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

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**

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26   **Abstract**

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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_2 and CH_4) 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.

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

51   use change

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Introduction

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

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

Peatlands cover a total area of about 185-423 million hectares throughout the world (1.2-2.8% of the earth's total land area) (Xu, Morris, Liu, & Holden, 2018). In the tropical area, zones covered by peat range from 90-170 million hectares and are located mainly in South America, Southeast Asia and Central Africa (Gumbricht et al., 2017). These system store large 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_2).

81 However, they can also act as major sources of greenhouse gas (GHG) emissions, such as CO2

82 and methane (CH4), 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; Gumbricht 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 s, 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 (Gumbricht 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.; Lähteenoja 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-González 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."

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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 km³ (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   km³ (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 km³, respectively), Indonesia (14 Mha

193   and 578 km³) and the Democratic Republic of the Congo (9 Mha and 445 km³, 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   km³ 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 (Leifield & Menichetti, 2018), 104.7 (Dargie etal, 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^{-1} 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 Gumbricht 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   Gumbricht 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, Lähteenoja et al., 2013; Lähteenoja et al., 2009), however, to date

227   there has been limited ground-truthing of the former (Lähteenoja 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; Lähteenoja 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.

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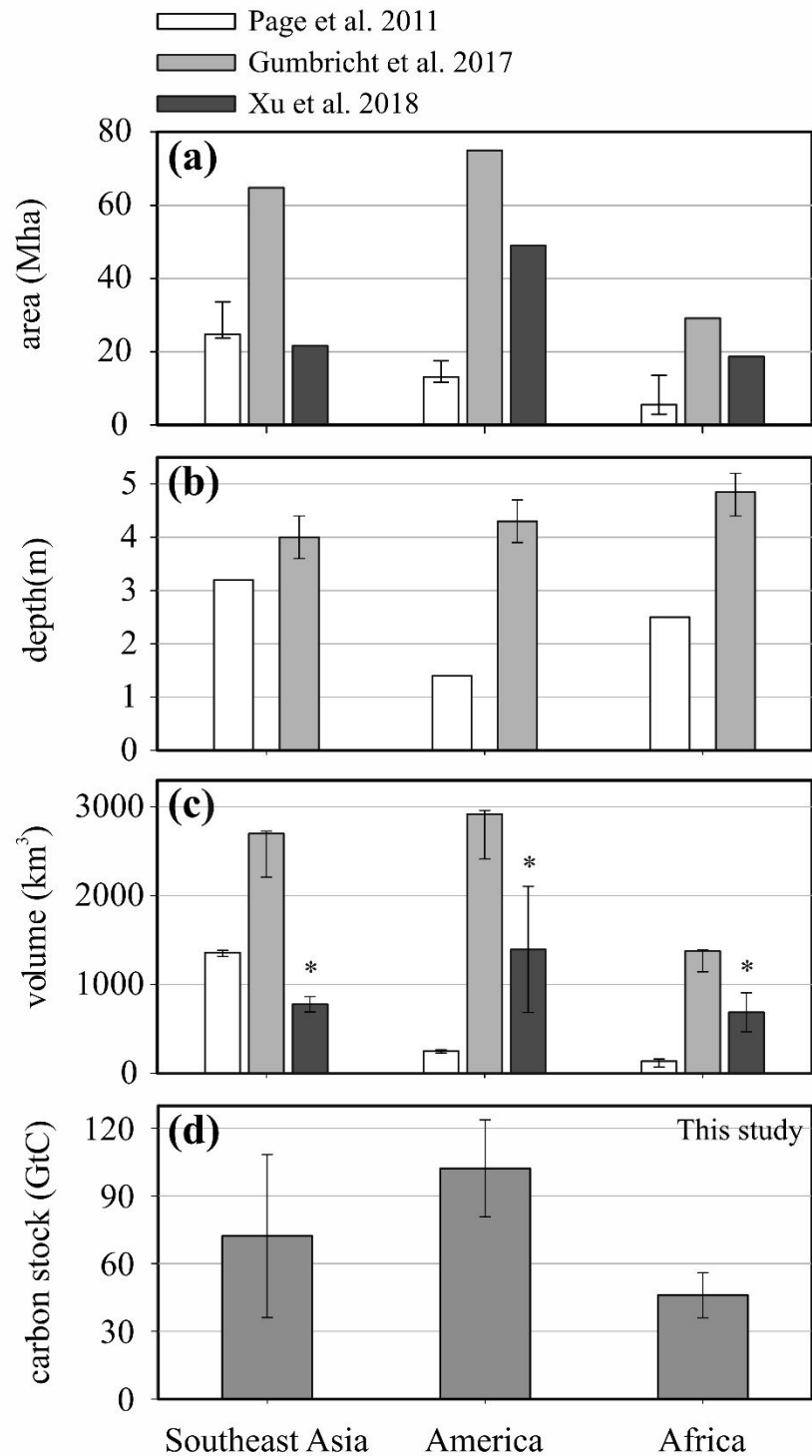
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268   Figure 1 – Estimated peat area (a), depth (b) and volume (c), presented by Page et al. (2011),

