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

Kelly Ribeiro[1] | Felipe S. Pacheco[1] | José W. Ferreira[1] | Eráclito R. de Sousa-Neto[1] | Adam Hastie[2] | Guenther C. Krieger Filho[3] | Plínio C. Alvalá[1] | Maria C. Forti[1] | Jean P. Ometto[1]

[1]Earth System Science Center (CCST), National Institute for Space Research (INPE), São Paulo, Brazil

[2]School of GeoSciences, University of Edinburgh, Edinburgh, UK

[3]Laboratory of Thermal and Environmental Engineering, Polytechnic School of the University of São Paulo, São Paulo, Brazil

Correspondence
Kelly Ribeiro, Earth System Science Center (CCST), National Institute for Space Research (INPE), Av. Astronautas, 1758, São José dos Campos, São Paulo 12227-000, Brazil.
Email: kelly.ribeiro@inpe.br

Abstract

Peatlands are carbon-rich ecosystems that cover 185–423 million hectares (Mha) of the earth's surface. The majority of the world's peatlands are in temperate and boreal zones, whereas tropical ones cover only a total area of 90–170 Mha. However, there are still considerable uncertainties in C stock estimates as well as a lack of information about depth, bulk density and carbon accumulation rates. The incomplete data are notable especially in tropical peatlands located in South America, which are estimated to have the largest area of peatlands in the tropical zone. This paper displays the current state of knowledge surrounding tropical peatlands and their biophysical characteristics, distribution and carbon stock, role in the global climate, the impacts of direct human disturbances on carbon accumulation rates and greenhouse gas (GHG) emissions. Based on the new peat extension and depth data, we estimate that tropical peatlands store 152–288 Gt C, or about half of the global peatland emitted carbon. We discuss the knowledge gaps in research on distribution, depth, C stock and fluxes in these ecosystems which play an important role in the global carbon cycle and risk releasing large quantities of GHGs into the atmosphere (CO_2 and CH_4) when subjected to anthropogenic interferences (e.g., drainage and deforestation). Recent studies show that although climate change has an impact on the carbon fluxes of these ecosystems, the direct anthropogenic disturbance may play a greater role. The future of these systems as carbon sinks will depend on advancing current scientific knowledge and incorporating local understanding to support policies geared toward managing and conserving peatlands in vulnerable regions, such as the Amazon where recent records show increased forest fires and deforestation.

KEYWORDS
carbon cycling, climate change, greenhouse gas emissions, land-use change, tropical peatlands

1 | 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 et al., 2013), as well as seasonal or annual floods with geomorphological features where water is retained (Finlayson & Milton, 2018; Kelly (Letcher) et al., 2013; Warner & Rubec, 1997). While 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 et al., 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 30–40 cm (Dargie et al., 2017; Page & Baird, 2016; Page et al., 2011).

These ecosystems provide unique ecosystem services, such as water storage by regulating the river's discharge, thereby benefiting ecosystems and human communities (Harenda et al., 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 et al., 2001).

Peatlands cover a total area of about 185–423 million hectares (Mha) throughout the world (1.2%–2.8% of the earth's total land area; Xu et al., 2018). In the tropical area, zones covered by peat range from 90 to 170 Mha and are located mainly in South America, Southeast Asia and Central Africa (Gumbricht et al., 2017). These systems store large amounts of C (469–694 Giga tons of C; Lähteenoja et al., 2012; Leifeld & Menichetti, 2018; Page et al., 2011; Yu, Fang, et al., 2010; Yu, Loisel, et al., 2010) and act as net sinks of atmospheric carbon dioxide (CO_2). However, they can also act as major sources of greenhouse gas (GHG) emissions, such as CO_2 and methane (CH_4), into the atmosphere (Leifeld & Menichetti, 2018; Roulet, 2012), due to either natural processes such as changes in autotrophic and heterotrophic respiration rates, changes in river paths, droughts and natural fires or anthropogenic interferences including logging, drainage, deforestation, fires, and land-use and land cover (LULC) changes (Hooijer et al., 2010; Leng et al., 2019; Yule et al., 2016).

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

In contrast to temperate peatlands, in which the relationship between climate, ecosystem dynamics and carbon (C) accumulation is well studied, the body of literature on tropical peatlands is mainly concentrated on Southeast Asia (Page et al., 1999; Hartmann & Niklaus, 2012), Peru in South America (Kelly et al., 2017; Lähteenoja et al., 2012; Roucoux et al., 2017; Sorribas et al., 2016) and, to a lesser degree, the Cuvette Centrale basin in Africa (Dargie et al., 2017, 2019). This paper presents an extensive review about tropical peatlands in terms of their biophysical conditions that promotes peat formation (e.g., temperature, rainfall, groundwater, nutrient pool and substrate quality), spatial distribution and carbon stock, as well as how these ecosystems are affected under different disturbance regimes. Moreover, the paper identifies and discusses knowledge gaps surrounding this highly threatened, yet poorly understood ecosystem in several regions of the tropical area.

2 | PEAT FORMATION PROCESS AND BIOPHYSICAL CHARACTERISTICS OF TROPICAL PEATLANDS

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

In many tropical peatlands, the soil is seasonally flooded mostly by large rivers with high nutrient content and intense sediment deposition. These factors associated to high precipitation patterns and temperatures favor the development of flooded peatlands concomitant of dense tree coverage, with high floristic diversity and high net primary productivity (Gillman et al., 2015) and absence of mosses (Page et al., 1999). On the contrary, in many northern peatlands, the low temperature and low nutrient inputs favors the dominance of the bryophyte genus Sphagnum (Clymo, 1987) and a shrub layer is usually well developed with sparse occurrence of large trees (Ingram, 1978; Vitt, 2013).

The peatland vegetation cover described above is an important characteristic that influences the composition and the process of peat formation. Peat in tropical peatlands is mainly formed by woody material and dead branches and roots (Dommain et al., 2015; Gallego-Sala et al., 2018), whereas most of the peat in northern peatlands is formed of Sphagnum mosses and sedges. The woody material contains high C:N and lignin:N ratios that degrade slowly (Gandois et al., 2012, 2014). This promotes the release of phenolic components that inhibit decomposition (Wang et al., 2015). These conditions increase the aromatic content in the soil and create a reduced oxidation state in which C remains and recalcitrance is high, despite high temperatures (Hodgkins et al., 2018). Divergent from the peat formation process in northern peatlands, the low soil temperatures, freezing and the acid characteristics of the cell wall of Sphagnum species favor the reduction of C oxidative processes even with abundant labile carbohydrates (Sphagnum; Clymo, 1984; Vitt, 2013).

In general, there are two types of peatlands: ombrotrophic and minerotrophic (Clymo, 1987), being divided according to the origin

of nutrient input in the system. Ombrotrophic peatlands are influenced exclusively by water from precipitation (no other sources; Bourbonniere, 2009; Takada et al., 2016; Vitt, 2013) while minerotrophic peatlands are typically formed in depressions and floodplains and receive mineral nutrients with incoming surface or groundwater (Bourbonniere, 2009; International Peatland Society (IPS), n.d.; Lähteenoja, Ruokolainen, Schulman, & Alvarez, 2009; Lähteenoja, Ruokolainen, Schulman, & Oinonen, 2009; Takada et al., 2016; Vitt, 2013).

