  
199 km<sup>3</sup> of peat (Lähteenoja et al., 2009), we estimated that peat in the tropics stores an equivalent  
200 of 152-288 GtC (Table 1), which is significantly higher than previously reported estimates of  
201 119.2 (Leiffield & Menichetti, 2018), 104.7 (Dargie et al., 2017), 90 (Moore et al., 2013), 88.6  
202 (Page et al., 2011) and 52 GtC (Zoltai & Martikainen, 1996). The stock of 152-288 GtC is  
203 equivalent to the amount of C emitted by burning fossil fuels at a rate of 10 GtC year<sup>-1</sup> for the  
204 next 15-30 years (Murdiyarso, Hergoualch, & Verchot, 2010; Raupach et al., 2013). C emission  
205 from fossil fuel in 2014 were 9.8 GtC, (<https://www.globalcarbonproject.org/>). In addition, the  
206 mid-range value of our estimated C stock (215 Gt) represents about 25% of the terrestrial carbon

207 pool in the tropics (846.3 GtC), considering both carbon above ground (374.9 GtC, phytomass)  
208 and stored in the soil (571.3 GtC, Scharlemann et al., 2014).

209 The main explanation for the large range in our new estimate of tropical peatland C stock  
210 (152-288 GtC) is the different methodological approaches adopted for the estimation of the  
211 area. For instance, the numerical model that Gumbrecht et al. (2017) adopted to estimate total  
212 area uses a set of factors associated with hydrological modeling, time series of vegetation, soil  
213 moisture and hydro-geomorphological data. Xu et al. (2018) considered a wide variety of  
214 sources from different authors and regions and applied criteria of relevance, spatial resolution  
215 as well as age, and combined these data sources to produce a new amalgamated global map of  
216 peatland distribution. For areas where peatland-specific datasets were not available, they  
217 estimated peatland extent based on the distribution of histosols derived from the Harmonized  
218 World Soil Database v1.2 (HWSD). Page et al., (2011) considered data from national soil  
219 inventories from different countries. Data from the latter may not be comparable given the  
220 different definitions of peat and inclusion of non-peat organic soils. The new estimates of  
221 Gumbrecht et al. (2017) and Xu et al. (2018) suggest that the extent of differing with what was  
222 previously reported of what was previously reported (Page et al., 2011).

223 Peatlands in the tropical zone are found in many countries, however some regions have  
224 large peatland areas and carbon stock. The South American peatlands are estimated to be  
225 located mainly in the Rio Negro Basin (Brazil) and Pastaza-Marañón Foreland Basin (PMFB,  
226 Peru) (Draper et al., 2014, Lahteenoja et al., 2013; Lahteenoja et al., 2009), however, to date  
227 there has been limited ground-truthing of the former (Lahteenoja et al., 2013) and therefore  
228 larger uncertainty associated with the extent and volume of Brazilian peatlands. The PMFB  
229 alone is estimated to represent a C stock of 3.14 (0.44–8.15) GtC with 90% of this total  
230 contained belowground. The large uncertainty reflects the need for more field-data.

231 In Africa, peatlands occur in many countries, but extensive peatlands are located in the  
232 Rugezi Marsh in Rwanda, the Okavango Delta in Botswana, the Sudd catchment in Sudan and  
233 in particular the Congo basin (Grundling and Grootjans, 2018). The Cuvette Centrale wetland  
234 of the Congo basin is estimated to contain a C stock of 30.6 (6.3–46.8) Gt C (Bwangoy et al.,  
235 2010; Dargie et al., 2017, Table 1). Again, note the large uncertainty range, which is a reflection  
236 of the fact that this estimate is based on a relatively sparse set of field measurements (Dargie et  
237 al., 2017). Peatlands have also been reported in southern Africa, mainly along the eastern coast  
238 (Mozambique Coastal Plain) and in the central plateau (Grundling & Grobler, 2005; McWethy  
239 et al., 2016).

240 The total area covered by peatlands in Southeast Asia is roughly 21 Mha (Xu et al., 2018).  
241 Most of these peatlands are in Indonesia (15 Mha), Malaysia (2.2 Mha), Thailand (40 thousand  
242 ha) and, to a lesser extent, Vietnam, Brunei and the Philippines. A recent estimate put the peat  
243 C store in Indonesia alone at 28.1 (13.6–40.5) Gt C (Warren et al., 2017). Unlike other large  
244 tropical peat reservoirs in the world that are either untouched or have had little alteration,  
245 peatlands in Southeast Asia have faced intense anthropogenic disturbances since the 1970s,  
246 when permission was granted to use these extensive areas for commercial purposes.

247 Due to the current large uncertainties around carbon stocks in tropical peatlands, it is  
248 notorious that with the advance of knowledge in the identification of tropical peatlands (mainly  
249 extension and depth) resulted in significantly higher estimates for carbon stocks in the tropical  
250 zones. For South America and Africa the large uncertainty reflects the need for more field-data  
251 (Dargie et al., 2017). Peatlands in relatively remote African and Amazonian regions currently  
252 face low human intervention, however as anthropogenic activities, such as commercial  
253 agriculture, exploitation of waters for hydropower (in Andes), forestry (including  
254 deforestation), construction of impoundments, roads and ports, and gas exploration in peatlands  
255 increase, so does the degradation of these ecosystems (Baker, 2014; Lahteenoja et al., 2009;

256 Roucoux et al., 2017). Therefore, decreasing uncertainties about area, and C stock in such  
257 remote regions is crucial to estimate the true C accumulation potential of these peatlands and  
258 to prevent future impact of human activities that peatlands may face mainly in South America  
259 and Africa.

260

261

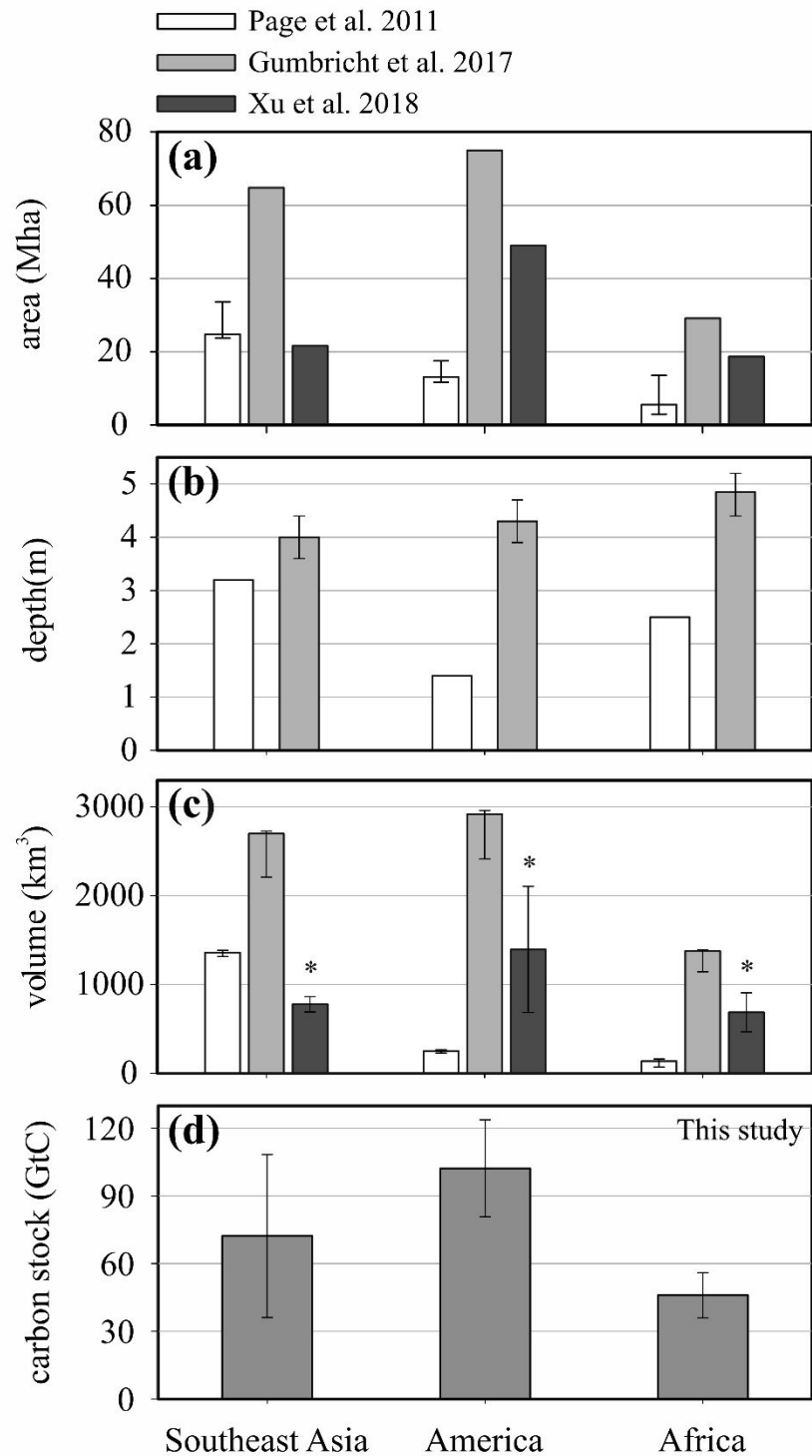
262

263

264

265

266



267

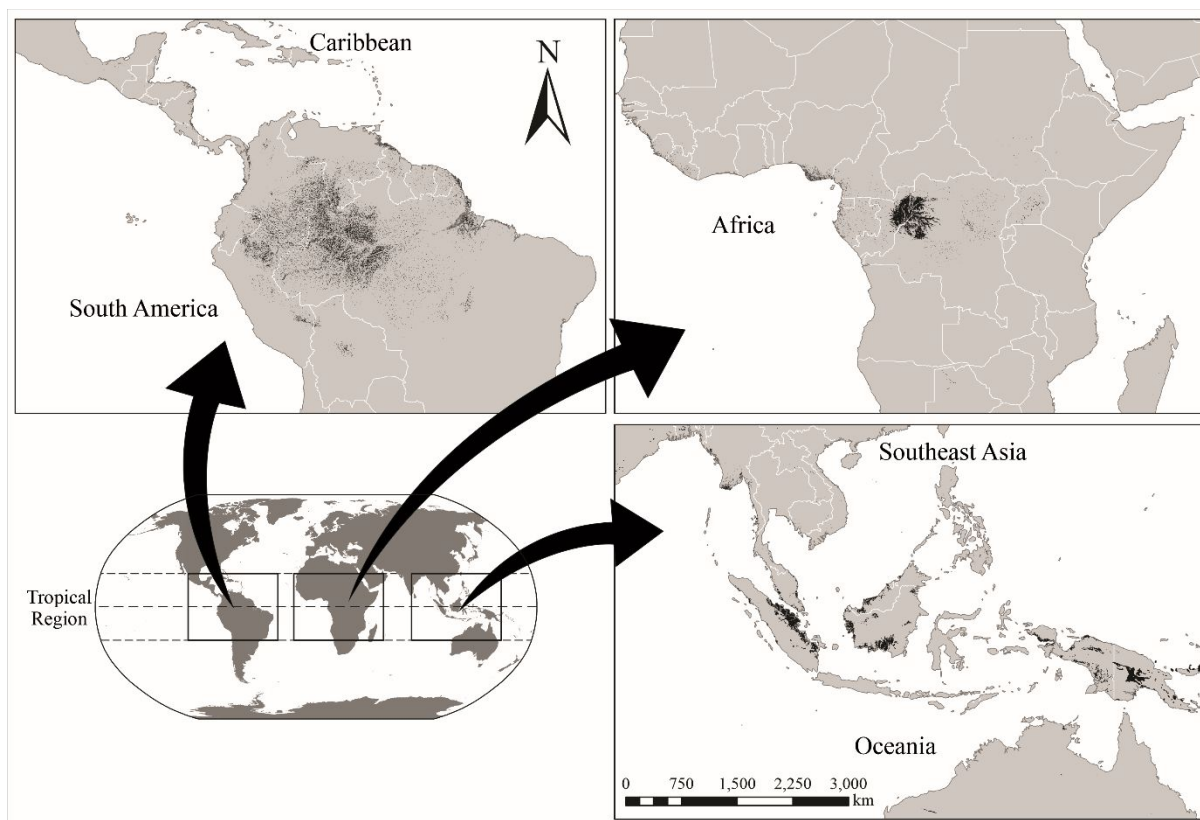
268 Figure 1 – Estimated peat area (a), depth (b) and volume (c), presented by Page et al. (2011),

269 Gumbrecht et al. (2017) and Xu et al. (2018) of tropical peatlands. (d) Estimated carbon stock

270 (GtC) in tropical peatlands. Error bars are minimum and maximum estimates when available.

271 \*Values estimated using peatland area from Xu et al. (2018) and mean depth from Gumbrecht

272 et al. (2017) and Page et al. (2011).