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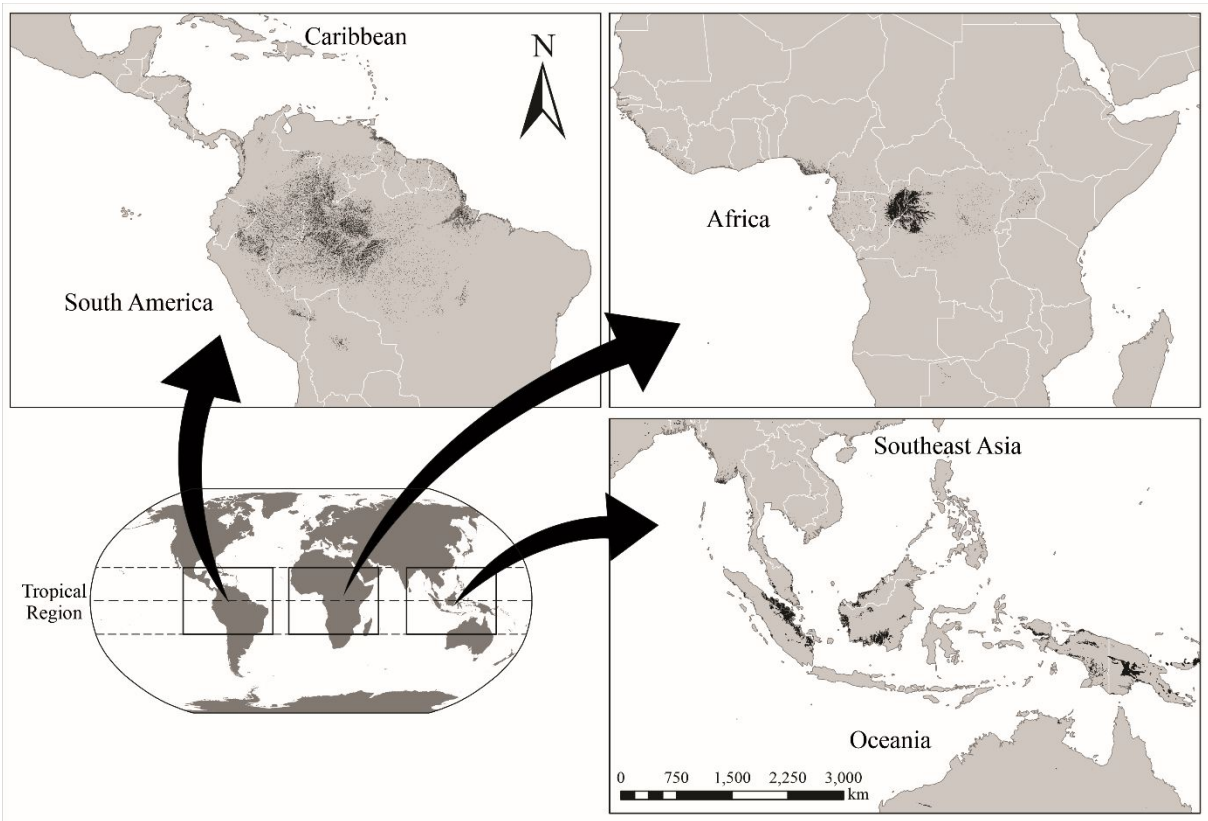
272   et al. (2017) and Page et al. (2011).