At the start of the peat formation, the peatland is initially minerotrophic (Clymo, 1987). As the peat layer grows in height, the dome becomes elevated and the peatland may no longer be affected by the river that feeds into it or by the entry of groundwater, thereby obtaining water exclusively from precipitation and becoming ombrotrophic. At this stage, nutrient and mineral deposits are mainly from atmospheric dry deposition or precipitation, but large amounts of nutrients can also come from dust and air pollution (Ponette-González et al., 2016). For instance, according to Swindles et al. (2018), the oldest Peruvian tropical peatlands discovered to date were formed in three stages: first, peat was formed in an abandoned river channel with open water and aquatic plants; then inundated forest swamp was formed and finally the peat dome raised as the peat accumulated.

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

3 | DISTRIBUTION AND CARBON STOCK OF TROPICAL PEATLANDS

There is a lot of variation in the published data about the occurrence and distribution of tropical peatlands. Up to a few years ago, Southeast Asia (Indonesia, East Sumatra, Kalimantan, Papua New Guinea, Papua New Guinea and Malaysia) was considered to have the largest peatland C reservoirs in the tropical area (Dargie et al., 2017; Joosten, 2009; Lähteenoja, Ruokolainen, Schulman, & Alvarez, 2009; Lähteenoja, Ruokolainen, Schulman, & Oinonen, 2009; Miettinen & Liew, 2010; Miettinen et al., 2016;

Page et al., 2002, 2011); however, large intact peatlands have recently been described in South America (Draper et al., 2014) and Africa (Dargie et al., 2017). For example, Dargie et al. (2017) used field measurements combined with remote sensing data to estimate the extent of a peat complex in the Cuvette Centrale region of the Congo Basin, the largest intact tropical peatland to date at 14.6 (13.2–15.6) Mha. As a result of these recent studies, estimates of tropical peatlands have been revised (see Gumbricht et al., 2017; Xu et al., 2018) and the total area of tropical peatlands is now considered to cover 90–170 Mha (23%–30% of the total area covered by peatlands throughout the world). This new estimate is two to three

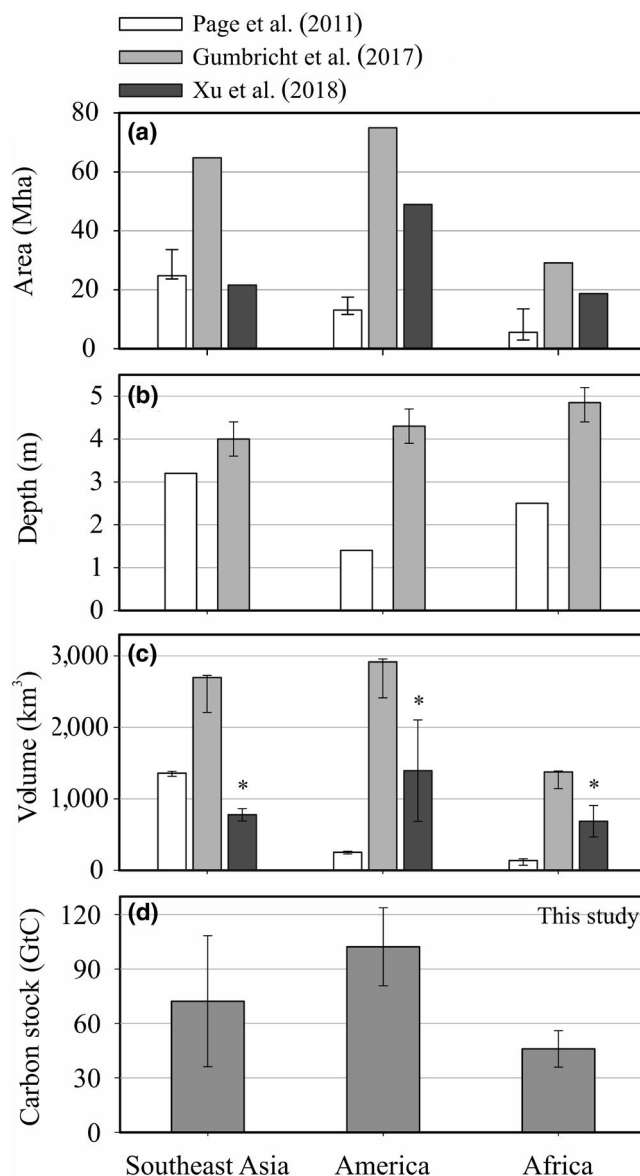**FIGURE 1** Estimated peat area (a), depth (b) and volume (c), presented by Page et al. (2011), Gumbricht et al. (2017) and Xu et al. (2018) of tropical peatlands. (d) Estimated carbon stock (Gt C) in tropical peatlands. Error bars are minimum and maximum estimates when available. *Values estimated using peatland area from Xu et al. (2018) and mean depth from Gumbricht et al. (2017) and Page et al. (2011)
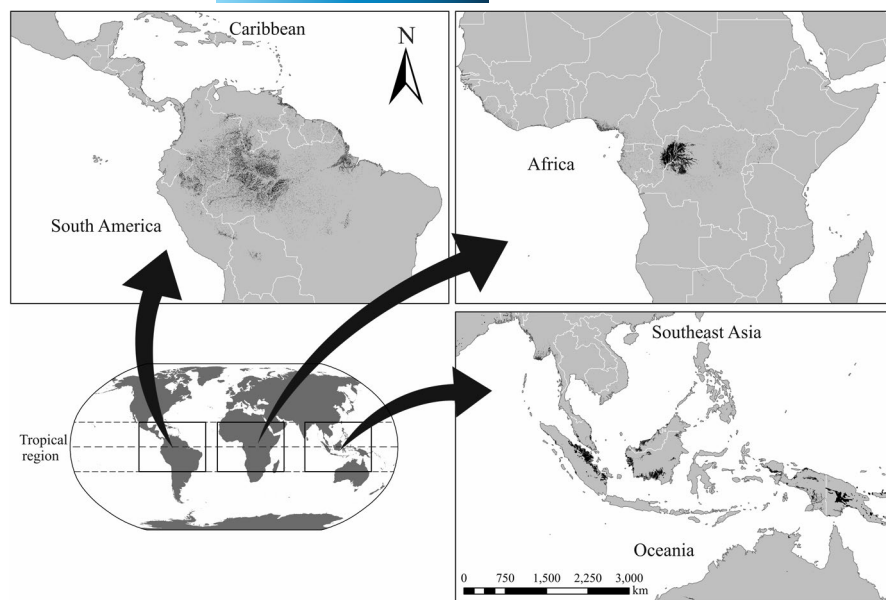
FIGURE 2 Distribution of peatlands in tropical regions. Data from Xu et al. (2018)

times larger than the 56 Mha that Page et al. (2011) reported and which led to new discussions on the physical and chemical factors that define wetlands and peatlands (Figure 1).

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

Based on the estimated volume of peat in the tropics and the average carbon content per km^3 of peat (Lähteenoja, Ruokolainen, Schulman, & Alvarez, 2009; Lähteenoja, Ruokolainen, Schulman, & Oinonen, 2009), we estimated that peat in the tropics stores an equivalent of 152–288 Gt C (Table 1), which is significantly higher than previously reported estimates of 119.2 Gt C (Leifeld & Menichetti, 2018), 104.7 Gt C (Dargie et al., 2017), 90 Gt C (Moore et al., 2013), 88.6 Gt C (Page et al., 2011) and 52 Gt C (Zoltai & Martikainen, 1996). The stock of 152–288 Gt C is equivalent to the amount of C emitted by burning fossil fuels at a rate of 10 Gt C/year for the next 15–30 years (Murdiyarso et al., 2010; Raupach et al., 2013). C emission from fossil fuel in 2014 were 9.8 Gt C (https://www.globalcarbonproject.org/). In addition, the mid-range value of our estimated C stock (215 Gt) represents about 25% of the terrestrial carbon pool in the tropics (846.3 Gt C), considering both carbon aboveground (374.9 Gt C, phytomass) and stored in the soil (571.3 Gt C, Scharlemann et al., 2014).