273  
274

275

276 Figure 2 – Distribution of peatlands in tropical regions. Data from Xu et al., (2018)

277

278 **Tropical peatland carbon accumulation, climate change and the global carbon cycle**

279 The carbon accumulation rates in undisturbed tropical peatlands range from 24-300 gC  
 280 m<sup>-2</sup> yr<sup>-1</sup> (Table 2), while for boreal and temperate undisturbed peatlands they are generally lower  
 281 (vary from 2 to 271 gC m<sup>-2</sup> yr<sup>-1</sup>, Olefeldt et al. 2012; Renou-Wilson et al. 2019). Although  
 282 substantial variation occurs depending on peatland type, hydrology, vegetation type and peat  
 283 formation (C. Craft, Washburn, & Parker, 2008; Sjögersten et al., 2014), C accumulation rates  
 284 are, with a few exceptions, greater in the tropics and decrease with latitude (Sjögersten et al.,  
 285 2014). Additionally, the carbon accumulation rates in undisturbed tropical peatlands are  
 286 generally much higher than in intact old-growth tropical forests, commonly over mineral soils,  
 287 in Africa and Amazonia (40-91 and 0-47 gC m<sup>2</sup> yr<sup>-1</sup>, respectively) (Hubau et al., 2020).

288 The accumulation rates depend on the balance between carbon uptake by vegetation and  
 289 carbon emitted to the atmosphere and lost to adjacent terrestrial or aquatic system. CO<sub>2</sub>

290 emission vary greatly in tropical peatlands ( $250$  and  $13841$   $\text{gC m}^{-2} \text{yr}^{-1}$  (Table 3) and tend to be  
291 greater than in non-tropical systems ( $411 \pm 128$   $\text{gC m}^{-2} \text{yr}^{-1}$ ) (Bubier, Bhatia, Moore, Roulet,  
292 & Lafleur, 2003; Clair, Arp, Moore, Dalva, & Meng, 2002; Crow & Wieder, 2005; Mäkiranta  
293 et al., 2009; Silvola, Alm, Ahlholm, Nykanen, & Martikainen, 1996). Estimated fluxes of  $\text{CH}_4$   
294 from peatlands are typically several orders of magnitude lower than those for  $\text{CO}_2$  (Table 3).  
295  $\text{CH}_4$  emissions are indeed undetectable in some peatlands and an uptake from the atmosphere  
296 might occur instead (Sjögersten et al., 2014). Previous studies have estimated that undisturbed  
297 temperate and boreal environments emit moderate to high level of  $\text{CH}_4$  ( $-7.1$ – $2088.6$   $\text{gC m}^{-2} \text{yr}$   
298  $^{-1}$ ) (Inubushi, Furukawa, Hadi, Purnomo, & Tsuruta, 2003; Martikainen, Nykänen, Alm, &  
299 Silvola, 1995; Melling, Hatano, & Goh, 2005; Mitsch et al., 2010; Turetsky 2014), whereas  
300  $\text{CH}_4$  emissions from undisturbed tropical peatlands have been estimated at moderate range of -  
301  $9.2$ – $110.6$   $\text{gC m}^{-2} \text{yr}^{-1}$  (Table 3).

302 Methane formation is driven by methanogenic microorganisms activity (anaerobic  
303 decomposers) that degrades organic matter slowly in an anoxic environment (Mitsch et al.,  
304 2010). A peatland's capacity to emit less  $\text{CH}_4$  appears to be a complex mechanism developed  
305 over several thousands of years, given that formerly human-disturbed restored peatlands in  
306 temperate systems with well-established vegetation and carbon stock have  $\text{CH}_4$  emissions about  
307 150% higher than older peatlands (Renou-Wilson et al., 2019). This fact suggests that to  
308 maintain low  $\text{CH}_4$  emissions and higher carbon sequestration rates it is important to not only  
309 invest in actions that seek to recover impacted areas, but also to ensure that ecosystems are  
310 protected.

311 In the absence of direct human disturbance, many tropical peat deposits are actively  
312 accumulating carbon or are in steady states (Dargie et al., 2017; Fatoyinbo, 2017). However,  
313 climate change may significantly impact peatlands, and this relationship is poorly understood,  
314 particularly in the case of tropical peatlands, and thus the fate of peatlands under future change

315 remains uncertain (Frey & Smith, 2005; Gallego-Sala et al., 2018; Hapsari et al., 2017; Hirano  
316 et al., 2012; Hodgkins et al., 2018; Rieley et al., 2008). The effect of climate change will depend  
317 mainly on how temperature, total precipitation, sea level and frequency of extreme events will  
318 change in a specific region and how they will affect hydrology, vegetation composition and,  
319 consequently, primary production, substrate quality, decomposition process, lateral carbon  
320 fluxes and C accumulation rates of peatlands.

321         Some recent work, using Dynamic Global Vegetation Models (DGVMs) indicated, for  
322 Northern Hemisphere peatlands, a carbon sink twice as big than the 1861-2005 mean under two  
323 climate scenarios (defined by the RCPs 2.6 and 6.0), even though rapid climate change (under  
324 RCP8.5) might impact negatively the extent of northern peatlands, and the capacity of these  
325 areas to act as a carbon sink (Chaudhary et al, 2019; Qiu et al, 2020). As well, some models  
326 have predicted continued peat accumulation through to 2100 (Gallego-Sala et al., 2018; Spahni  
327 et al.,2013), while most models agree that there will be substantial losses over the next centuries  
328 (Avis, Weaver, & Meissner, 2011; Gallego-Sala et al., 2018; Ise et al.,2008), and some models  
329 have predicted that loss to start before 2100 (Avis, Weaver, & Meissner, 2011; Ise et al.,2008).  
330 Few pan-tropic modelling studies have been undertaken (Gallego-Sala et al., 2018; Treat et al.,  
331 2019) largely due to the sparsity of available data on tropical peatlands that is needed for model  
332 parametrization and validation. Climate models for the western Amazon predict increasing  
333 precipitation and river discharge over the century (Duffy et al., 2015; Sorribas et al., 2016;  
334 Zulkafli et al., 2016) whereas the opposite is predicted for the Eastern Amazon (Duffy et al.,  
335 2015; Sorribas et al., 2016), meaning that Brazilian peatlands are likely to be more vulnerable  
336 than those in Peru. However, a recent modelling study in the PMFB in Peru predicted that  
337 temperature increases would offset any positive effect of increased precipitation on peat  
338 accumulation by the end of the century through an increase in decomposition. i.e., Peruvian  
339 peatlands will cease peat accumulation despite increases in precipitation (Wang et al., 2018).

340 Likewise, in the Congo Basin there is a clear consensus that temperature will increase under all  
341 future scenarios while precipitation is predicted to increase under high emission scenarios and  
342 remain relatively unchanged under low emission scenarios (Haensler, Saeed, & Jacob, 2013)  
343 and, therefore, Congolese peatlands may also be vulnerable to future climate change. Likewise,  
344 studies in Southeast Asian peatlands, many of which are already degraded from deforestation  
345 and drainage, have been shown that additional carbon emission could also occur if dry seasons  
346 are extended or are more severe due to future climate change (Warren, et al., 2017).

347         Conversely, there is evidence to suggest that tropical peats may be more resistant to  
348 temperature changes. Hodgkins et al. (2018) observed that the higher aromatic content of  
349 tropical peat compared to the peat located at higher latitudes creates both a reduced oxidation  
350 state and higher recalcitrance, which prevents carbon release, even at high temperatures. In  
351 many peatlands in the northern hemisphere, deep peat has also high recalcitrance  
352 characteristics, which means that despite the expected temperature increases from climate  
353 change, the deep peat will probably remain stable, suggesting that these carbon stocks may be  
354 preserved in the face of climate change given their similar characteristics to tropical peat.  
355 Although there may only be a direct relationship between temperature and decomposition in  
356 high recalcitrant peat, it is recognized that changes in precipitation can alter the natural  
357 hydrology of these environments and enhance the degradation processes of recalcitrant peat  
358 (Chimner & Ewel, 2005).

359         In summary, many peatland areas are projected to stop accumulating peat by the end of  
360 the century and beyond, thus creating a positive climate feedback loop where further warming  
361 means C losses and, in turn, greater radiative forcing (Gallego-Sala et al., 2018). However,  
362 across the entire tropics, and particularly the Amazon and Congo basins, further field data is  
363 required to better parameterize and validate models so that we can improve projections of the  
364 future C balance in tropical peatlands, which at the moment remain highly uncertain.

365           Although climate change (such as changes to temperatures and precipitation) has an  
366 impact on the dynamics of these ecosystems, direct anthropogenic changes (LULC changes,  
367 drainage and deforestation) currently play a greater role. Therefore, understanding the impact  
368 of direct anthropogenic changes on these ecosystems can help us understand whether tropical  
369 peatlands are a net sink or net source in the global carbon cycle.

370

### 371 **Direct human disturbances and their impacts on carbon accumulation rates and GHG** 372 **emissions in tropical peatlands**

373           Anthropogenic activities, such as logging, drainage, deforestation, fires and the  
374 conversion of native forests to agricultural lands, have been rapidly increasing in peatlands  
375 since the 1990s (Hooijer et al., 2010), particularly in developing countries, and have put these  
376 ecosystems at risk (Swindles et al., 2018). Although most of the scientific literature on the  
377 degradation processes of tropical peatlands focuses on Southeast Asia (Hapsari et al., 2017;  
378 Hirano, Jauhiainen, Inoue, & Takahashi, 2009; Hirano et al., 2012; Inubushi et al., 2003;  
379 Könönen, Jauhiainen, Laiho, Kusin, & Vasander, 2015; Rieley et al., 2008), the degradation of  
380 large areas of peat and the impacts that may alter their natural conditions have also been  
381 documented in both South America and Africa (Baker, 2014; Dargie et al., 2017; Dargie et al.,  
382 2019; Roucoux et al., 2017; Swindles et al., 2018).

383           In Southeast Asia, domestic and international demand for agricultural and forest products  
384 and services has put pressure on tropical peatlands and, by 2010, it was estimated that only 36%  
385 of the original peatland area in the Southeast Asia was covered by primary and secondary peat  
386 swamp forest (Miettinen, Shi, & Liew, 2012; Dohong, Aziz & Dargusch, 2017). In the  
387 Indonesian regions of Sumatra and Kalimantan, the two regions of Indonesia with the greatest  
388 impacts, only 6% were pristine peat swamp forests (Miettinen, Shi, & Liew, 2012). To meet  
389 the high demand of agricultural products, the peatlands have been subjected to deforestation  
390 (Hirano et al., 2012), widespread drainage (Fatoyinbo, 2017), and recurrent fires (Page et al.,

391 2002). Page et al. (2011) argues that, on the one hand, expansion of agriculture and forestry in  
392 the region has provided opportunities to industries and businesses, yet on the other hand it has  
393 also had, has also had negative environmental impacts. Between 2000 and 2010, Southeast Asia  
394 has had the highest annual rate of deforestation (rate of 2.2%) among all tropical humid regions  
395 in the world. This deforestation has resulted in the loss of 11 Mha of native forests and has led  
396 to significant changes in natural ecosystem dynamics, mainly related to carbon balance  
397 (Miettinen & Liew, 2010). Harris et al. (2013) projected land use and emissions from peatlands  
398 between 2010 and 2050 across Indonesia, Malaysia, and in Papua New Guinea and found that  
399 under the “business as usual” scenario, in which total production of oil palm will increase  
400 without peatland protection measures, the average annual CO<sub>2</sub> emissions would almost double  
401 between 2020 and 2050 (from 264 to 424 Tg CO<sub>2</sub> yr<sup>-1</sup>). In contrast, restoring the peat to native  
402 forest vegetation (restoration scenario) would bring annual emissions close to zero.

403 In Africa, increased economic development could have a negative impact on peatlands  
404 through hydrocarbon exploration, logging, plantations and other forms of disturbance that  
405 significantly damage these ecosystems, although they are still intact today (Dargie et al., 2019).  
406 Additionally, land-use changes occur as a result of multiple complex and interacting  
407 environmental, economic and political factors, which can accelerate the negative impacts of  
408 human activities. In Cuvette Centrale region in Congo, rivers are the main transport network  
409 and there are relatively few roads. This, along with the large distance from any international  
410 port and low population densities, is among the reasons why the Congo basin peatlands have  
411 so far been spared from more severe degradation typical for Southeast Asian peatlands.  
412 Although limited in number, roads have already been constructed across some of the peatland  
413 areas of the Cuvette Centrale. No studies have yet considered the specific impacts of these roads  
414 on the peat properties, hydrology or vegetation; however, the observed swamp forest death  
415 following road construction suggests that roads could be having a negative impact on the

416 wetlands of the region (Dargie et al., 2017). The low level of human intervention in the Cuvette  
417 Centrale peatlands at present suggests that there is still time to protect the peatlands in a largely  
418 intact state, possibly by encouraging funding for mitigation of land-use change (Dargie et al.,  
419 2019).