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

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

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

The accumulation rates depend on the balance between carbon uptake by vegetation and carbon emitted to the atmosphere and lost to adjacent terrestrial or aquatic system. CO_2

290   emission vary greatly in tropical peatlands (250 and 13841 gC m^{-2} yr^{-1} (Table 3) and tend to be

291   greater than in non-tropical systems (411 ± 128 gC m^{-2} 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 CH_4

294   from peatlands are typically several orders of magnitude lower than those for CO_2 (Table 3).

295   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 CH_4 (-7.1–2088.6 gC m^{-2} yr^{-1}

298   ^{1}) (Inubushi, Furukawa, Hadi, Purnomo, & Tsuruta, 2003; Martikainen, Nykänen, Alm, &

299   Silvola, 1995; Melling, Hatano, & Goh, 2005; Mitsch et al., 2010; Turetisky 2014), whereas

300   CH_4 emissions from undisturbed tropical peatlands have been estimated at moderate range of -

301   9.2–110.6 gC m^{-2} 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 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 CH_4 emissions about

307   150% higher than older peatlands (Renou-Wilson et al., 2019). This fact suggests that to

308   maintain low 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_2 emissions would almost double

401   between 2020 and 2050 (from 264 to 424 Tg CO_2 yr^{-1}). 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_2 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^{-1} yr^{-1} 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_2 emissions from organic matter

451   decomposition in drained peat soil were equivalent to 1% to 3% of all global CO_2 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^{-1} of CO_2, 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_2, CO and CH_4. With

459   an average emission rate of 11.3 Tg CO_2 per day during these events, emissions exceeded the

460   European Union's (EU28) fossil fuel CO_2 release rate of 8.9 Tg CO_2 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_4 emissions after

466   being converted from peatland forests (Table 3) because the production of CH_4 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 *Elaesis guineensis* (oil palm)

472   monocultures in Indonesia were reported by Hadi et al. (2005) at 9.1 gC m^{-2} years^{-1}, higher than

473   those reported by Inubushi et al. (2003) in native peat forests, 1.25 gC m^{-2} years^{-1}.

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^{-1}) 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.

System/Location	Land cover	Carbon stock (GtC)	Ref.
Tropical Asia		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)
Tropical America		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)
Tropical Africa		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)
Global scenario		(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^{-2} yr^{-1}) 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.

System/Location	Land cover	Carbon accumulation rates (gC m^{-2} yr^{-1})	Ref.
Tropical Asia			
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 (*Shorea albida*)	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)
Tropical America			
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 (*Raphia*)	(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)
Tropical Africa			
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			

System/Location	Land cover	CO$_2$*	CH$_4$**	Ref.
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$_2$ and CH$_4$ from peatlands (gC m^{-2} yr^{-1}) showing mean values and/or (range) if available. *Values of

497 CO$_2$ 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$_2$* (gC m^{-2} yr^{-1})	CH$_4$** (gC m^{-2} yr^{-1})	Ref.
Tropical Asia				
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, Malásia	Sago	(552 – 2146)		Melling et al. (2005)
Sarawak, Malásia	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 (*Elaesis* guineensis)	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 (*Acacia* sp e *Metroxylon* sagu)	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		Jauhiainen et al. (2012)
Tropical America				
Bocas del Toro, Panama	Forested peatland (*Raphia* sp.)	1857 (96 – 14839)	(1.1 – 110.6)	Wright et al. (2011)
Bocas del Toro, Panama	Forested peatland (*Campnosperma* sp.)	2085 (543 – 7017)	(-7.7 – 31.8)	Wright et al. (2011)
Bocas del Toro, Panama	Open peatland (*Cyperus* 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)
Global scenario				
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^{-2} yr^{-1} (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**