The main explanation for the large range in our new estimate of tropical peatland C stock (152–288 Gt C) is the different

methodological approaches adopted for the estimation of the area. For instance, the numerical model that Gumbricht et al. (2017) adopted to estimate total area uses a set of factors associated with hydrological modeling, time series of vegetation, soil moisture and hydro-geomorphological data. Xu et al. (2018) considered a wide variety of sources from different authors and regions and applied criteria of relevance, spatial resolution as well as age, and combined these data sources to produce a new amalgamated global map of peatland distribution. For areas where peatland-specific datasets were not available, they estimated peatland extent based on the distribution of histosols derived from the Harmonized World Soil Database v1.2 (HWSD). Page et al. (2011) considered data from national soil inventories from different countries. Data from the latter may not be comparable given the different definitions of peat and inclusion of non-peat organic soils. The new estimates of Gumbricht et al. (2017) and Xu et al. (2018) suggest that the extent of differing with what was previously reported of what was previously reported (Page et al., 2011).

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

In Africa, peatlands occur in many countries, but extensive peatlands are located in the Rugezi Marsh in Rwanda, the Okavango Delta in Botswana, the Sudd catchment in Sudan and in particular the Congo basin (Grundling & Grootjans, 2018). The Cuvette Centrale

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TABLE 1 Tropical peatland carbon stock (Gt C) showing mean values and/or (range) if available

System/location	Land cover	Carbon stock (Gt C)	Reference
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, Fang, et al. (2010); Yu, Loisel, et al. (2010)
Tropical undisturbed		(139–251)	Miettinen and Liew (2010); Zoltai (1996)
Tropical disturbed		(13–37)	Kurnianto et al. (2015); Zoltai and Martikainen (1996)
Tropical		(152–288)	This study
Non-tropical		(387–394)	Gorham (1991); Immirzi and Maltby (1993); Page et al. (2011)

wetland of the Congo basin is estimated to contain a C stock of 30.6 (6.3–46.8) Gt C (Bwangoy et al., 2010; Dargie et al., 2017; Table 1). Again, note the large uncertainty range, which is a reflection of the fact that this estimate is based on a relatively sparse set of field measurements (Dargie et al., 2017). Peatlands have also been reported in southern Africa, mainly along the eastern coast (Mozambique Coastal Plain) and in the central plateau (Grundlin and Glober, 2005; McWethy et al., 2016).

The total area covered by peatlands in Southeast Asia is roughly 21 Mha (Xu et al., 2018). Most of these peatlands are in Indonesia (15 Mha), Malaysia (2.2 Mha), Thailand (40,000 ha) and, to a lesser extent, Vietnam, Brunei and the Philippines. A recent estimate put the peat C store in Indonesia alone at 28.1 (13.6–40.5) Gt C (Warren et al., 2017). Unlike other large tropical peat reservoirs in the world that are either untouched or have had little alteration, peatlands in Southeast Asia have faced intense anthropogenic disturbances since the 1970s, when permission was granted to use these extensive areas for commercial purposes.

Due to the current large uncertainties around carbon stocks in tropical peatlands, it is notorious that with the advance of knowledge in the identification of tropical peatlands (mainly extension and depth) resulted in significantly higher estimates for carbon stocks in the tropical zones. For South America and Africa, the large uncertainty reflects the need for more field data (Dargie et al., 2017).

Peatlands in relatively remote African and Amazonian regions currently face low human intervention, however as anthropogenic activities, such as commercial agriculture, exploitation of waters for hydropower (in Andes), forestry (including deforestation), construction of impoundments, roads and ports, and gas exploration in peatlands increase, so does the degradation of these ecosystems (Baker et al., 2014; Lähteenoja, Ruokolainen, Schulman, & Alvarez, 2009; Lähteenoja, Ruokolainen, Schulman, & Oinonen, 2009; Roucoux et al., 2017). Therefore, decreasing uncertainties about area, and C stock in such remote regions is crucial to estimate the true C accumulation potential of these peatlands and to prevent future impact of human activities that peatlands may face mainly in South America and Africa.

4 | TROPICAL PEATLAND CARBON ACCUMULATION, CLIMATE CHANGE AND THE GLOBAL CARBON CYCLE

The carbon accumulation rates in undisturbed tropical peatlands range from 24 to 300 g C m^{-2} year^{-1} (Table 2), while for boreal and temperate undisturbed peatlands they are generally lower (vary from 2 to 271 g C m^{-2} year^{-1}, Olefeldt et al., 2012; Renou-Wilson et al., 2019). Although substantial variation occurs depending on

TABLE 2 Carbon accumulation rates (g C m^{-2} year^{-1}) from tropical peatlands and from non-tropical peatlands (for comparison) showing mean values and/or (range) if available. Positive values are carbon accumulation and negative values are carbon loss

System/location	Land cover	Carbon accumulation rates (g C m^{-2} year^{-1})	Reference
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 (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 to −174)	Rieley et al. (2008)
West Kalimantan	Drained peatlands and forest	(74–85)	Neuzil (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 et al. (2010)
French Guiana	Pristine tropical rain forest	−138	Bonal 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)
Cayambe-Coca	Peatlands in the Andes Mountains	51.1	Chimner and 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	Pajunen (1996)
Burundi	Ndurumu Swamp	65	Pajunen (1996)
Rwanda	Cyili Swamp	113	Pajunen (1996)
Rwanda	Gishoma Swamp	(86–106)	Pajunen (1996)
Rwanda	Mashya Bog	91	Pajunen (1996)
Rwanda	Cyabaralika Swamp	33	Pajunen (1996)
Rwanda	Kiguhu Swamp	31	Pajunen (1996)
Global scenario			
Tropical undisturbed		(24–300)	Chimner (2004); Kurnianto et al. (2015)
Tropical disturbed		(−499 to −174)	Rieley et al. (2008)
Non-tropical		(−248 to 271)	Olefeldt et al. (2012); Renou-Wilson et al. (2019); Roulet et al. (2007)

peatland type, hydrology, vegetation type and peat formation (Craft et al., 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 g C m^{-2} year^{-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 emission vary greatly in tropical peatlands (250 and 13,841 g C m^{-2} year^{-1}; Table 3) and tend to be greater than in non-tropical systems (411 ± 128 g C m^{-2} year^{-1}; Bubier et al., 2003; Clair et al., 2002; Crow & Wieder, 2005; Mäkiranta et al., 2009; Silvola et al., 1996). Estimated fluxes of CH_4 from peatlands are typically several orders of magnitude lower than those for CO_2 (Table 3). CH_4 emissions are indeed undetectable in some peatlands and an uptake from the atmosphere might occur instead (Sjögersten et al., 2014). Previous studies have estimated that undisturbed temperate and boreal environments emit moderate to high level of CH_4 (–7.1 to 2,088.6 g C m^{-2} year^{-1}; Inubishi et al., 2003; Martikainen et al., 1995; Melling et al., 2005; Mitsch et al., 2010; Turetsky et al., 2014), whereas CH_4 emissions from undisturbed tropical peatlands have been estimated at moderate range of –9.2 to 110.6 g C m^{-2} year^{-1} (Table 3).

Methane formation is driven by methanogenic microorganisms activity (anaerobic decomposers) that degrades organic matter slowly in an anoxic environment (Mitsch et al., 2010). A peatland's capacity to emit less CH_4 appears to be a complex mechanism developed over several thousands of years, given that formerly human-disturbed restored peatlands in temperate systems with well-established vegetation and carbon stock have CH_4 emissions about 150% higher than older peatlands (Renou-Wilson et al., 2019). This fact suggests that to maintain low CH_4 emissions and higher carbon sequestration rates, it is important to not only invest in actions that seek to recover impacted areas but also to ensure that ecosystems are protected.