420 In South America, large areas of undisturbed peatlands are increasingly facing a range  
421 of threats, including hydroelectricity (river damming) projects, road and railway projects (Finer  
422 & Orta-Martínez, 2010; Gutiérrez-Vélez et al., 2011), ore, gas, and oil exploration, logging and  
423 drainage for agriculture (Baker, 2014; Roucoux et al., 2017). Over exploitation of the palm fruit  
424 (*Mauritia flexuosa* – commonly found in wetlands) is also an increasing concern (Kahn &  
425 Mejia, 1990; Lilleskiv et al, 2019). In contrast with the better-known but highly degraded and  
426 at-risk peatlands of Southeast Asia (Miettinen et al., 2012), many peatlands in South America  
427 remain largely intact and the threat of destruction from direct human impacts is comparatively  
428 low (Baker, 2014).

429 In general, the degradation process of tropical peatlands begins with the felling of natural  
430 vegetation, which reduces the amount of biomass in the system (Könönen et al., 2016), and  
431 promotes an increase of C oxidation rates and a reduction of soil moisture because of the  
432 increased incidence of direct radiation (Dargie et al., 2019; Jauhiainen, Hooijer, & Page, 2012).  
433 However to a lesser extent, a reduction in vegetation can also lead to increase in soil moisture  
434 due to the decrease in transpiration (Porporato, Laio, Ridolfi, & Rodriguez-Iturbe, 2001). After  
435 the deforestation process, the peatlands are artificially drained in order to reduce groundwater  
436 levels to plant perennial and rotating crops (Dargie et al., 2019) are not adapted to the naturally  
437 flooded environment. Next, aerial biomass crops are produced, which reduce the ecosystem  
438 carbon uptake because the soil no longer has the environmental conditions of peatlands to  
439 accumulate carbon, and the carbon accumulated by the crop primary production is removed  
440 from the system through the harvest (Roucoux et al., 2017)

441 The most recent studies on GHG soil emissions from natural and impacted environments  
442 show that tropical peatlands have high CO<sub>2</sub> emissions in drained environments used for  
443 agricultural production and in recovering areas (Leifeld & Menichetti, 2018). Although non-  
444 impacted forests emit C through soil respiration, on average emissions are lower due to the  
445 maintenance of natural soil moisture conditions and groundwater levels.

446 In Indonesia, the carbon lost in peatlands after LULC changes has averaged  
447 approximately 60 Mg ha<sup>-1</sup> yr<sup>-1</sup> over 25 years of interference (Murdiyarso et al., 2010). This loss  
448 is, in part, due to the absence of vegetation in impacted and/or drained peatlands, given that in  
449 undisturbed peatlands C sequestration from vegetation cover offsets C emissions from the soil.  
450 In Southeast Asia, it is estimated that in 2006 CO<sub>2</sub> emissions from organic matter  
451 decomposition in drained peat soil were equivalent to 1% to 3% of all global CO<sub>2</sub> emissions  
452 from burning fossil fuels (~630 Mt), and that 82% of these emissions were from Indonesian  
453 peatlands (Hooijer et al., 2010). Other studies have pointed to even higher emission rates  
454 associated with peat decomposition in Indonesia, reaching about 8% of global emissions from  
455 burning fossil fuels (2000 Mt yr<sup>-1</sup> of CO<sub>2</sub>, Rieley et al., 2008). Moreover, major events were  
456 reported in 1997 and 2015, in which widespread forest and peatland fires burned large areas of  
457 the Southeast Asia (Page et al. 2002; Huijnen et al., 2016), especially Indonesia, releasing large  
458 amounts of carbon land-based in the atmosphere, mainly in the form of CO<sub>2</sub>, CO and CH<sub>4</sub>. With  
459 an average emission rate of 11.3 Tg CO<sub>2</sub> per day during these events, emissions exceeded the  
460 European Union's (EU28) fossil fuel CO<sub>2</sub> release rate of 8.9 Tg CO<sub>2</sub> per day (Huijnen et al.,  
461 2016).

462 Methane fluxes also change as a result of human disturbance (Reay et al., 2018). The  
463 conversion of peatland forests to areas of intensive cultivation, along with significant inputs of  
464 nitrogen fertilizers, may alter the natural dynamics of methane and nitrous oxide emissions  
465 (Tian et al., 2015). Rice crops in Indonesia have shown very significant CH<sub>4</sub> emissions after

466 being converted from peatland forests (Table 3) because the production of CH<sub>4</sub> by  
467 methanogenic microorganisms is boosted by both the ever-flooded system and the use of  
468 nitrogen fertilizers (Conrad, 2002). Emissions from these crops may be about 20-fold greater  
469 than emissions from natural areas. Nitrous oxide emissions in Indonesia have been shown to  
470 increase substantially with land use change and the introduction of agricultural activities in  
471 peatlands (Oktarita et al., 2017). Nitrous oxide emissions from *Elaeisis guineensis* (oil palm)  
472 monocultures in Indonesia were reported by Hadi et al. (2005) at 9.1 gC m<sup>-2</sup> years<sup>-1</sup>, higher than  
473 those reported by Inubushi et al. (2003) in native peat forests, 1.25 gC m<sup>-2</sup> years<sup>-1</sup>.

474 In addition to GHG emissions, drainage enables organic matter to be transported to  
475 adjacent watercourses in the form of dissolved organic carbon (DOC), particulate organic  
476 matter and dissolved inorganic matter. For instance, Baum et al. (2007) suggest that Indonesian  
477 rivers, particularly those receiving effluents drained from peatlands, transfer large amounts of  
478 carbon, in the form of DOC, to the oceans (21 Tg yr<sup>-1</sup>) and that this accounts for approximately  
479 10% of global riverine DOC inputs into the ocean (Rieley et al., 2008).

480 Roucoux et al. (2017) examined the services provided by large, intact tropical peatlands,  
481 the factors threatening them, and opportunities to conserve them, and cite that, although their  
482 contribution from tropical peatlands to climate regulation on the planet is evident, their  
483 importance is weakly articulated within existing conservation agendas, mainly because they are  
484 poorly described and mapped and are frequently unrecognized by local agencies and  
485 institutions. Fortunately, in Amazonia, Africa, and New Guinea tropical peatland ecosystems  
486 are also widespread and often much less intensively exploited. Many can be described as intact  
487 at the landscape scale; their hydrology is unaffected by human activity and their vegetation  
488 cover is not fragmented or substantially degraded.

489

490 Table 1 –Tropical peatland carbon stock (GtC) showing mean values and/or (range) if available.

<b>System/Location</b>	<b>Land cover</b>	<b>Carbon stock (GtC)</b>	<b>Ref.</b>
<i>Tropical Asia</i>		68.9 (66.6 – 70.4)	Page et al. (2011)
Central Kalimantan, South Sumatra and West Papua	Peat swamp forest	55 ± 10	Jaenicke et al. (2008)
Indonesia	Native Forest	23.2	Dommain et al. (2014)
Indonesia	Native vegetation and impacted areas	30	Rudiyanto et al. (2015)
Indonesia	Native vegetation and impacted areas	57.4	Page et al. (2011)
Malaysia	Native vegetation and impacted areas	9.1	Page et al. (2011)
Southeast Asia	Native vegetation and impacted areas	172	Sjögersten et al. (2014)
Southeast Asia	Native Forest	65	Dommain et al. (2011)
Southeast Asia	Native vegetation and impacted areas	20	Dommain et al. (2011), (2014)
<i>Tropical America</i>		12.7 (11.5 – 13.4)	Page et al. (2011)
Peru (Pastaza-Marañon)	Native Forest	3.14 (0.4 – 8.1)	Baker, (2014)
Peru (Pastaza-Marañon)	Native Forest	3.12 (0.8 - 9.5)	Lähteenoja et al. (2012)
<i>Tropical Africa</i>		6.9 (3.5 – 8.1)	Page et al. (2011)
Cuvette Centrale, Congo	Native Forest	30.6 (6.3 – 46.8)	Dargie et al. (2017)
<i>Global scenario</i>		(469 – 694)	Page et al. (2011); Yu et al (2010)
Tropical undisturbed		(139 – 251)	Miettinen & Liew (2010); Zoltai (1996)
Tropical disturbed		(13 – 37)	Kurnianto et al. (2015); Zoltai & Martikainen (1996)
Tropical		(152-288)	This study
Non-Tropical		(387 – 394)	Page et al. (2011); Gorham (1991); Immirzi & Maltby (1993); Gorham (1991)

491

492

493 Table 2 – Carbon accumulation rates (gC m<sup>-2</sup> yr<sup>-1</sup>) from tropical peatlands and from non-tropical peatlands (for comparison) showing mean values  
494 and/or (range) if available. Positive values are carbon accumulation and negative values are carbon loss.

<b>System/Location</b>	<b>Land cover</b>	<b>Carbon accumulation rates (gC m<sup>-2</sup> yr<sup>-1</sup>)</b>	<b>Ref.</b>
<i>Tropical Asia</i>			
Central Kalimantan	Native Forest	22.3 (6.5 – 121.4)	Page et al. (2004)

Central Kalimantan	Native Forest	31.3 (16.6 – 73.2)	Dommain et al. (2011)
Central Sumatra, Indonesia	Secondary peat swamp forest	55	Hapsari et al. (2017)
Indonesia	Native Forest	72	Dommain et al. (2015)
Indonesia	Native Forest	94	Page et al. (2004)
Brunei (Borneo)	Peat swamp forest (mangrove forest)	300	Dommain et al.(2015)
Brunei (Borneo)	Peat swamp forest ( <i>Shorea albida</i> )	50	Dommain et al.(2015)
Kalimantan Central	Drained peatlands and forest	85	Page et al. (2004)
Kalimantan, Indonesia	Peat swamp forest	94.3	Page et al. (2004)
Malaysia	Rain forest	(79 – 147)	Kosugi et al. (2008)
Riau, Sumatra	Native Forest	81 ± 1.4	Neuzil et al. (1997)
Sarawak, Malaysia	Undrained peat swamp forest	8.46 ± 0.51	Wong et al. (2020)
Sarawak, Malaysia	Relatively disturbed secondary peat swamp forest	4.17 ± 0.69	Wong et al. (2020)
Sarawak, Malaysia	oil palm plantation	2.19 ± 0.21	Wong et al. (2020)
Southeast Asia	Native Forest	(30 – 270)	Page et al. (2004)
Southeast Asia	Drained affected peat swamp forest	(-499 – -174)	Rieley et al. (2008)
West Kalimantan	Drained peatlands and forest	(74 – 85)	Neuzil et al. (1997)
<i>Tropical America</i>			
Amazonia	Amazonian forests without El Niño event	-100	Saleska et al. (2003)
Amazonia	Amazonian forests with El Niño event	(100 – 200)	Saleska et al. (2003)
Amazonian peatlands	Forested peatland	(26 – 195)	Lähteenoja et al. (2009)
Costa Rica	Fragments of Yolillo ( <i>Raphia</i> )	(250 – 260)	Mitsch eta al. (2010)
French Guiana	Pristine tropical rain forest	-138	Bonalet et al. (2008)
Peru (Pastaza-Marañon)	Native Forest	52 ± 22 (36 – 85)	Lähteenoja et al. (2009)
Peru (Pastaza-Marañon)	Native Forest	(28 – 108)	Lähteenoja et al. (2012)
Cayambre-Coca	Peatlands in the Andes Mountains	51.1	Chimner & Ewel (2005)
<i>Tropical Africa</i>			
Cuvette Centrale, Congo	Native Forest	23.9 ± 5.8 (18.3 – 33.1)	Dargie et al. (2017)
Kenya	Tropical papyrus peatland	160	Jones and Humphries (2002)
Burundi	Buyongwe Swamp	125	Panujen (1996)
Burundi	Ndurumu Swamp	65	Panujen (1996)
Rwanda	Cyili Swamp	113	Panujen (1996)
Rwanda	Gishoma Swamp	(86-106)	Panujen (1996)
Rwanda	Mashya Bog	91	Panujen (1996)
Rwanda	Cyabaralika Swamp	33	Panujen (1996)
Rwanda	Kiguhu Swamp	31	Panujen (1996)

*Global scenario*

Tropical undisturbed	(24 – 300)	Kurnianto et al. (2015); Chimner (2004)
Tropical disturbed	(-499 – -174)	Rieley et al. (2008)
Non-Tropical	(-248 – 271)	Roulet et al. (2007); Olefeldt et al. (2012); Renou-Wilson et al. (2019)

495

496 Table 3 – Estimates of soil emission of CO<sub>2</sub> and CH<sub>4</sub> from peatlands (gC m<sup>-2</sup> yr<sup>-1</sup>) showing mean values and/or (range) if available. \*Values of  
497 CO<sub>2</sub> emission are from autotrophic and heterotrophic respiration and do not consider primary production. \*Positive values of soil emission mean  
498 carbon emission and negative mean carbon uptake.