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

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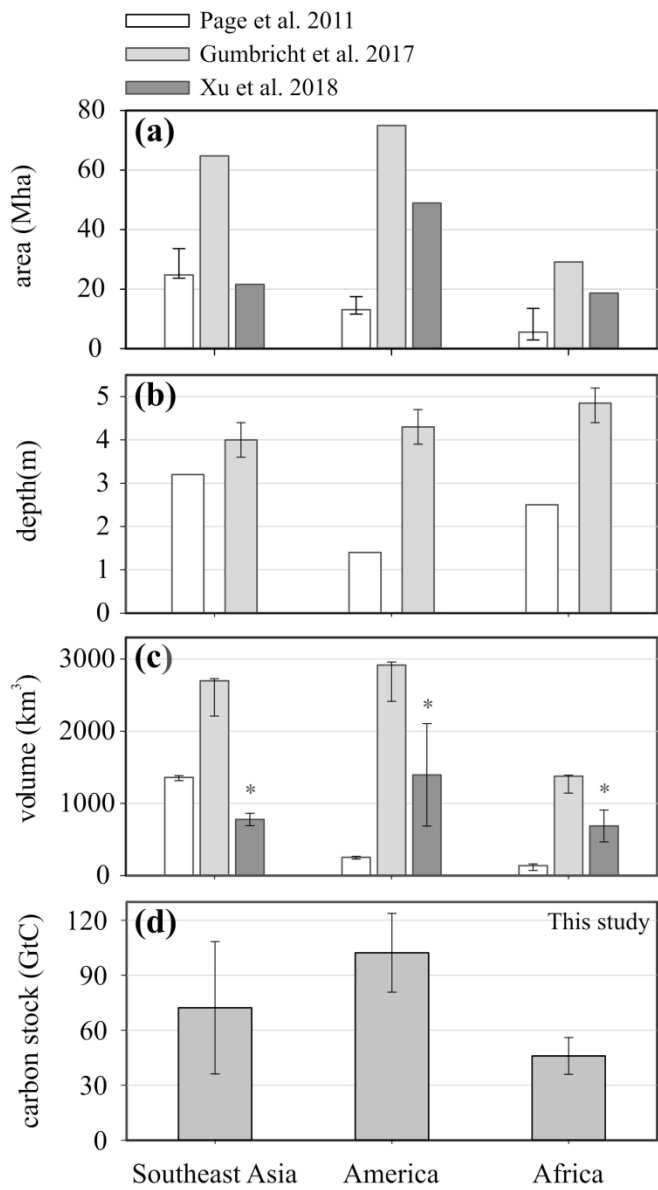1023   9326/11/1/014013

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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).
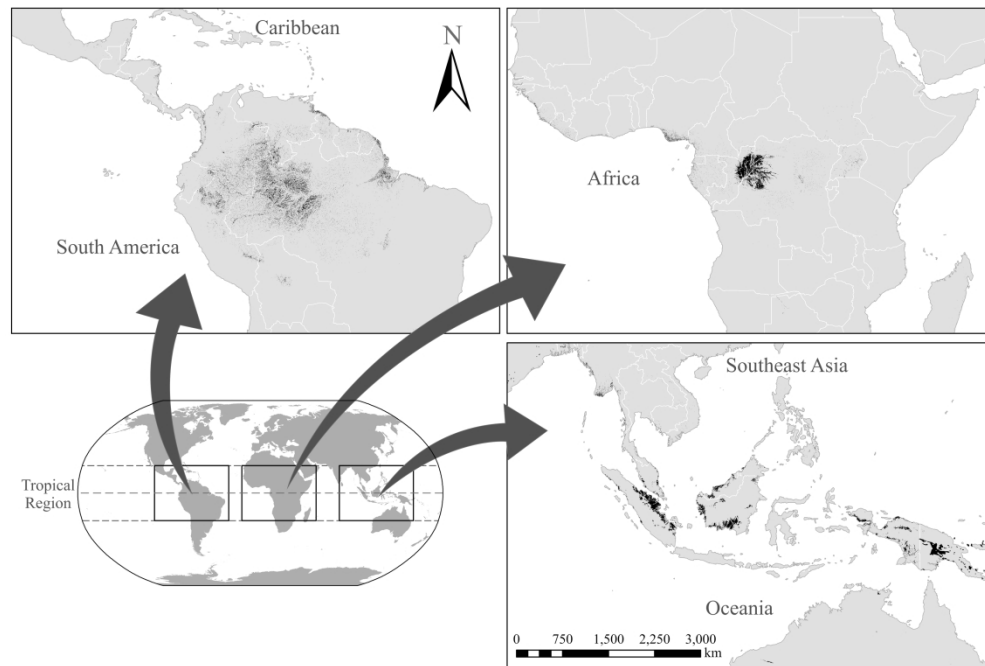
136x241mm (300 x 300 DPI)

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

307x208mm (300 x 300 DPI)