In the absence of direct human disturbance, many tropical peat deposits are actively accumulating carbon or are in steady states (Dargie et al., 2017; Fatoyinbo, 2017). However, climate change may significantly impact peatlands, and this relationship is poorly understood, particularly in the case of tropical peatlands, and thus the fate of peatlands under future change remains uncertain (Frey & Smith, 2005; Gallego-Sala et al., 2018; Hapsari et al., 2017; Hirano et al., 2012; Hodgkins et al., 2018; Rieley et al., 2008). The effect of climate change will depend mainly on how temperature, total precipitation, sea level and frequency of extreme events will change in a specific region and how they will affect hydrology, vegetation composition and, consequently, primary production, substrate quality, decomposition process, lateral carbon fluxes and C accumulation rates of peatlands.

Some recent work, using Dynamic Global Vegetation Models (DGVMs) indicated, for Northern Hemisphere peatlands, a carbon sink twice as big than the 1861–2005 mean under two climate scenarios (defined by the RCPs 2.6 and 6.0), even though rapid climate change (under RCP8.5) might impact negatively the extent of northern peatlands, and the capacity of these areas to act as a carbon sink (Chaudhary et al., 2020; Qiu et al., 2020). As well, some models have predicted continued peat accumulation through to 2100 (Gallego-Sala et al., 2018; Spahni et al., 2013), while most models agree that there will be substantial losses over the next centuries (Avis et al., 2011; Gallego-Sala et al., 2018; Ise et al., 2008), and some models have predicted that loss to start before 2100 (Avis et al., 2011; Ise et al., 2008). Few pan-tropic modeling, studies have been undertaken (Gallego-Sala et al., 2018; Treat et al., 2019) largely due to the sparsity of available data on tropical peatlands that is needed for model parametrization and validation. Climate models for the western Amazon predict increasing precipitation and river discharge over the century (Duffy et al., 2015; Sorribas et al., 2016; Zulkafli et al., 2016), whereas the opposite is predicted for the Eastern Amazon (Duffy et al., 2015; Sorribas et al., 2016), meaning that Brazilian peatlands are likely to be more vulnerable than those in Peru. However, a recent modeling study in the PMFB in Peru predicted that temperature increases would offset any positive effect of increased precipitation on peat accumulation by the end of the century through an increase in decomposition, that is, Peruvian peatlands will cease peat accumulation despite increases in precipitation (Wang et al., 2018). Likewise, in the Congo Basin, there is a clear consensus that temperature will increase under all future scenarios while precipitation is predicted to increase under high emission scenarios and remain relatively unchanged under low emission scenarios (Haensler et al., 2013) and, therefore, Congolese peatlands may also be vulnerable to future climate change. Likewise, studies in Southeast Asian peatlands, many of which are already degraded from deforestation and drainage, have been shown that additional carbon emission could also occur if dry seasons are extended or are more severe due to future climate change (Warren et al., 2017).

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

In summary, many peatland areas are projected to stop accumulating peat by the end of the century and beyond, thus creating a positive climate feedback loop where further warming means C losses and,

TABLE 3 Estimates of soil emission of CO_2 and CH_4 from peatlands (g C m^{-2} year^{-1}) showing mean values and/or (range) if available

| System/location | Land cover | (g C m^{-2} year^{-1}) | | Reference |
		CO_2[a]	CH_4[b]	
Tropical Asia				
Malaysia	Forested peatland		0.02 (−0.05 to 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	3,493 ± 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	2,777 ± 8,322		Hirano et al. (2009)
Kalimantan, Indonesia	Secondary forest	4,494	1.66	Hadi et al. (2005)
Kalimantan, Indonesia	Secondary forest	3,460 (1,603–35,522)	4.4 (0–29)	Hadi et al. (2005)
Kalimantan, Indonesia	Forested peatland	3,495 ± 315 (438–4,818)	1.4 ± 5.7 (−0.09 to 3.1)	Jauhiainen et al. (2004)
Kalimantan, Indonesia	Forested peatland		9.6 ± 5.3	Inubushi et al. (1998)
Malaysia	Forested peatland	3,889		Murayama and Bakar (1996)
Micronesia	Forested peatland	3,469 ± 315 (2,978–3,522)		Chimner (2004)
Sarawak, Malásia	Sago	(552–2,146)		Melling et al. (2005)
Sarawak, Malásia	Oil palm	(403–29,334)		Melling et al. (2005)
Sarawak, Malaysia	Forest ecosystem	(876–4,669)		Melling et al. (2005)
South Kalimantan	Secondary forest	1,200 ± 430	1.2 ± 0.4	Inubushi et al. (2003)
South Kalimantan	Secondary forest peatland to paddy field	(1,200–1,500)	(1.2–1.9)	Inubushi et al. (2003)
South Kalimantan	Changing land-use from Secondary forest to upland tended	(1,000–2,000)	(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	1,540 ± 290	1.9 ± 0.5	Inubushi et al. (2003)
Southeast Asia	Secondary Native Forest	3,460	4.4	Hadi et al. (2005)
Southeast Asia	Secondary forest	3,500	0.5	Hadi et al. (2005)
Southeast Asia	Forest ecosystem	2,100		Melling et al. (2005)
Southeast Asia	Lowland peatlands	250	1.09	Couwenberg et al. (2010)
Southeast Asia	Undrained peat swamp forest	3,892 ± 304	1.36 ± 0.57	Rieley et al. (2008)
Southeast Asia	Drained uncultivated agricultural land	1,928 ± 526	0.12 ± 0.09	Rieley et al. (2008)
Southeast Asia	Drained affected peat swamp forest	4,000 ± 1,091	1.3 ± 0.98	Rieley et al. (2008)
Southeast Asia	Burned areas	2,900		Hadi et al. (2005)
Southeast Asia	Converting peat swamp forests into oil palm	5,940		Murdiyarso et al. (2010)
Southeast Asia	Paddy field	1,389	19.6	Radjagukguk (1997)
Southeast Asia	Rice-soybean rotation field	2,019	2.6	Bouwman (1990)
Southeast Asia	Paddy field	1,400	1.4	Hadi et al. (2005)
Southeast Asia	Rice-soybean rotation field	2,000		Hadi et al. (2005)
Southeast Asia	Oil palm	1,500		Melling et al. (2005)

(Continues)

TABLE 3 (Continued)