499

System/Location	Land cover	CO <sub>2</sub> * CH <sub>4</sub> ** (gC m <sup>-2</sup> yr <sup>-1</sup> )		Ref.
<i>Tropical Asia</i>				
Malaysia	Forested peatland		0.02 (-0.05 – 0.10)	Melling et al. (2005)
Thailand	Forest peatland		9.81 ± 23.6 (1.7 – 110.4)	Ueda et al. (2000)
Central Kalimantan	Peat swamp forest floor	3493 ± 316	1.36 ± 0.57	Jauhiainen et al. (2004)
Indonesia	Peat swamp forest floor		1.35	Jauhiainen et al. (2004)
Indonesia	Poorly drained forest	174 ± 203		Hirano et al. (2012)
Indonesia	Drained forest	328 ± 204		Hirano et al. (2012)
Indonesia	Burnt and drained forest	499 ± 72		Hirano et al. (2012)
Indonesia	Tropical peatlands (including rice)		(4.4 – 19.3)	Hadi et al.(2005)
Kalimantan, Indonesia	Forested peatland	2777 ± 8322		Hirano et al.(2009)
Kalimantan, Indonesia	Secondary forest	4494	1.66	Hadi et al. (2005)
Kalimantan, Indonesia	Secondary forest	3460 (1603 - 35522)	4.4 (0 – 29)	Hadi et al. (2005)
Kalimantan, Indonesia	Forested peatland	3495 ± 315 (438 - 4818)	1.4 ± 5.7 (-0.09 – 3.1)	Jauhiainen et al. (2004)
Kalimantan, Indonesia	Forested peatland	4932 (692 - 13841)		Sundari et al. (2012)
Kalimantan, Indonesia	Forested peatland		9.6 ± 5.3	Inubushi et al. (1998)
Malaysia	Forested peatland	3889		Murayama and Bakar (1996)
Micronesia	Forested peatland	3469 ± 315 (2978 - 3522)		Chimner 2004
Sarawak, Malasia	Sago	(552 – 2146)		Melling et al. (2005)
Sarawak, Malasia	Oil palm	(403 – 29334)		Melling et al. (2005)
Sarawak, Malaysia	Forest ecosystem	(876 – 4669)		Melling et al. (2005)
South Kalimantan	Secondary forest	1200 ± 430	1.2 ± 0.4	Inubushi et al. (2003)
South Kalimantan	Secondary forest peatland to paddy field	(1200 – 1500)	(1.2 – 1.9)	Inubushi et al. (2003)
South Kalimantan	Changing land-use from Secondary forest to upland tended	(1000 – 2000)	(1.2 – 0.6)	Inubushi et al. (2003)

South Kalimantan	Abandoned upland crops field	990 ± 110	0.6 ± 0.7	Inubushi et al. (2003)
South Kalimantan	Abandoned paddy fields	1540 ± 290	1.9 ± 0.5	Inubushi et al. (2003)
Southeast Asia	Secondary Native Forest	3460	4.4	Hadi et al. (2005)
Southeast Asia	Secondary forest	3500	0.5	Hadi et al. (2005)
Southeast Asia	forest ecosystem	2100		Melling et al. (2005)
Southeast Asia	Lowland peatlands	250	1.09	Couwenberg et al. (2010)
Southeast Asia	Undrained peat swamp forest	3892 ± 304	1.36 ± 0.57	Rieley et al. (2008)
Southeast Asia	Drained uncultivated agricultural land	1928 ± 526	0.12 ± 0.09	Rieley et al. (2008)
Southeast Asia	Drained affected peat swamp forest	4000 ± 1091	1.3 ± 0.98	Rieley et al. (2008)
Southeast Asia	Burned areas	2900		Hadi et al. (2005)
Southeast Asia	Converting peat swamp forests into oil palm	5940		Murdiyarso et al. (2010)
Southeast Asia	Paddy field	1389	19.6	Radjagukguk (1997)
Southeast Asia	Rice-soybean rotation field	2019	2.6	Bouwman (1990)
Southeast Asia	Paddy field	1400	1.4	Hadi et al. (2005)
Southeast Asia	Rice-soybean rotation field	2000		Hadi et al. (2005)
Southeast Asia	Oil palm	1500		Melling et al. (2005)
Southeast Asia	Sago	1100		Melling et al. (2005)
Southeast Asia	Cultivation of palm oil ( <i>Elaeis guineensis</i> )	5940		Murdiyarso et al. (2010)
Southeast Asia	Rice crops (Mega Rice Project)	2178		Hadi et al. (2005)
Southeast Asia	Rice crops	1389	26.6	Hadi et al. (2005)
Southeast Asia	Agricultural Soils	2019	1.7	Hadi et al. (2005)
Southeast Asia	Horticulture	1500	1.9	Inubushi et al. (2003)
Southeast Asia	Cultures with nitrogen fertilization ( <i>Acacia</i> sp e <i>Metroxylon sagu</i> )	2130	2.6	Couwenberg et al. (2010)
Southeast Asia	Clear felled recovering peat Swamp forest	3400 ± 927	2 ± 1.5	Rieley et al. (2008)
Sumatra, Indonesia	Forested peatland	3329 ± 481.8	7.8 ± 4.2	Furukawa et al. (2005)
Sumatra, Indonesia	Forested peatland	2435 ± 140	10.6 ± 11.9	Furukawa et al. (2005)
Sumatra, Indonesia	Forested peatland	3294 ± 937	6.7 ± 2.4	Furukawa et al. (2005)
Sumatra, Indonesia	Natural swamp forest drained more than 5 years	267		Jauhainen et al. (2012)
<i>Tropical America</i>				
Bocas del Toro, Panama	Forested peatland ( <i>Raphia</i> sp.)	1857 (96 – 14839)	(1.1 – 110.6)	Wright et al. (2011)
Bocas del Toro, Panama	Forested peatland ( <i>Camptosperma</i> sp.)	2085 (543 – 7017)	(-7.7 – 31.8)	Wright et al. (2011)
Bocas del Toro, Panama	Open peatland ( <i>Cyperus</i> sp.)	1269 (61 – 8322)	(-9.3 – 27.2)	Wright et al. (2011)
Ka'au, Hawaii	Montane swamp	1112.5 ± 412		Chimner (2004)
Mauim, Hawaii	Montane peatland	2497 ± 657		Chimner (2004)
Orinoco Llanos, Venezuela	Palm peatland	263 (149 – 473)		Bracho & San José (1990)
Brazil (Lowlands in São Paulo state)	Pastureland (dry season and wet season)	3210	(-5.2 – 4.0)	Ribeiro et al. (2018)

Brazil (Lowlands in São Paulo state)	Native forest (dry season and wet season)	2174	(-3.1 – 4.2)	Ribeiro et al. (2018)
Brazil (Lowlands in São Paulo state)	Irrigated rice crop (dry season and wet season)	2074	3.1	Ribeiro et al. (2018)
<i>Global scenario</i>				
Tropical undisturbed		(250 – 13841)	( -9.3 – 110.6)	Kurnianto et al. (2015); Chimner (2004)
Tropical disturbed		(263 – 29334)	(1.9 – 26.6)	Kurnianto et al. (2015); Zoltai & Martikainen (1996)
Non-Tropical		411 ± 128	35.1 ± 2.6 (-7.1 – 2088.6)	Lund et al.(2010)

500

501

**502 Final remarks**

503 Tropical peatlands are different from boreal and temperate peatlands, particularly their  
504 climatic settings, peat matter formation, and vegetation coverage. They cover 90-170 Mha  
505 which represents 23% to 30% of the total area covered by peatlands throughout the world.  
506 Bringing together the most up-to-date estimates of peatland area, peat depth, peat volume and  
507 peat carbon content, we estimate that tropical peatlands store 152-288 Gt of carbon, which is  
508 significantly higher than the previously reported values. The large uncertainty in these estimates  
509 is related to methodological approach and the sparse field data on depth and C content, mainly  
510 in South America and Africa. Despite tropical peatlands covering a smaller area and storing  
511 less carbon than non-tropical peatlands, carbon accumulation rates are greater in the tropics and  
512 decrease with latitude, which gives tropical peatlands the important role of accumulating carbon  
513 emitted by human activities now and in the future.

514 Climate change is a threat to peatlands, but at local and regional levels, direct human  
515 interventions have played a more important role in impairing the capacity of peatlands to  
516 sequester carbon. In the tropical zone, the carbon sequestration rate of peatlands in Southeast  
517 Asia has changed from 79-300 (uptake) to (-499) – (-174) g m<sup>-2</sup> yr<sup>-1</sup> (emission) after direct  
518 human interference. Integrated development and management mechanisms supported by strong  
519 policies and meaningful incentives can balance this scenario and contribute to more effective  
520 measures.

521 The Amazon region potentially holds the largest natural peatland across the tropics.  
522 However, the factors that contribute to tropical peatland degradation are only well understood  
523 for Southeast Asian peatlands. To date, very few studies have addressed the impacts of peatland  
524 degradation in South America and in Africa. Thus, advancing to fill the current scientific  
525 knowledge gaps and incorporating local understanding is crucial for supporting policies geared  
526 toward managing and conserving undisturbed peatlands in these regions. Furthermore,

527 understanding and mapping peatlands in Brazil by encouraging research projects can enhance  
528 the current knowledge about the potential of these system to uptake and store carbon, and can  
529 encourage actions aimed to protect peatlands in this region. Due to the high level of  
530 conservation and the expected high capacity of carbon accumulation, the Amazon region  
531 peatlands are particularly important in the context of climate change mitigation.

532

### 533 **Acknowledgement**

534 We thank the financial support of the Coordenação de Aperfeiçoamento de Pessoal de Nível  
535 Superior (CAPES) through the program AUXPE-PROEX (number 0711/2018) and the São  
536 Paulo Research Foundation (FAPESP, project number 15/24201-0 and Nexus Project). The  
537 authors are grateful to Dr. G. Dargie for commenting on a draft and reorganize the manuscript  
538 and to Dr. M. Miranda for her valuable help with data and references.

539

### 540 **Data Sharing and Accessibility**

541 Data sharing is not applicable to this article as no new data were created or analyzed in this  
542 study.

543

### 544 **References**

- 545 Avis, C. A., Weaver, A. J., & Meissner, K. J. (2011). Reduction in areal extent of high-latitude  
546 wetlands in response to permafrost thaw. *Nature Geoscience*, 4(7), 444–448.  
547 <https://doi.org/10.1038/ngeo1160>
- 548 Baker, F. C. D. and K. H. R. and I. T. L. and E. T. A. M. and E. N. H. C. and O. L. and L. T.  
549 M. and E. V. S. and R. Z. and T. R. (2014). The distribution and amount of carbon in the  
550 largest peatland complex in Amazonia. *Environmental Research Letters*, 9(12), 124017.  
551 Retrieved from <http://stacks.iop.org/1748-9326/9/i=12/a=124017>
- 552 Baum, A., Rixen, T., & Samiaji, J. (2007). Relevance of peat draining rivers in central Sumatra  
553 for the riverine input of dissolved organic carbon into the ocean. *Estuarine, Coastal and*  
554 *Shelf Science*, 73(3), 563–570.

- 555 <https://doi.org/http://dx.doi.org/10.1016/j.ecss.2007.02.012>
- 556 Biancalani, R., & Avagyan, A. (2014). Towards climate-responsible peatlands management.  
557 *Mitigation of Climate Change in Agriculture Series (MICCA)*, (9).
- 558 Blodau, C. (2002). Carbon cycling in peatlands □ A review of processes and controls.  
559 *Environmental Reviews*, 10(2), 111–134. <https://doi.org/10.1139/a02-004>
- 560 BONAL, D., BOSCH, A., PONTON, S., GORET, J.-Y., BURBAN, B., GROSS, P., ...  
561 GRANIER, A. (2008). Impact of severe dry season on net ecosystem exchange in the  
562 Neotropical rainforest of French Guiana. *Global Change Biology*, 14(8), 1917–1933.  
563 <https://doi.org/10.1111/j.1365-2486.2008.01610.x>
- 564 Bourbonniere, R. A. (2009). Review of water chemistry research in natural and disturbed  
565 peatlands. *Canadian Water Resources Journal*, 34, 393+.
- 566 Bouwman, A. F. (1990). Global distribution of the major soils and land cover types. *Soils and*  
567 *the Greenhouse Effect*, 33–59.
- 568 Bracho, R., & San José, J. (1990). Energy fluxes in a morichal (swamp palm community) at the  
569 Orinoco Llanos, Venezuela: microclimate, water vapour and CO<sub>2</sub> exchange.  
570 *Photosynthetica*, 24(3), 468–494.
- 571 Bubier, J. L., Bhatia, G., Moore, T. R., Roulet, N. T., & Lafleur, P. M. (2003). Spatial and  
572 Temporal Variability in Growing-Season Net Ecosystem Carbon Dioxide Exchange at a  
573 Large Peatland in Ontario, Canada. *Ecosystems*, 6(4), 353–367.  
574 <https://doi.org/10.1007/s10021-003-0125-0>
- 575 Bwangoy, J.-R. B., Hansen, M. C., Roy, D. P., Grandi, G. De, & Justice, C. O. (2010). Wetland  
576 mapping in the Congo Basin using optical and radar remotely sensed data and derived  
577 topographical indices. *Remote Sensing of Environment*, 114(1), 73–86.  
578 <https://doi.org/http://dx.doi.org/10.1016/j.rse.2009.08.004>
- 579 Chimner, R.A. (2004). Soil respiration rates of tropical peatlands in Micronesia and Hawaii.  
580 *Wetlands*, 24(1), 51–56. Retrieved from [http://www.bioone.org/bioone/?request=get-](http://www.bioone.org/bioone/?request=get-journals-list&issn=0277-5212)  
581 [journals-list&issn=0277-5212](http://www.bioone.org/bioone/?request=get-journals-list&issn=0277-5212)
- 582 Chimner, Rodney A, & Ewel, K. C. (2005). A Tropical Freshwater Wetland: II. Production,  
583 Decomposition, and Peat Formation. *Wetlands Ecology and Management*, 13(6), 671–684.  
584 <https://doi.org/10.1007/s11273-005-0965-9>
- 585 Clair, T. A., Arp, P., Moore, T. R., Dalva, M., & Meng, F.-R. (2002). Gaseous carbon dioxide  
586 and methane, as well as dissolved organic carbon losses from a small temperate wetland  
587 under a changing climate. *Environmental Pollution*, 116, S143–S148.  
588 [https://doi.org/https://doi.org/10.1016/S0269-7491\(01\)00267-6](https://doi.org/https://doi.org/10.1016/S0269-7491(01)00267-6)

- 589 Clymo, R. S. (1987). The ecology of peatlands. *Science Progress (1933- )*, 71(4 (284)), 593–  
590 614. Retrieved from <http://www.jstor.org/stable/43420701>
- 591 Conrad, R. (2002). Conrad R.. Control of microbial methane production in wetland rice fields  
592 [Review]. *Nutr Cycl Agroecosyst* 64: 59-69. *Nutrient Cycling in Agroecosystems*, 64, 59–  
593 69. <https://doi.org/10.1023/A:1021178713988>
- 594 COUWENBERG, J., DOMMAIN, R., & JOOSTEN, H. (2010). Greenhouse gas fluxes from  
595 tropical peatlands in south-east Asia. *Global Change Biology*, 16(6), 1715–1732.  
596 <https://doi.org/10.1111/j.1365-2486.2009.02016.x>
- 597 Craft, C. B. T.-C. and R. W. (Ed.). (2016). *Index*. [https://doi.org/https://doi.org/10.1016/B978-](https://doi.org/https://doi.org/10.1016/B978-0-12-407232-9.18001-7)  
598 0-12-407232-9.18001-7
- 599 Craft, C., Washburn, C., & Parker, A. (2008). *Latitudinal Trends in Organic Carbon*  
600 *Accumulation in Temperate Freshwater Peatlands BT - Wastewater Treatment, Plant*  
601 *Dynamics and Management in Constructed and Natural Wetlands* (J. Vymazal, Ed.).  
602 [https://doi.org/10.1007/978-1-4020-8235-1\\_3](https://doi.org/10.1007/978-1-4020-8235-1_3)
- 603 Crow, S. E., & Wieder, R. K. (2005). SOURCES OF CO<sub>2</sub> EMISSION FROM A NORTHERN  
604 PEATLAND: ROOT RESPIRATION, EXUDATION, AND DECOMPOSITION.  
605 *Ecology*, 86(7), 1825–1834. <https://doi.org/10.1890/04-1575>
- 606 Dargie, G. C., Lawson, I. T., Rayden, T. J., Miles, L., Mitchard, E. T. A., Page, S. E., ... Lewis,  
607 S. L. (2019). Congo Basin peatlands: threats and conservation priorities. *Mitigation and*  
608 *Adaptation Strategies for Global Change*, 24(4), 669–686.  
609 <https://doi.org/10.1007/s11027-017-9774-8>
- 610 Dargie, G. C., Lewis, S. L., Lawson, I. T., Mitchard, E. T. A., Page, S. E., Bocko, Y. E., & Ifo,  
611 S. A. (2017). Age, extent and carbon storage of the central Congo Basin peatland complex.  
612 *Nature*, 542(7639), 86–90. Retrieved from <http://dx.doi.org/10.1038/nature21048>
- 613 Dommain, R., Cobb, A., Joosten, H., Glaser, P., Chua, A., Gandois, L., ... Harvey, C. (2015).  
614 Forest dynamics and tip-up pools drive pulses of high carbon accumulation rates in a  
615 tropical peat dome in Borneo (Southeast Asia). *Journal of Geophysical Research:*  
616 *Biogeosciences*, 120. <https://doi.org/10.1002/2014JG002796>
- 617 Dommain, R., Couwenberg, J., & Joosten, H. (2011). Development and carbon sequestration  
618 of tropical peat domes in south-east Asia: Links to post-glacial sea-level changes and  
619 Holocene climate variability. *Quaternary Science Reviews - QUATERNARY SCI REV*, 30,  
620 999–1010. <https://doi.org/10.1016/j.quascirev.2011.01.018>
- 621 Duffy, P. B., Brando, P., Asner, G. P., & Field, C. B. (2015). Projections of future  
622 meteorological drought and wet periods in the Amazon. *Proceedings of the National*

- 623 *Academy of Sciences*, 112(43), 13172 LP – 13177.  
624 <https://doi.org/10.1073/pnas.1421010112>
- 625 Fatoyinbo, L. (2017). Ecology: Vast peatlands found in the Congo Basin. *Nature*, 542(7639),  
626 38–39. Retrieved from <http://dx.doi.org/10.1038/542038b>
- 627 Finer, M., & Orta-Martínez, M. (2010). A second hydrocarbon boom threatens the Peruvian  
628 Amazon: trends, projections, and policy implications. *Environmental Research Letters*,  
629 5(1), 14012. <https://doi.org/10.1088/1748-9326/5/1/014012>
- 630 Finlayson, C. M., & Milton, G. R. (2018). *Peatlands BT - The Wetland Book: II: Distribution,*  
631 *Description, and Conservation* (C. M. Finlayson, G. R. Milton, R. C. Prentice, & N. C.  
632 Davidson, Eds.). [https://doi.org/10.1007/978-94-007-4001-3\\_202](https://doi.org/10.1007/978-94-007-4001-3_202)
- 633 Frey, K. E., & Smith, L. C. (2005). Amplified carbon release from vast West Siberian peatlands  
634 by 2100. *Geophysical Research Letters*, 32(9), n/a-n/a.  
635 <https://doi.org/10.1029/2004GL022025>
- 636 Furukawa, Y., Inubushi, K., Ali, M., Itang, A. M., & Tsuruta, H. (2005). Effect of changing  
637 groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical  
638 peat lands. *Nutrient Cycling in Agroecosystems*, 71(1), 81–91.  
639 <https://doi.org/10.1007/s10705-004-5286-5>
- 640 Gallego-Sala, A. V, Charman, D. J., Brewer, S., Page, S. E., Prentice, I. C., Friedlingstein, P.,  
641 ... Zhao, Y. (2018). Latitudinal limits to the predicted increase of the peatland carbon sink  
642 with warming. *Nature Climate Change*, 8(10), 907–913. [https://doi.org/10.1038/s41558-](https://doi.org/10.1038/s41558-018-0271-1)  
643 [018-0271-1](https://doi.org/10.1038/s41558-018-0271-1)
- 644 Gandois, L., Cobb, A., Lim, I., Kamariah, A. S., & Harvey, C. (2012). Impact of deforestation  
645 on solid and dissolved organic matter characteristics of tropical peat forests: Implications  
646 for carbon release. *Biogeochemistry*, 114, 1–17. [https://doi.org/10.1007/s10533-012-](https://doi.org/10.1007/s10533-012-9799-8)  
647 [9799-8](https://doi.org/10.1007/s10533-012-9799-8)
- 648 Gandois, L., Teisserenc, R., Cobb, A., Hei Ing, C., Lim, L., Kamariah, A. S., ... Harvey, C.  
649 (2014). Origin, composition, and transformation of dissolved organic matter in tropical  
650 peatlands. *Geochimica et Cosmochimica Acta*, 137, 35–47.  
651 <https://doi.org/10.1016/j.gca.2014.03.012>
- 652 Gillman, L. N., Wright, S. D., Cusens, J., McBride, P. D., Malhi, Y., & Whittaker, R. J. (2015).  
653 Latitude, productivity and species richness. *Global Ecology and Biogeography*, 24(1),  
654 107–117. <https://doi.org/10.1111/geb.12245>
- 655 Gorham, E. (1991). Northern Peatlands: Role in the Carbon Cycle and Probable Responses to  
656 Climatic Warming. *Ecological Applications*, 1(2), 182–195.

- 657 <https://doi.org/10.2307/1941811>
- 658 Grundlin, P.-L., & Guber, R. (2005). Peatlands and Mires of South Africa. *Biologiezentrum*  
659 *Linz/Austria*, (35), 379–396. Retrieved from [www.biologiezentrum.at](http://www.biologiezentrum.at)
- 660 Grundling, P.-L., & Grootjans, A. P. (2018). *Peatlands of Africa BT - The Wetland Book: II: Distribution, Description, and Conservation* (C. M. Finlayson, G. R. Milton, R. C.  
661 Prentice, & N. C. Davidson, Eds.). [https://doi.org/10.1007/978-94-007-4001-3\\_112](https://doi.org/10.1007/978-94-007-4001-3_112)
- 662 Gumbrecht, T., Roman-Cuesta, R. M., Verchot, L., Herold, M., Wittmann, F., Householder, E.,  
663 ... Murdiyarso, D. (2017). An expert system model for mapping tropical wetlands and  
664 peatlands reveals South America as the largest contributor. *Global Change Biology*, 23(9),  
665 3581–3599. <https://doi.org/10.1111/gcb.13689>
- 666 Gutiérrez-Vélez, V. H., DeFries, R., Pinedo-Vásquez, M., Uriarte, M., Padoch, C., Baethgen,  
667 W., ... Lim, Y. (2011). High-yield oil palm expansion spares land at the expense of forests  
668 in the Peruvian Amazon. *Environmental Research Letters*, 6(4), 44029.  
669 <https://doi.org/10.1088/1748-9326/6/4/044029>
- 670 Hadi, A., Inubushi, K., Furukawa, Y., Purnomo, E., Rasmadi, M., & Tsuruta, H. (2005).  
671 Greenhouse gas emissions from tropical peatlands of Kalimantan, Indonesia. *Nutrient*  
672 *Cycling in Agroecosystems*, 71(1), 73–80. <https://doi.org/10.1007/s10705-004-0380-2>
- 673 Haensler, A., Saeed, F., & Jacob, D. (2013). Assessing the robustness of projected precipitation  
674 changes over central Africa on the basis of a multitude of global and regional climate  
675 projections. *Climatic Change*, 121(2), 349–363. [https://doi.org/10.1007/s10584-013-](https://doi.org/10.1007/s10584-013-0863-8)  
676 [0863-8](https://doi.org/10.1007/s10584-013-0863-8)
- 677 Hapsari, K. A., Biagioni, S., Jennerjahn, T. C., Reimer, P. M., Saad, A., Achnopha, Y., ...  
678 Behling, H. (2017). Environmental dynamics and carbon accumulation rate of a tropical  
679 peatland in Central Sumatra, Indonesia. *Quaternary Science Reviews*, 169, 173–187.  
680 <https://doi.org/https://doi.org/10.1016/j.quascirev.2017.05.026>
- 681 Harenda, K., Lamentowicz, M., Samson, M., & Chojnicki, B. (2018). The Role of Peatlands  
682 and Their Carbon Storage Function in the Context of Climate Change. In *GeoPlanet: Earth*  
683 *and Planetary Sciences* (pp. 169–187). [https://doi.org/10.1007/978-3-319-71788-3\\_12](https://doi.org/10.1007/978-3-319-71788-3_12)
- 684 Hirano, T., Jauhiainen, J., Inoue, T., & Takahashi, H. (2009). Controls on the Carbon Balance  
685 of Tropical Peatlands. *Ecosystems*, 12(6), 873–887. [https://doi.org/10.1007/s10021-008-](https://doi.org/10.1007/s10021-008-9209-1)  
686 [9209-1](https://doi.org/10.1007/s10021-008-9209-1)
- 687 Hirano, T., Segah, H., Kusin, K., Limin, S., Takahashi, H., & Osaki, M. (2012). Effects of  
688 disturbances on the carbon balance of tropical peat swamp forests. *Global Change*  
689 *Biology*, 18(11), 3410–3422. <https://doi.org/10.1111/j.1365-2486.2012.02793.x>
- 690