System/location	Land cover	(g C m^{-2} year^{-1})		Reference
		CO$_2$[a]	CH$_4$[b]	
Southeast Asia	Sago	1,100		Melling et al. (2005)
Southeast Asia	Cultivation of palm oil (*Elaesis guineensis*)	5,940		Murdiyarso et al. (2010)
Southeast Asia	Rice crops (Mega Rice Project)	2,178		Hadi et al. (2005)
Southeast Asia	Rice crops	1,389	26.6	Hadi et al. (2005)
Southeast Asia	Agricultural Soils	2,019	1.7	Hadi et al. (2005)
Southeast Asia	Horticulture	1,500	1.9	Inubushi et al. (2003)
Southeast Asia	Cultures with nitrogen fertilization (*Acacia* sp e *Metroxylon* sagu)	2,130	2.6	Couwenberg et al. (2010)
Southeast Asia	Clear felled recovering peat Swamp forest	3,400 ± 927	2 ± 1.5	Rieley et al. (2008)
Sumatra, Indonesia	Forested peatland	3,329 ± 481.8	7.8 ± 4.2	Furukawa et al. (2005)
Sumatra, Indonesia	Forested peatland	2,435 ± 140	10.6 ± 11.9	Furukawa et al. (2005)
Sumatra, Indonesia	Forested peatland	3,294 ± 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.)	1,857 (96–14,839)	(1.1–110.6)	Wright et al. (2011)
Bocas del Toro, Panama	Forested peatland (*Campnosperma* sp.)	2,085 (543–7,017)	(−7.7 to 31.8)	Wright et al. (2011)
Bocas del Toro, Panama	Open peatland (*Cyperus* sp.)	1,269 (61–8,322)	(−9.3 to 27.2)	Wright et al. (2011)
Ka'au, Hawaii	Montane swamp	1,112.5 ± 412		Chimner (2004)
Mauim, Hawaii	Montane peatland	2,497 ± 657		Chimner (2004)
Orinoco Llanos, Venezuela	Palm peatland	263 (149–473)		Bracho and San José (1990)
Brazil (Lowlands in São Paulo state)	Pastureland (dry season and wet season)	3,210	(−5.2 to 4.0)	Ribeiro et al. (2018)
Brazil (Lowlands in São Paulo state)	Native forest (dry season and wet season)	2,174	(−3.1 to 4.2)	Ribeiro et al. (2018)
Brazil (Lowlands in São Paulo state)	Irrigated rice crop (dry season and wet season)	2,074	3.1	Ribeiro et al. (2018)
Global scenario				
Tropical undisturbed		(250–13,841)	(−9.3 to 110.6)	Chimner (2004); Kurnianto et al. (2015)
Tropical disturbed		(263–29,334)	(1.9–26.6)	Kurnianto et al. (2015); Zoltai and Martikainen (1996)
Non-tropical		411 ± 128	35.1 ± 2.6 (−7.1 to 2,088.6)	Lund et al. (2010)

[a]Values of CO$_2$ emission are from autotrophic and heterotrophic respiration and do not consider primary production.

[b]Positive values of soil emission mean carbon emission and negative mean carbon uptake.

in turn, greater radiative forcing (Gallego-Sala et al., 2018). However, across the entire tropics, and particularly the Amazon and Congo basins, further field data are required to better parameterize and validate models so that we can improve projections of the future C balance in tropical peatlands, which at the moment remain highly uncertain.

Although climate change (such as changes to temperatures and precipitation) has an impact on the dynamics of these ecosystems, direct anthropogenic changes (LULC changes, drainage and deforestation) currently play a greater role. Therefore, understanding the impact of direct anthropogenic changes on these ecosystems can

help us understand whether tropical peatlands are a net sink or net source in the global carbon cycle.

5 | DIRECT HUMAN DISTURBANCES AND THEIR IMPACTS ON CARBON ACCUMULATION RATES AND GHG EMISSIONS IN TROPICAL PEATLANDS

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

In Southeast Asia, domestic and international demand for agricultural and forest products and services has put pressure on tropical peatlands and, by 2010, it was estimated that only 36% of the original peatland area in the Southeast Asia was covered by primary and secondary peat swamp forest (Aziz et al., 2017; Miettinen et al., 2012). In the Indonesian regions of Sumatra and Kalimantan, the two regions of Indonesia with the greatest impacts, only 6% were pristine peat swamp forests (Miettinen et al., 2012). To meet the high demand of agricultural products, the peatlands have been subjected to deforestation (Hirano et al., 2012), widespread drainage (Fatoyinbo, 2017) and recurrent fires (Page et al., 2002). Page et al. (2011) argue that, on the one hand, expansion of agriculture and forestry in the region has provided opportunities to industries and businesses, yet on the other hand it has also had negative environmental impacts. Between 2000 and 2010, Southeast Asia has had the highest annual rate of deforestation (rate of 2.2%) among all tropical humid regions in the world. This deforestation has resulted in the loss of 11 Mha of native forests and has led to significant changes in natural ecosystem dynamics, mainly related to carbon balance (Miettinen & Liew, 2010). Netzer et al. (2013) projected land-use and emissions from peatlands between 2010 and 2050 across Indonesia, Malaysia and in Papua New Guinea and found that under the "business as usual" scenario, in which total production of oil palm will increase without peatland protection measures, the average annual CO_2 emissions would almost double between 2020 and 2050 (from 264 to 424 Tg CO_2/year). In contrast, restoring the peat to native forest vegetation (restoration scenario) would bring annual emissions close to zero.

In Africa, increased economic development could have a negative impact on peatlands through hydrocarbon exploration, logging, plantations and other forms of disturbance that significantly damage these ecosystems, although they are still intact today (Dargie et al., 2019). Additionally, land-use changes occur as a result of

multiple complex and interacting environmental, economic and political factors, which can accelerate the negative impacts of human activities. In Cuvette Centrale region in Congo, rivers are the main transport network and there are relatively few roads. This, along with the large distance from any international port and low population densities, is among the reasons why the Congo basin peatlands have so far been spared from more severe degradation typical for Southeast Asian peatlands. Although limited in number, roads have already been constructed across some of the peatland areas of the Cuvette Centrale. No studies have yet considered the specific impacts of these roads on the peat properties, hydrology or vegetation; however, the observed swamp forest death following road construction suggests that roads could be having a negative impact on the wetlands of the region (Dargie et al., 2017). The low level of human intervention in the Cuvette Centrale peatlands at present suggests that there is still time to protect the peatlands in a largely intact state, possibly by encouraging funding for mitigation of land-use change (Dargie et al., 2019).

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

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

The most recent studies on GHG soil emissions from natural and impacted environments show that tropical peatlands have high CO_2 emissions in drained environments used for agricultural production and in recovering areas (Leifeld & Menichetti, 2018). Although non-impacted forests emit C through soil respiration, on average emissions are lower due to the maintenance of natural soil moisture conditions and groundwater levels.

In Indonesia, the carbon lost in peatlands after LULC changes has averaged approximately 60 Mg ha^{-1} year^{-1} over 25 years of interference (Murdiyarso et al., 2010). This loss is, in part, due to the absence of vegetation in impacted and/or drained peatlands, given that in undisturbed peatlands C sequestration from vegetation cover offsets C emissions from the soil. In Southeast Asia, it is estimated that in 2006 CO_2 emissions from organic matter decomposition in drained peat soil were equivalent to 1%–3% of all global CO_2 emissions from burning fossil fuels (~630 Mt), and that 82% of these emissions were from Indonesian peatlands (Hooijer et al., 2010). Other studies have pointed to even higher emission rates associated with peat decomposition in Indonesia, reaching about 8% of global emissions from burning fossil fuels (2,000 Mt/year of CO_2, Rieley et al., 2008). Moreover, major events were reported in 1997 and 2015, in which widespread forest and peatland fires burned large areas of the Southeast Asia (Huijnen et al., 2016; Page et al., 2002), especially Indonesia, releasing large amounts of carbon in the land-based atmosphere, mainly in the form of CO_2, CO and CH_4. With an average emission rate of 11.3 Tg CO_2/day during these events, emissions exceeded the European Union's (EU28) fossil fuel CO_2 release rate of 8.9 Tg CO_2/day (Huijnen et al., 2016).

Methane fluxes also change as a result of human disturbance (Reay et al., 2018). The conversion of peatland forests to areas of intensive cultivation, along with significant inputs of nitrogen fertilizers, may alter the natural dynamics of methane and nitrous oxide emissions (Tian et al., 2015). Rice crops in Indonesia have shown very significant CH_4 emissions after being converted from peatland forests (Table 3) because the production of CH_4 by methanogenic microorganisms is boosted by both the ever-flooded system and the use of nitrogen fertilizers (Conrad, 2002). Emissions from these crops may be about 20-fold greater than emissions from natural areas. Nitrous oxide emissions in Indonesia have been shown to increase substantially with land-use change and the introduction of agricultural activities in peatlands (Oktarita et al., 2017). Nitrous oxide emissions from *Elaesis guineensis* (oil palm) monocultures in Indonesia were reported by Hadi et al. (2005) at 9.1 g C m^{-2} year^{-1}, higher than those reported by Inubushi et al. (2003) in native peat forests, 1.25 g C m^{-2} year^{-1}.

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

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

6 | FINAL REMARKS

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

Climate change is a threat to peatlands, but at local and regional levels, direct human interventions have played a more important role in impairing the capacity of peatlands to sequester carbon. In the tropical zone, the carbon sequestration rate of peatlands in Southeast Asia has changed from 79 to 300 (uptake) to (−499) to (−174) g C m^{-2} year^{-1} (emission) after direct human interference. Integrated development and management mechanisms supported by strong policies and meaningful incentives can balance this scenario and contribute to more effective measures.

The Amazon region potentially holds the largest natural peatland across the tropics. However, the factors that contribute to tropical peatland degradation are only well understood for Southeast Asian peatlands. To date, very few studies have addressed the impacts of peatland degradation in South America and in Africa. Thus, advancing to fill the current scientific knowledge gaps and incorporating local understanding is crucial for supporting policies geared toward managing and conserving undisturbed peatlands in these regions. Furthermore, understanding and mapping peatlands in Brazil by encouraging research projects can enhance the current knowledge about the potential of these system to uptake and store carbon, and can encourage actions aimed to protect peatlands in this region. Due to the high level of conservation and the expected high capacity of carbon accumulation, the Amazon region peatlands are particularly important in the context of climate change mitigation.

DATA AVAILABILITY STATEMENT

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

ORCID

Kelly Ribeiro https://orcid.org/0000-0002-4263-009X
Felipe S. Pacheco https://orcid.org/0000-0003-2143-5225
José W. Ferreira https://orcid.org/0000-0003-4636-868X
Eráclito R. de Sousa-Neto https://orcid.org/0000-0002-1140-7872
Adam Hastie https://orcid.org/0000-0003-2098-3510
Guenther C. Krieger Filho https://orcid.org/0000-0002-3115-565X
Plínio C. Alvalá https://orcid.org/0000-0002-7446-3994
Maria C. Forti https://orcid.org/0000-0002-9170-4518
Jean P. Ometto https://orcid.org/0000-0002-4221-1039

REFERENCES

Avis, C. A., Weaver, A. J., & Meissner, K. J. (2011). Reduction in areal extent of high-latitude wetlands in response to permafrost thaw. *Nature Geoscience*, 4(7), 444–448. https://doi.org/10.1038/ngeo1160

Aziz, A., Dohong, A., & Dargusch, P. (2017). A review of the drivers of tropical peatland degradation in South-East Asia. *Land Use Policy*, 69. https://doi.org/10.1016/j.landusepol.2017.09.035

Baker, F. C. D., Roucoux, K. H., Lawson, I. T., Mitchard, E. T. A., Honorio Coronado, E. N., Lähteenoja, O., Torres Montenegro, L., Valderrama Sandoval, E., Zaráte, R., & Timothy, R. (2014). The distribution and amount of carbon in the largest peatland complex in Amazonia. *Environmental Research Letters*, 9(12), 124017. Retrieved from http://stacks.iop.org/1748-9326/9/i=12/a=124017

Baum, A., Rixen, T., & Samiaji, J. (2007). Relevance of peat draining rivers in central Sumatra for the riverine input of dissolved organic carbon into the ocean. *Estuarine, Coastal and Shelf Science*, 73(3), 563–570. https://doi.org/10.1016/j.ecss.2007.02.012

Blodau, C. (2002). Carbon cycling in peatlands – A review of processes and controls. *Environmental Reviews*, 10(2), 111–134. https://doi.org/10.1139/a02-004

Bonal, D., Bosc, A., Ponton, S., Goret, J.-Y., Burban, B., Gross, P., Bonnefond, J.-M., Elbers, J., Longdoz, B., Epron, D., Guehl, J.-M., & Granier, A. (2008). Impact of severe dry season on net ecosystem exchange in the Neotropical rainforest of French Guiana. *Global Change Biology*, 14(8), 1917–1933. https://doi.org/10.1111/j.1365-2486.2008.01610.x

Bourbonniere, R. A. (2009). Review of water chemistry research in natural and disturbed peatlands. *Canadian Water Resources Journal*, 34, 393–414. https://doi.org/10.4296/cwrj3404393

Bouwman, A. F. (1990). Global distribution of the major soils and land cover types. *Soils and the Greenhouse Effect*, 33–59.

Bracho, R., & San José, J. (1990). Energy fluxes in a morichal (swamp palm community) at the Orinoco Llanos, Venezuela: Microclimate, water vapour and CO_2 exchange. *Photosynthetica*, 24(3), 468–494.

Bubier, J. L., Bhatia, G., Moore, T. R., Roulet, N. T., & Lafleur, P. M. (2003). Spatial and temporal variability in growing-season net ecosystem carbon dioxide exchange at a large peatland in Ontario, Canada. *Ecosystems*, 6(4), 353–367. https://doi.org/10.1007/s10021-003-0125-0

Bwangoy, J.-R.-B., Hansen, M. C., Roy, D. P., Grandi, G. D., & Justice, C. O. (2010). Wetland mapping in the Congo Basin using optical and radar remotely sensed data and derived topographical indices. *Remote Sensing of Environment*, 114(1), 73–86. https://doi.org/10.1016/j.rse.2009.08.004

Chaudhary, N., Westermann, S., Lamba, S., Shurpali, N., Sannel, A. B. K., Schurgers, G., Miller, P. A., & Smith, B. (2020). Modelling past and future peatland carbon dynamics across the pan-Arctic. *Global Change Biology*, 26(7), 4119–4133. https://doi.org/10.1111/gcb.15099

Chimner, R. A. (2004). Soil respiration rates of tropical peatlands in Micronesia and Hawaii. *Wetlands*, 24(1), 51–56. https://doi.org/10.1672/0277-5212(2004)024[0051:SRROTP]2.0.CO;2

Chimner, R. A., & Ewel, K. C. (2005). A tropical freshwater wetland: II. Production, decomposition, and peat formation. *Wetlands Ecology and Management*, 13(6), 671–684. https://doi.org/10.1007/s11273-005-0965-9

Clair, T. A., Arp, P., Moore, T. R., Dalva, M., & Meng, F.-R. (2002). Gaseous carbon dioxide and methane, as well as dissolved organic carbon losses from a small temperate wetland under a changing climate. *Environmental Pollution*, 116, S143–S148. https://doi.org/10.1016/S0269-7491(01)00267-6

Clymo, R. S. (1984). Sphagnum-dominated peat-bog: A naturally acid ecosystem. *Proceedings of the Royal Society of London A*, 305, 487–499. Retrieved from http://www.jstor.org/stable/2396100

Clymo, R. S. (1987). The ecology of peatlands. *Science Progress*, 71(284), 593–614. Retrieved from http://www.jsftor.org/stable/43420701

Conrad, R. (2002). Control of microbial methane production in wetland rice fields [Review]. *Nutrient Cycling in Agroecosystems*, 64, 59–69. https://doi.org/10.1023/A:1021178713988