- 691 Hodgkins, S. B., Richardson, C. J., Dommain, R., Wang, H., Glaser, P. H., Verbeke, B., ...  
692 Chanton, J. P. (2018). Tropical peatland carbon storage linked to global latitudinal trends  
693 in peat recalcitrance. *Nature Communications*, 9. [https://doi.org/10.1038/s41467-018-](https://doi.org/10.1038/s41467-018-06050-2)  
694 06050-2
- 695 Hooijer, A., Page, S., Canadell, J. G., Silvius, M., Kwadijk, J., Wosten, H., & Jauhiainen, J.  
696 (2010). *Current and future CO2 emissions from drained peatlands in Southeast Asia*. 7,  
697 1505–1514. Retrieved from <http://edepot.wur.nl/160538>
- 698 Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A.,  
699 ... Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian  
700 tropical forests. *Nature*, 579(7797), 80–87. <https://doi.org/10.1038/s41586-020-2035-0>
- 701 Huijnen, V., Wooster, M. J., Kaiser, J. W., Gaveau, D. L. A., Flemming, J., Parrington, M., ...  
702 van Weele, M. (2016). Fire carbon emissions over maritime southeast Asia in 2015 largest  
703 since 1997. *Scientific Reports*, 6(1), 26886. <https://doi.org/10.1038/srep26886>
- 704 Immirzi, C. ., & Maltby, E. (1993). The Global Status of Peatlands and their Role in Carbon  
705 Cycling, a report for Friends of the Earth by the Wetland Ecosystem. *Oryx*, 27(2), 127.  
706 [https://doi.org/DOI: 10.1017/S0030605300020755](https://doi.org/DOI:10.1017/S0030605300020755)
- 707 INGRAM, H. A. P. (1978). SOIL LAYERS IN MIRES: FUNCTION AND TERMINOLOGY.  
708 *Journal of Soil Science*, 29(2), 224–227. [https://doi.org/10.1111/j.1365-](https://doi.org/10.1111/j.1365-2389.1978.tb02053.x)  
709 2389.1978.tb02053.x
- 710 International Peatland Society (IPS). (n.d.). Types of peatlands. Retrieved from  
711 <https://peatlands.org/peatlands/types-of-peatlands/>
- 712 Inubushi, K., Furukawa, Y., Hadi, A., Purnomo, E., & Tsuruta, H. (2003). Seasonal changes of  
713 CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes in relation to land-use change in tropical peatlands located in  
714 coastal area of South Kalimantan. *Chemosphere*, 52(3), 603–608.  
715 [https://doi.org/http://dx.doi.org/10.1016/S0045-6535\(03\)00242-X](https://doi.org/http://dx.doi.org/10.1016/S0045-6535(03)00242-X)
- 716 Inubushi, K., Hadi, A., Okazaki, M., & Yonebayashi, K. (1998). Effect of converting wetland  
717 forest to sago palm plantations on methane gas flux and organic carbon dynamics in  
718 tropical peat soil. *Hydrological Processes*, 12(13-14), 2073–2080.  
719 [https://doi.org/10.1002/\(SICI\)1099-1085\(19981030\)12:13/14<2073::AID-](https://doi.org/10.1002/(SICI)1099-1085(19981030)12:13/14<2073::AID-HYP720>3.0.CO;2-K)  
720 HYP720>3.0.CO;2-K
- 721 Ise, T., Dunn, A. L., Wofsy, S. C., & Moorcroft, P. R. (2008). High sensitivity of peat  
722 decomposition to climate change through water-table feedback. *Nature Geoscience*, 1(11),  
723 763–766. <https://doi.org/10.1038/ngeo331>
- 724 Jaenicke, J., Rieley, J. O., Mott, C., Kimman, P., & Siebert, F. (2008). Determination of the

- 725 amount of carbon stored in Indonesian peatlands. *Geoderma*, 147(3), 151–158.  
726 <https://doi.org/http://dx.doi.org/10.1016/j.geoderma.2008.08.008>
- 727 Jauhiainen, J., Hooijer, A., & Page, S. E. (2012). Carbon dioxide emissions from an *Acacia*  
728 plantation on peatland in Sumatra, Indonesia. *Biogeosciences*, 9(2), 617–630.  
729 <https://doi.org/10.5194/bg-9-617-2012>
- 730 Jauhiainen, Jyrki, Jaya, A., Inoue, T., Heikkinen, J. E. P., Martikainen, P., & Vasander, H.  
731 (2004). Carbon balance in managed tropical peat in central Kalimantan, Indonesia. *Proc.*  
732 *12th Int. Peat Congr*, 653–659.
- 733 Jones, M. B., & Humphries, S. W. (2002). Impacts of the C4 sedge *Cyperus papyrus* L. on  
734 carbon and water fluxes in an African wetland. *Hydrobiologia*, 488(1), 107–113.  
735 <https://doi.org/10.1023/A:1023370329097>
- 736 Joosten, H. (2009). *The Global Peatland CO2 Picture: peatland status and drainage related*  
737 *emissions in all countries of the world.* (p. 35 pp.). p. 35 pp. Wageningen: Wetlands  
738 International.
- 739 Joseph, H. (2005). Peatland hydrology and carbon release: why small-scale process matters.  
740 *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*  
741 *Engineering Sciences*, 363(1837), 2891–2913. <https://doi.org/10.1098/rsta.2005.1671>
- 742 Kahn, F., & Mejia, K. (1990). Palm communities in wetland forest ecosystems of Peruvian  
743 Amazonia. *Forest Ecology and Management*, 33–34, 169–179.  
744 [https://doi.org/https://doi.org/10.1016/0378-1127\(90\)90191-D](https://doi.org/https://doi.org/10.1016/0378-1127(90)90191-D)
- 745 Kelly (Letcher), R. A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., ElSawah, S., Hamilton, S.  
746 H., ... Voinov, A. A. (2013). Selecting among five common modelling approaches for  
747 integrated environmental assessment and management. *Environmental Modelling &*  
748 *Software*, 47, 159–181. <https://doi.org/https://doi.org/10.1016/j.envsoft.2013.05.005>
- 749 Kelly, T. J., Lawson, I. T., Roucoux, K. H., Baker, T. R., Jones, T. D., & Sanderson, N. K.  
750 (2017). The vegetation history of an Amazonian domed peatland. *Palaeogeography,*  
751 *Palaeoclimatology,* *Palaeoecology*, 468, 129–141.  
752 <https://doi.org/https://doi.org/10.1016/j.palaeo.2016.11.039>
- 753 Könönen, M., Jauhiainen, J., Laiho, R., Kusin, K., & Vasander, H. (2015). Physical and  
754 chemical properties of tropical peat under stabilised land uses. *Mires and Peat*, 16, Article  
755 8.
- 756 Könönen, M., Jauhiainen, J., Laiho, R., Spetz, P., Kusin, K., Limin, S., & Vasander, H. (2016).  
757 Land use increases the recalcitrance of tropical peat. *Wetlands Ecology and Management*,  
758 24(6), 717–731. <https://doi.org/10.1007/s11273-016-9498-7>

- 759 Kosugi, Y., Takanashi, S., Ohkubo, S., Matsuo, N., Tani, M., Mitani, T., ... Nik, A. R. (2008).  
760 CO<sub>2</sub> exchange of a tropical rainforest at Pasoh in Peninsular Malaysia. *Agricultural and*  
761 *Forest Meteorology*, 148(3), 439–452.  
762 <https://doi.org/https://doi.org/10.1016/j.agrformet.2007.10.007>
- 763 Kurnianto, S., Warren, M., Talbot, J., Kauffman, B., Murdiyarso, D., & Frohking, S. (2015).  
764 Carbon accumulation of tropical peatlands over millennia: a modeling approach. *Global*  
765 *Change Biology*, 21(1), 431–444. <https://doi.org/10.1111/gcb.12672>
- 766 Lähteenoja, O., Flores, B., & Nelson, B. (2013). Tropical Peat Accumulation in Central  
767 Amazonia. *Wetlands*, 33(3), 495–503. <https://doi.org/10.1007/s13157-013-0406-0>
- 768 Lähteenoja, O., Reátegui, Y. R., Räsänen, M., Torres, D. D. C., Oinonen, M., & Page, S. (2012).  
769 The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland  
770 basin, Peru. *Global Change Biology*, 18(1), 164–178. [https://doi.org/10.1111/j.1365-](https://doi.org/10.1111/j.1365-2486.2011.02504.x)  
771 [2486.2011.02504.x](https://doi.org/10.1111/j.1365-2486.2011.02504.x)
- 772 Lähteenoja, O., Ruokolainen, K., Schulman, L., & Alvarez, J. (2009). Amazonian floodplains  
773 harbour minerotrophic and ombrotrophic peatlands. *CATENA*, 79(2), 140–145.  
774 <https://doi.org/https://doi.org/10.1016/j.catena.2009.06.006>
- 775 LÄHTEENOJA, O., RUOKOLAINEN, K., SCHULMAN, L., & OINONEN, M. (2009).  
776 Amazonian peatlands: an ignored C sink and potential source. *Global Change Biology*,  
777 15(9), 2311–2320. <https://doi.org/10.1111/j.1365-2486.2009.01920.x>
- 778 Leifeld, J., & Menichetti, L. (2018). The underappreciated potential of peatlands in global  
779 climate change mitigation strategies. *Nature Communications*, 9(1), 1071.  
780 <https://doi.org/10.1038/s41467-018-03406-6>
- 781 Leng, L. Y., Ahmed, O. H., & Jalloh, M. B. (2019). Brief review on climate change and tropical  
782 peatlands. *Geoscience Frontiers*, 10(2), 373–380.  
783 <https://doi.org/https://doi.org/10.1016/j.gsf.2017.12.018>
- 784 Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., ... Schaepman-  
785 Strub, G. (2008). Peatlands and the carbon cycle: from local processes to global  
786 implications – a synthesis. *Biogeosciences*, 5(5), 1475–1491. [https://doi.org/10.5194/bg-](https://doi.org/10.5194/bg-5-1475-2008)  
787 [5-1475-2008](https://doi.org/10.5194/bg-5-1475-2008)
- 788 LUND, M., LAFLEUR, P. M., ROULET, N. T., LINDROTH, A., CHRISTENSEN, T. R.,  
789 AURELA, M., ... NILSSON, M. B. (2010). Variability in exchange of CO<sub>2</sub> across 12  
790 northern peatland and tundra sites. *Global Change Biology*, 16(9), 2436–2448.  
791 <https://doi.org/10.1111/j.1365-2486.2009.02104.x>
- 792 Mäkiranta, P., Laiho, R., Fritze, H., Hytönen, J., Laine, J., & Minkkinen, K. (2009). Indirect

- 793 regulation of heterotrophic peat soil respiration by water level via microbial community  
794 structure and temperature sensitivity. *Soil Biology and Biochemistry*, 41(4), 695–703.  
795 <https://doi.org/https://doi.org/10.1016/j.soilbio.2009.01.004>
- 796 Martikainen, P. J., Nykänen, H., Alm, J., & Silvola, J. (1995). Change in fluxes of carbon  
797 dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy.  
798 *Plant and Soil*, 168(1), 571–577. <https://doi.org/10.1007/BF00029370>
- 799 McWethy, D. B., Neumann, F. H., Steinbruch, F., Ryan, C. M., & Valsecchi, V. (2016). Late  
800 Quaternary vegetation development and disturbance dynamics from a peatland on Mount  
801 Gorongosa, central Mozambique. *Quaternary Science Reviews*, 137, 221–233.  
802 <https://doi.org/https://doi.org/10.1016/j.quascirev.2016.02.004>
- 803 Melling, L., Hatano, R., & Goh, K. J. (2005). Soil CO<sub>2</sub> flux from three ecosystems in tropical  
804 peatland of Sarawak, Malaysia. *Tellus B: Chemical and Physical Meteorology*, 57(1), 1–  
805 11. <https://doi.org/10.3402/tellusb.v57i1.16772>
- 806 Miettinen, J., & Liew, S. C. (2010). Status of Peatland Degradation and Development in  
807 Sumatra and Kalimantan. *AMBIO: A Journal of the Human Environment*, 39(5–6), 394–  
808 401. <https://doi.org/10.1007/s13280-010-0051-2>
- 809 Miettinen, J., Shi, C., & Liew, S. C. (2012). Two decades of destruction in Southeast Asia's  
810 peat swamp forests. *Frontiers in Ecology and the Environment*, 10(3), 124–128.  
811 <https://doi.org/10.1890/100236>
- 812 Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of  
813 Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global  
814 Ecology and Conservation*, 6, 67–78.  
815 <https://doi.org/http://dx.doi.org/10.1016/j.gecco.2016.02.004>
- 816 Mitsch, W. J., Nahlik, A., Wolski, P., Bernal, B., Zhang, L., & Ramberg, L. (2010). Tropical  
817 wetlands: seasonal hydrologic pulsing, carbon sequestration, and methane emissions.  
818 *Wetlands Ecology and Management*, 18(5), 573–586. [https://doi.org/10.1007/s11273-009-  
819 9164-4](https://doi.org/10.1007/s11273-009-9164-4)
- 820 Moore, S., Evans, C. D., Page, S. E., Garnett, M. H., Jones, T. G., Freeman, C., ... Gauci, V.  
821 (2013). Deep instability of deforested tropical peatlands revealed by fluvial organic carbon  
822 fluxes. *Nature*, 493(7434), 660–663. Retrieved from  
823 <http://dx.doi.org/10.1038/nature11818>
- 824 Murdiyarso, D., Hergoualch, K., & Verchot, L. (2010). *Opportunities for reducing greenhouse  
825 gas emissions in tropical peatlands* (Vol. 107, p. 19655–19660). Vol. 107, p.  
826 19655–19660. <https://doi.org/http://dx.doi.org/10.1073/pnas.0911966107>

- 827 Neuzil, S. G. (1997). Onset and rate of peat and carbon accumulation in four domed  
828 ombrogenous peat deposit. In R. And & S. E. Page (Eds.), *Biodiversity and Sustainability*  
829 *of Tropical Peatlands – Proceedings of the International Symposium on Tropical*  
830 *Peatlands* (pp. 55–72). Palangkaraya, Indonesia; Cardigan.
- 831 Oktarita, S., Hergoualc’h, K., Anwar, S., & Verchot, L. V. (2017). Substantial N<sub>2</sub>O emissions  
832 from peat decomposition and N fertilization in an oil palm plantation exacerbated by  
833 hotspots. *Environmental Research Letters*, *12*(10), 104007. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/aa80f1)  
834 [9326/aa80f1](https://doi.org/10.1088/1748-9326/aa80f1)
- 835 Olefeldt, D., Roulet, N. T., Bergeron, O., Crill, P., Bäckstrand, K., & Christensen, T. R. (2012).  
836 Net carbon accumulation of a high-latitude permafrost tundra mire similar to permafrost-  
837 free peatlands. *Geophysical Research Letters*, *39*(3).  
838 <https://doi.org/10.1029/2011GL050355>
- 839 PAGE, S. E., RIELEY, J. O., & BANKS, C. J. (2011). Global and regional importance of the  
840 tropical peatland carbon pool. *Global Change Biology*, *17*(2), 798–818.  
841 <https://doi.org/10.1111/j.1365-2486.2010.02279.x>
- 842 Page, S E, & Baird, A. J. (2016). Peatlands and Global Change: Response and Resilience.  
843 *Annual Review of Environment and Resources*, *41*(1), 35–57.  
844 <https://doi.org/10.1146/annurev-environ-110615-085520>
- 845 Page, S E, Rieley, J. O., Shotyk, W., & Weiss, D. (1999). Interdependence of peat and  
846 vegetation in a tropical peat swamp forest. *Philosophical Transactions of the Royal Society*  
847 *of London. Series B, Biological Sciences*, *354*(1391), 1885–1897.  
848 <https://doi.org/10.1098/rstb.1999.0529>
- 849 Page, S E, Rieley, J. O., & Wüst, R. (2006). Chapter 7 Lowland tropical peatlands of Southeast  
850 Asia. In I. P. Martini, A. Martínez Cortizas, & W. B. T.-D. in E. S. P. Chesworth (Eds.),  
851 *Peatlands* (Vol. 9, pp. 145–172). [https://doi.org/https://doi.org/10.1016/S0928-](https://doi.org/10.1016/S0928-2025(06)09007-9)  
852 [2025\(06\)09007-9](https://doi.org/10.1016/S0928-2025(06)09007-9)
- 853 Page, S E, Siegert, F., Rieley, J. O., Boehm, H. D. V, Jaya, A., Limin, S., ... Limin, S. H. (n.d.).  
854 Inception, history and development of peatlands in the Amazon Basin. *Dynamics*, *19*, 625–  
855 635.
- 856 Page, S E, Wüst, R. A. J., Weiss, D., Rieley, J. O., Shotyk, W., & Limin, S. H. (2004). A record  
857 of Late Pleistocene and Holocene carbon accumulation and climate change from an  
858 equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future  
859 carbon dynamics. *Journal of Quaternary Science*, *19*(7), 625–635.  
860 <https://doi.org/10.1002/jqs.884>

- 861 Page, Susan E, Siegert, F., Rieley, J. O., Boehm, H.-D. V, Jaya, A., & Limin, S. (2002). The  
862 amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*,  
863 *420*(6911), 61–65. Retrieved from <http://dx.doi.org/10.1038/nature01131>
- 864 Pajunen, H. (1996). Mires as late Quaternary accumulation basins in Rwanda and Burundi,  
865 Central Africa. In *Geological Survey of Finland* (p. 106).
- 866 Ponette-González, A. G., Curran, L. M., Pittman, A. M., Carlson, K. M., Steele, B. G.,  
867 Ratnasari, D., ... Weathers, K. C. (2016). Biomass burning drives atmospheric nutrient  
868 redistribution within forested peatlands in Borneo. *Environmental Research Letters*, *11*(8),  
869 85003. <https://doi.org/10.1088/1748-9326/11/8/085003>
- 870 Porporato, A., Laio, F., Ridolfi, L., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled  
871 ecosystems: active role in hydrologic processes and response to water stress: III.  
872 Vegetation water stress. *Advances in Water Resources*, *24*(7), 725–744.  
873 [https://doi.org/https://doi.org/10.1016/S0309-1708\(01\)00006-9](https://doi.org/https://doi.org/10.1016/S0309-1708(01)00006-9)
- 874 Qiu, C., Zhu, D., Ciais, P., Guenet, B., & Peng, S. (2020). The role of northern peatlands in the  
875 global carbon cycle for the 21st century. *Global Ecology and Biogeography*, *29*(5), 956–  
876 973. <https://doi.org/10.1111/geb.13081>
- 877 Radjagukguk. B. (1997). Peat soil of Indonesia: Location, classification and problem for  
878 sustainability. In R. J.O. & P. S.E (Eds.), *Biodiversity and Sustainability of Tropical*  
879 *Peatlands* (pp. 42–54). Samara Publishing Ltd.
- 880 Raupach, M., Gloor, M., Sarmiento, J., G. Canadell, J., Frölicher, T., Gasser, T., ... Trudinger,  
881 C. (2013). The declining uptake rate of atmospheric CO<sub>2</sub> by land and ocean sinks. In  
882 *Biogeosciences Discussions* (Vol. 10). <https://doi.org/10.5194/bgd-10-18407-2013>
- 883 Reay, D., Smith, P., Christensen, T. R., James, R., & Clark, H. (2018). Methane and Global  
884 Environmental Change. *Annual Review of Environment and Resources*, *43*.  
885 <https://doi.org/10.1146/annurev-environ-102017-030154>
- 886 Rebelo, L.-M., Finlayson, C. M., & Nagabhatla, N. (2009). Remote sensing and GIS for wetland  
887 inventory, mapping and change analysis. *Journal of Environmental Management*, *90*(7),  
888 2144–2153.
- 889 Reiche, M., Gleixner, G., & Küsel, K. (2010). Effect of peat quality on microbial greenhouse  
890 gas formation in an acidic fen. *Biogeosciences*, *7*(1), 187–198.
- 891 Renou-Wilson, F., Moser, G., Fallon, D., Farrell, C. A., Müller, C., & Wilson, D. (2019).  
892 Rewetting degraded peatlands for climate and biodiversity benefits: Results from two  
893 raised bogs. *Ecological Engineering*, *127*, 547–560.  
894 <https://doi.org/https://doi.org/10.1016/j.ecoleng.2018.02.014>

- 895 Ribeiro, K., Pacheco, F. S., Ferreira, W., Sousa Neto, E. R., Ometto, J. P., Forti, M. C., ...  
896 Alvalá, P. C. (2018). Effect of land use and land cover on greenhouse gas emissions from  
897 peatlands in the Paraíba Valley, Brazil. *AGUFM*, 2018, GC21I-1213.
- 898 Rieley, J., Wüst, R., Jauhiainen, J., Page, S., Wösten, H., Hooijer, A., ... Stahlhut, M. (2008).  
899 Tropical peatlands: Carbon stores, carbon gas emissions and contribution to climate  
900 change processes. In *Peatlands and climate change* (pp. 148–181). University of Calgary,  
901 Canada.
- 902 Roucoux, K. H., Lawson, I. T., Baker, T. R., Del Castillo Torres, D., Draper, F. C., Lähteenoja,  
903 O., ... Vriesendorp, C. F. (2017). Threats to intact tropical peatlands and opportunities for  
904 their conservation. *Conservation Biology*, 31(6), 1283–1292.  
905 <https://doi.org/10.1111/cobi.12925>
- 906 Roulet, N. (2012). Peatlands, carbon storage, greenhouse gases, and the Kyoto Protocol:  
907 Prospects and significance for Canada. *Wetlands*, 20, 605–615.  
908 [https://doi.org/10.1672/0277-5212\(2000\)020\[0605:PCSGGA\]2.0.CO;2](https://doi.org/10.1672/0277-5212(2000)020[0605:PCSGGA]2.0.CO;2)
- 909 ROULET, N. T., LAFLEUR, P. M., RICHARD, P. J. H., MOORE, T. I. M. R., HUMPHREYS,  
910 E. R., & BUBIER, J. (2007). Contemporary carbon balance and late Holocene carbon  
911 accumulation in a northern peatland. *Global Change Biology*, 13(2), 397–411.  
912 <https://doi.org/10.1111/j.1365-2486.2006.01292.x>
- 913 Rudiyanto, Setiawan, B. I., Arief, C., Saptomo, S. K., Gunawan, A., Kuswarman, ... Indriyanto,  
914 H. (2015). Estimating Distribution of Carbon Stock in Tropical Peatland Using a  
915 Combination of an Empirical Peat Depth Model and GIS. *Procedia Environmental*  
916 *Sciences*, 24, 152–157. <https://doi.org/https://doi.org/10.1016/j.proenv.2015.03.020>
- 917 Saleska, S. R., Miller, S. D., Matross, D. M., Goulden, M. L., Wofsy, S. C., da Rocha, H. R.,  
918 ... Silva, H. (2003). Carbon in Amazon forests: unexpected seasonal fluxes and  
919 disturbance-induced losses. *Science (New York, N.Y.)*, 302(5650), 1554–1557.  
920 <https://doi.org/10.1126/science.1091165>
- 921 San José, J., Montes, R., Nikonova, N., Grace, J., Buendía, C., Davidson, E. a., ... Tayasu, I.  
922 (2013). Effects of simulated drought and nitrogen fertilizer on plant productivity and  
923 nitrous oxide (N<sub>2</sub>O) emissions of two pastures. *Biogeosciences*, 55(1–2), 291–302.  
924 <https://doi.org/10.1007/s11104-012-1248-x>
- 925 Scharlemann, J. P. W., Tanner, E. V. J., Hiederer, R., & Kapos, V. (2014). Global soil carbon:  
926 understanding and managing the largest terrestrial carbon pool. *Carbon Management*,  
927 5(1), 81–91. <https://doi.org/10.4155/cmt.13.77>
- 928 Schumann, M., & Joosten, H. (2008). *Global peatland restoration manual*. Retrieved from

- 929 [http://www.imcg.net/media/download\\_gallery/books/gprm\\_01.pdf](http://www.imcg.net/media/download_gallery/books/gprm_01.pdf)
- 930 Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., & Martikainen, P. J. (1996).  $\mathrm{CO}_2$
- 931 Fluxes from Peat in Boreal Mires under Varying Temperature and Moisture Conditions.
- 932 *Journal of Ecology*, 84(2), 219–228. <https://doi.org/10.2307/2261357>
- 933 Sjögersten, S., Black, C., Evers, S., Hoyos-Santillan, J., Wright, E., & Turner, B. (2014).
- 934 Tropical wetlands: A missing link in the global carbon cycle? *Global Biogeochemical*
- 935 *Cycles*. <https://doi.org/10.1002/2014GB004844>
- 936 Sorensen, K. W. (1993). Indonesian peat swamp forests and their role as a carbon sink.
- 937 *Chemosphere*, 27(6), 1065–1082.
- 938 Sorribas, M. V., Paiva, R. C. D., Melack, J. M., Bravo, J. M., Jones, C., Carvalho, L., ... Costa,
- 939 M. H. (2016). Projections of climate change effects on discharge and inundation in the
- 940 Amazon basin. *Climatic Change*, 136(3), 555–570. <https://doi.org/10.1007/s10584-016->
- 941 1640-2
- 942 Spahni, R., Joos, F., Stocker, B. D., Steinacher, M., & Yu, Z. C. (2013). Transient simulations
- 943 of the carbon and nitrogen dynamics in northern peatlands: from the Last Glacial
- 944 Maximum to the 21st century. *Clim. Past*, 9(3), 1287–1308. <https://doi.org/10.5194/cp-9->
- 945 1287-2013
- 946 Swindles, G. T., Morris, P. J., Whitney, B., Galloway, J. M., Gałka, M., Gallego-Sala, A., ...
- 947 Läähteenoja, O. (2018). Ecosystem state shifts during long-term development of an
- 948 Amazonian peatland. *Global Change Biology*, 24(2), 738–757.
- 949 <https://doi.org/10.1111/gcb.13950>
- 950 Takada, M., Shimada, S., & Takahashi, H. (2016). *Tropical Peat Formation BT - Tropical*
- 951 *Peatland Ecosystems* (M. Osaki & N. Tsuji, Eds.). <https://doi.org/10.1007/978-4-431->
- 952 55681-7\_8
- 953 Tian, H., Chen, G., Lu, C., Xu, X., Ren, W., Zhang, B., ... Wofsy, S. (2015). Global methane
- 954 and nitrous oxide emissions from terrestrial ecosystems due to multiple environmental
- 955 changes. *Ecosystem Health and Sustainability*, 1(1), 1–20.
- 956 <https://doi.org/10.1890/EHS14-0015.1>
- 957 Treat, C. C., Kleinen, T., Broothaerts, N., Dalton, A. S., Dommain, R., Douglas, T. A., ...
- 958 Brovkin, V. (2019). Widespread global peatland establishment and persistence over the
- 959 last 130,000 y. *Proceedings of the National Academy of Sciences*, 116(11), 4822 LP –
- 960 4827. <https://doi.org/10.1073/pnas.1813305116>
- 961 Ueda, S., Go, C.-S. U., Yoshioka, T., Yoshida\* ast;, N., Wada, E., Miyajima\* ast;, T., ...
- 962 Boonprakub, S. (2000). Dynamics of dissolved O<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O in a tropical