Couwenberg, J., Dommain, R., & Joosten, H. (2010). Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology*, 16(6), 1715–1732. https://doi.org/10.1111/j.1365-2486.2009.02016.x

Craft, C., Washburn, C., & Parker, A. (2008). *Latitudinal trends in organic carbon accumulation in temperate freshwater peatlands BT – Wastewater treatment, plant dynamics and management in constructed and natural wetlands* (J. Vymazal, Ed.). https://doi.org/10.1007/978-1-4020-8235-1_3

Craft, R. W. & C.B.T.-C. (Eds.). (2016). *Index*. https://doi.org/10.1016/B978-0-12-407232-9.18001-7

Crow, S. E., & Wieder, R. K. (2005). Sources of CO_2 emission from a northern peatland: Root respiration, exudation and decomposition. *Ecology*, 86(7), 1825–1834. https://doi.org/10.1890/04-1575

Dargie, G. C., Lawson, I. T., Rayden, T. J., Miles, L., Mitchard, E. T. A., Page, S. E., Bocko, Y. E., Ifo, S. A., & Lewis, S. L. (2019). Congo Basin peatlands: Threats and conservation priorities. *Mitigation and Adaptation Strategies for Global Change*, 24(4), 669–686. https://doi.org/10.1007/s11027-017-9774-8

Dargie, G. C., Lewis, S. L., Lawson, I. T., Mitchard, E. T. A., Page, S. E., Bocko, Y. E., & Ifo, S. A. (2017). Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature*, 542(7639), 86–90. https://doi.org/10.1038/nature21048

Dommain, R., Cobb, A. R., Joosten, H., Glaser, P. H., Chua, A. F. L., Gandois, L., Kai, F.-M., Noren, A., Salim, K. A., Su'ut, N. S. H., & Harvey, C. F. (2015). Forest dynamics and tip-up pools drive pulses of high carbon accumulation rates in a tropical peat dome in Borneo (Southeast Asia). *Journal of Geophysical Research: Biogeosciences*, 120(4), 617–640. https://doi.org/10.1002/2014JG002796

Dommain, R., Couwenberg, J., & Joosten, H. (2011). Development and carbon sequestration of tropical peat domes in south-east Asia: Links to post-glacial sea-level changes and Holocene climate variability. *Quaternary Science Reviews*, 30, 999–1010. https://doi.org/10.1016/j.quascirev.2011.01.018

Draper, F. C., Roucoux, K. H., Lawson, I. T., Mitchard, E. T. A., Coronado, E. N. H., Lähteenoja, O., Torres Montenegro, L., Valderrama Sandoval, E., Zárate, R., & Baker, T. R. (2014). The distribution and amount of carbon in the largest peatland complex in Amazonia. *Environmental Research Letters*, *9*(12), 124017. Retrieved from http://stacks.iop.org/1748–9326/9/i=12/a=124017

Duffy, P. B., Brando, P., Asner, G. P., & Field, C. B. (2015). Projections of future meteorological drought and wet periods in the Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(43), 13172–13177. https://doi.org/10.1073/pnas.1421010112

FAO. (2014). Towards climate-responsible peatlands management. In R. Biancalani & A. Avagyan (Eds.), *Mitigation of climate change in agriculture series (MICCA)*. Retrieved from http://www.fao.org/3/a-i4029e.pdf

Fatoyinbo, L. (2017). Vast peatlands found in the Congo Basin. *Nature*, *542*(7639), 38–39. https://doi.org/10.1038/542038b

Finer, M., & Orta-Martínez, M. (2010). A second hydrocarbon boom threatens the Peruvian Amazon: Trends, projections, and policy implications. *Environmental Research Letters*, *5*(1), 14012. https://doi.org/10.1088/1748-9326/5/1/014012

Finlayson, C. M., & Milton, G. R. (2018). *Peatlands BT – The wetland book: II: Distribution, description, and conservation* (C. M. Finlayson, G. R. Milton, R. C. Prentice, & N. C. Davidson, Eds.). https://doi.org/10.1007/978-94-007-4001-3_202

Frey, K. E., & Smith, L. C. (2005). Amplified carbon release from vast West Siberian peatlands by 2100. *Geophysical Research Letters*, *32*(9). https://doi.org/10.1029/2004GL022025

Furukawa, Y., Inubushi, K., Ali, M., Itang, A. M., & Tsuruta, H. (2005). Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peat lands. *Nutrient Cycling in Agroecosystems*, *71*(1), 81–91. https://doi.org/10.1007/s10705-004-5286-5

Gallego-Sala, A. V., Charman, D. J., Brewer, S., Page, S. E., Prentice, I. C., Friedlingstein, P., Moreton, S., Amesbury, M. J., Beilman, D. W., Björck, S., Blyakharchuk, T., Bochicchio, C., Booth, R. K., Bunbury, J., Camill, P., Carless, D., Chimner, R. A., Clifford, M., Cressey, E., … Zhao, Y. (2018). Latitudinal limits to the predicted increase of the peatland carbon sink with warming. *Nature Climate Change*, *8*(10), 907–913. https://doi.org/10.1038/s41558-018-0271-1

Gandois, L., Cobb, A. R., Hei, I. C., Lim, L. B. L., Salim, K. A., & Harvey, C. F. (2012). Impact of deforestation on solid and dissolved organic matter characteristics of tropical peat forests: Implications for carbon release. *Biogeochemistry*, *114*(1–3), 183–199. https://doi.org/10.1007/s10533-012-9799-8

Gandois, L., Teisserenc, R., Cobb, A. R., Chieng, H. I., Lim, L., Kamariah, A. S., Hoyt, A., & Harvey, C. F. (2014). Origin, composition, and transformation of dissolved organic matter in tropical peatlands. *Geochimica et Cosmochimica Acta*, *137*, 35–47. https://doi.org/10.1016/j.gca.2014.03.012

Gillman, L. N., Wright, S. D., Cusens, J., McBride, P. D., Malhi, Y., & Whittaker, R. J. (2015). Latitude, productivity and species richness. *Global Ecology and Biogeography*, *24*(1), 107–117. https://doi.org/10.1111/geb.12245

Gorham, E. (1991). Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, *1*(2), 182–195. https://doi.org/10.2307/1941811

Grundlin, P.-L., & Glober, R. (2005). Peatlands and mires of South Africa. *Biologiezentrum Linz/Austria*, (*35*), 379–396. Retrieved from www.biologiezentrum.at

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. Prentice, & N. C. Davidson, Eds.). https://doi.org/10.1007/978-94-007-4001-3_112

Gumbricht, T., Roman-Cuesta, R. M., Verchot, L., Herold, M., Wittmann, F., Householder, E., Herold, N., & Murdiyarso, D. (2017). An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. *Global Change Biology*, *23*(9), 3581–3599. https://doi.org/10.1111/gcb.13689

Gutiérrez-Vélez, V. H., DeFries, R., Pinedo-Vásquez, M., Uriarte, M., Padoch, C., Baethgen, W., Fernandes, K., & Lim, Y. (2011). High-yield oil palm expansion spares land at the expense of forests in the Peruvian Amazon. *Environmental Research Letters*, *6*(4), 44029. https://doi.org/10.1088/1748-9326/6/4/044029

Hadi, A., Inubushi, K., Furukawa, Y., Purnomo, E., Rasmadi, M., & Tsuruta, H. (2005). Greenhouse gas emissions from tropical peatlands of Kalimantan, Indonesia. *Nutrient Cycling in Agroecosystems*, *71*(1), 73–80. https://doi.org/10.1007/s10705-004-0380-2