- 963 coastal swamp in southern Thailand. *Biogeochemistry*, 49(3), 191–215.  
964 <https://doi.org/10.1023/A:1006393214432>
- 965 Vitt, D. H. (2013). *Peatlands* ☆ (B. B. T.-E. of E. (Second E. Fath, Ed.).  
966 <https://doi.org/https://doi.org/10.1016/B978-0-12-409548-9.00741-7>
- 967 Wang, H., Richardson, C. J., & Ho, M. (2015). Dual controls on carbon loss during drought  
968 in peatlands. *Nature Climate Change*, 5, 584.
- 969 Wang, S., Zhuang, Q., Lähteenoja, O., Draper, F. C., & Cadillo-Quiroz, H. (2018). Potential  
970 shift from a carbon sink to a source in Amazonian peatlands under a changing climate.  
971 *Proceedings of the National Academy of Sciences*, 115(49), 12407 LP – 12412.  
972 <https://doi.org/10.1073/pnas.1801317115>
- 973 Warner, B. G., & Rubec, C. D. A. (1997). *The Canadian Wetland Classification System* (2nd  
974 ed.). National Wetlands Working Group.
- 975 Warren, M., Hergoualc'h, K., Kauffman, J. B., Murdiyarso, D., & Kolka, R. (2017). An  
976 appraisal of Indonesia's immense peat carbon stock using national peatland maps:  
977 uncertainties and potential losses from conversion. *Carbon Balance and Management*,  
978 12(1), 12. <https://doi.org/10.1186/s13021-017-0080-2>
- 979 Wilson, S., Griffiths, M., & Anielski, M. (2001). *The Alberta GPI Accounts: Wetlands and*  
980 *Peatlands*. Retrieved from  
981 [http://www.pembina.org/reports/23\\_wetlands\\_and\\_peatlands.pdf](http://www.pembina.org/reports/23_wetlands_and_peatlands.pdf)
- 982 Wong, G. X., Hirata, R., Hirano, T., Kiew, F., Aeries, E. B., Musin, K. K., ... Melling, L.  
983 (2020). How do land use practices affect methane emissions from tropical peat  
984 ecosystems? *Agricultural and Forest Meteorology*, 282–283, 107869.  
985 <https://doi.org/https://doi.org/10.1016/j.agrformet.2019.107869>
- 986 Worrall, F., Chapman, P., Holden, J., Evans, C., Artz, R., Smith, P., & Grayson, R. (2011). *A*  
987 *review of current evidence on carbon fluxes and greenhouse gas emissions from UK*  
988 *peatlands*. <https://doi.org/09638901>
- 989 Wösten, J. H. M., Clymans, E., Page, S. E., Rieley, J. O., & Limin, S. H. (2008). Peat–water  
990 interrelationships in a tropical peatland ecosystem in Southeast Asia. *CATENA*, 73(2),  
991 212–224. <https://doi.org/https://doi.org/10.1016/j.catena.2007.07.010>
- 992 WRIGHT, E. L., BLACK, C. R., CHEESMAN, A. W., DRAGE, T., LARGE, D., TURNER,  
993 B. L., & SJÖGERSTEN, S. (2011). Contribution of subsurface peat to CO<sub>2</sub> and CH<sub>4</sub>  
994 fluxes in a neotropical peatland. *Global Change Biology*, 17(9), 2867–2881.  
995 <https://doi.org/10.1111/j.1365-2486.2011.02448.x>
- 996 Wu, J., & Roulet, N. T. (2014). Climate change reduces the capacity of northern peatlands to

- 997 absorb the atmospheric carbon dioxide: The different responses of bogs and fens. *Global*  
998 *Biogeochemical Cycles*, 28(10), 1005–1024. <https://doi.org/10.1002/2014GB004845>
- 999 Xu, J., Morris, P. J., Liu, J., & Holden, J. (2018). PEATMAP: Refining estimates of global  
1000 peatland distribution based on a meta-analysis. *CATENA*, 160, 134–140.  
1001 <https://doi.org/https://doi.org/10.1016/j.catena.2017.09.010>
- 1002 Yu, G. R., Fang, H. J., Cheng, S. L., Zhu, T. H., Wang, Y. S., Yan, J. H., ... Zhou, M. (2010).  
1003 Effects of multiple environmental factors on CO<sub>2</sub> emission and CH<sub>4</sub> uptake from old-  
1004 growth forest soils. *Biogeosciences*, 7(1), 395–407.
- 1005 Yu, Z. (2011). Holocene carbon flux histories of the world's peatlands: Global carbon-cycle  
1006 implications. *The Holocene*, 21(5), 761–774. <https://doi.org/10.1177/0959683610386982>
- 1007 Yu, Z. C. (2012). Northern peatland carbon stocks and dynamics: a review. *Biogeosciences*, 9,  
1008 4071–4085. <https://doi.org/10.5194/bg-9-4071-2012>
- 1009 Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., & Hunt, S. J. (2010). Global peatland  
1010 dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, 37(13).  
1011 <https://doi.org/10.1029/2010GL043584>
- 1012 Yule, C. M., Lim, Y. Y., & Lim, T. Y. (2016). Degradation of Tropical Malaysian Peatlands  
1013 Decreases Levels of Phenolics in Soil and in Leaves of *Macaranga pruinosa*. *Frontiers*  
1014 *in Earth Science*, Vol. 4, p. 45. Retrieved from  
1015 <https://www.frontiersin.org/article/10.3389/feart.2016.00045>
- 1016 Zoltai, S. C., & Martikainen, P. J. (1996). *Estimated extent of forested peatlands and their role*  
1017 *in the global carbon cycle BT - Forest Ecosystems, Forest Management and the Global*  
1018 *Carbon Cycle* (M. J. Apps & D. T. Price, Eds.). [https://doi.org/10.1007/978-3-642-61111-](https://doi.org/10.1007/978-3-642-61111-7_5)  
1019 [7\\_5](https://doi.org/10.1007/978-3-642-61111-7_5)
- 1020 Zulkafli, Z., Buytaert, W., Manz, B., Rosas, C. V., Willems, P., Lavado-Casimiro, W., ...  
1021 Santini, W. (2016). Projected increases in the annual flood pulse of the Western Amazon.  
1022 *Environmental Research Letters*, 11(1), 14013. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/11/1/014013)  
1023 [9326/11/1/014013](https://doi.org/10.1088/1748-9326/11/1/014013)
- 1024

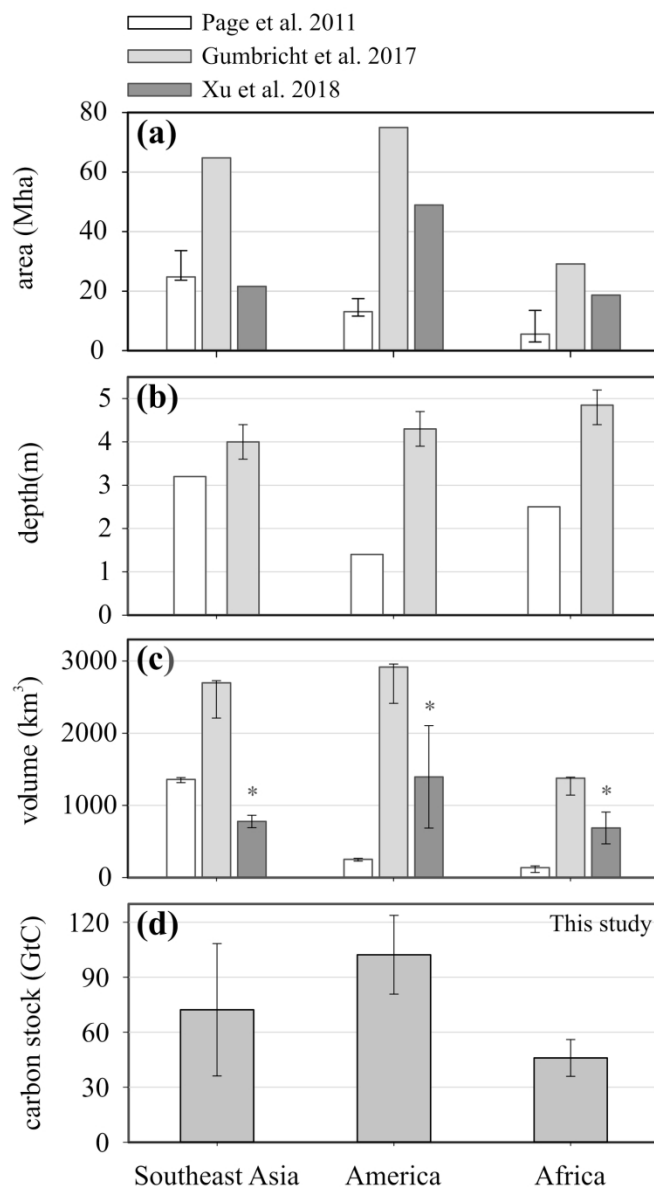


Figure 1 – Estimated peat area (a), depth (b) and volume (c), presented by Page et al. (2011), Gumbricht et al. (2017) and Xu et al. (2018) of tropical peatlands. (d) Estimated carbon stock (GtC) in tropical peatlands. Error bars are minimum and maximum estimates when available. \*Values estimated using peatland area from Xu et al. (2018) and mean depth from Gumbricht et al. (2017) and Page et al. (2011).

136x241mm (300 x 300 DPI)

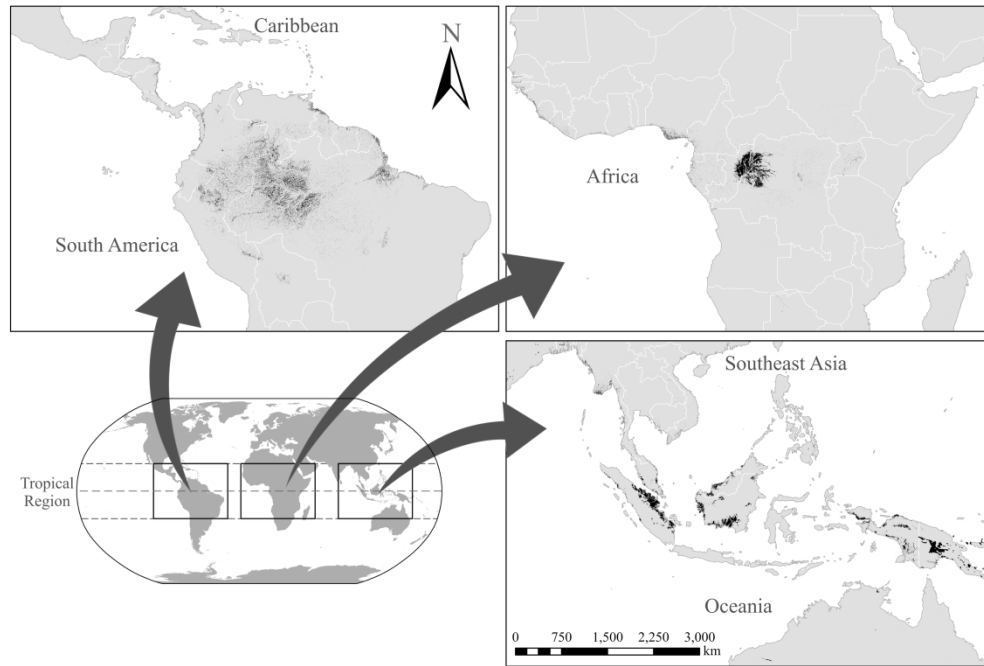


Figure 2 – Distribution of peatlands in tropical regions. Data from Xu et al., (2018)

307x208mm (300 x 300 DPI)