Haensler, A., Saeed, F., & Jacob, D. (2013). Assessing the robustness of projected precipitation changes over central Africa on the basis of a multitude of global and regional climate projections. *Climatic Change*, *121*(2), 349–363. https://doi.org/10.1007/s10584-013-0863-8

Hapsari, K. A., Biagioni, S., Jennerjahn, T. C., Reimer, P. M., Saad, A., Achnopha, Y., Sabiham, S., & Behling, H. (2017). Environmental dynamics and carbon accumulation rate of a tropical peatland in Central Sumatra, Indonesia. *Quaternary Science Reviews*, *169*, 173–187. https://doi.org/10.1016/j.quascirev.2017.05.026

Harenda, K., Lamentowicz, M., Samson, M., & Chojnicki, B. (2018). The role of peatlands and their carbon storage function in the context of climate change. In *GeoPlanet: Earth and planetary sciences* (pp. 169–187). https://doi.org/10.1007/978-3-319-71788-3_12

Hartmann, A. A., & Niklaus, P. A. (2012). Effects of simulated drought and nitrogen fertilizer on plant productivity and nitrous oxide (N_2O) emissions of two pastures. *Plant and Soil*, *361*(1–2), 411–426. https://doi.org/10.1007/s11104-012-1248-x

Hirano, T., Jauhiainen, J., Inoue, T., & Takahashi, H. (2009). Controls on the carbon balance of tropical peatlands. *Ecosystems*, *12*(6), 873–887. https://doi.org/10.1007/s10021-008-9209-1

Hirano, T., Segah, H., Kusin, K., Limin, S., Takahashi, H., & Osaki, M. (2012). Effects of disturbances on the carbon balance of tropical peat swamp forests. *Global Change Biology*, *18*(11), 3410–3422. https://doi.org/10.1111/j.1365-2486.2012.02793.x

Hodgkins, S. B., Richardson, C. J., Dommain, R., Wang, H., Glaser, P. H., Verbeke, B., Winkler, B. R., Cobb, A. R., Rich, V. I., Missilmani, M., Flanagan, N., Ho, M., Hoyt, A. M., Harvey, C. F., Vining, S. R., Hough, M. A., Moore, T. R., Richard, P. J. H., De La Cruz, F. B., … Chanton, J. P. (2018). Tropical peatland carbon storage linked to global latitudinal trends in peat recalcitrance. *Nature Communications*, *9*. https://doi.org/10.1038/s41467-018-06050-2

Hooijer, A., Page, S., Canadell, J. G., Silvius, M., Kwadijk, J., Wösten, H., & Jauhiainen, J. (2010). Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences*, *7*, 1505–1514. Retrieved from http://edepot.wur.nl/160538

Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., … Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, *579*(7797), 80–87. https://doi.org/10.1038/s41586-020-2035-0

Huijnen, V., Wooster, M. J., Kaiser, J. W., Gaveau, D. L. A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B., & van Weele, M. (2016). Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. *Scientific Reports*, *6*(1), 26886. https://doi.org/10.1038/srep26886

Immirzi, C., & Maltby, E. (1993). The global status of peatlands and their role in carbon cycling, a report for friends of the earth by the wetland ecosystem. *Oryx*, *27*(2), 127. https://doi.org/10.1017/S0030605300020755

Ingram, H. A. P. (1978). Soil layers in mires: Function and terminology. *Journal of Soil Science*, *29*(2), 224–227. https://doi.org/10.1111/j.1365-2389.1978.tb02053.x

International Peatland Society (IPS). (n.d.). Types of peatlands. Retrieved from https://peatlands.org/peatlands/types-of-peatlands/

Inubushi, K., Furukawa, Y., Hadi, A., Purnomo, E., & Tsuruta, H. (2003). Seasonal changes of CO_2, CH_4 and N_2O fluxes in relation to land-use change in tropical peatlands located in coastal area of South Kalimantan. *Chemosphere*, *52*(3), 603–608. https://doi.org/10.1016/S0045-6535(03)00242-X

Inubushi, K., Hadi, A., Okazaki, M., & Yonebayashi, K. (1998). Effect of converting wetland forest to sago palm plantations on methane gas flux and organic carbon dynamics in tropical peat soil. *Hydrological Processes*, *12*(13–14), 2073–2080. https://doi.org/10.1002/(SICI)1099-1085(19981030)12:13/14<2073:AID-HYP720>3.0.CO;2-K

Ise, T., Dunn, A. L., Wofsy, S. C., & Moorcroft, P. R. (2008). High sensitivity of peat decomposition to climate change through water-table feedback. *Nature Geoscience*, *1*(11), 763–766. https://doi.org/10.1038/ngeo331

Jaenicke, J., Rieley, J. O., Mott, C., Kimman, P., & Siegert, F. (2008). Determination of the amount of carbon stored in Indonesian peatlands. *Geoderma*, *147*(3), 151–158. https://doi.org/10.1016/j.geoderma.2008.08.008

Jauhiainen, J., Hooijer, A., & Page, S. E. (2012). Carbon dioxide emissions from an *Acacia* plantation on peatland in Sumatra, Indonesia. *Biogeosciences*, *9*(2), 617–630. https://doi.org/10.5194/bg-9-617-2012

Jauhiainen, J., Jaya, A., Inoue, T., Heikkinen, J. E. P., Martikainen, P., & Vasander, H. (2004). Carbon balance in managed tropical peat in central Kalimantan, Indonesia. *Proceedings of the 12th International Peat Congress*, 653–659.

Jones, M. B., & Humphries, S. W. (2002). Impacts of the C_4 sedge *Cyperus papyrus* L. on carbon and water fluxes in an African wetland. *Hydrobiologia*, *488*(1), 107–113. https://doi.org/10.1023/A:1023370329097

Joosten, H. (2009). *The global peatland CO_2 picture: Peatland status and drainage related emissions in all countries of the world*. Wetlands International, 35 pp.

Joseph, H. (2005). Peatland hydrology and carbon release: Why small-scale process matters. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *363*(1837), 2891–2913. https://doi.org/10.1098/rsta.2005.1671

Kahn, F., & Mejia, K. (1990). Palm communities in wetland forest ecosystems of Peruvian Amazonia. *Forest Ecology and Management*, *1127*(90), 169–179. https://doi.org/10.1016/0378-1127(90)90191-D

Kelly (Letcher), R. A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., ElSawah, S., Hamilton, S. H., Henriksen, H. J., Kuikka, S., Maier, H. R., Rizzoli, A. E., van Delden, H., & Voinov, A. A. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software*, *47*, 159–181. https://doi.org/10.1016/j.envsoft.2013.05.005

Kelly, T. J., Lawson, I. T., Roucoux, K. H., Baker, T. R., Jones, T. D., & Sanderson, N. K. (2017). The vegetation history of an Amazonian domed peatland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *468*, 129–141. https://doi.org/10.1016/j.palaeo.2016.11.039

Könönen, M., Jauhiainen, J., Laiho, R., Kusin, K., & Vasander, H. (2015). Physical and chemical properties of tropical peat under stabilised land uses. *Mires and Peat*, *16*, 8.

Könönen, M., Jauhiainen, J., Laiho, R., Spetz, P., Kusin, K., Limin, S., & Vasander, H. (2016). Land use increases the recalcitrance of tropical peat. *Wetlands Ecology and Management*, *24*(6), 717–731. https://doi.org/10.1007/s11273-016-9498-7

Kosugi, Y., Takanashi, S., Ohkubo, S., Matsuo, N., Tani, M., Mitani, T., Tsutsumi, D., & Nik, A. R. (2008). CO_2 exchange of a tropical rainforest at Pasoh in Peninsular Malaysia. *Agricultural and Forest Meteorology*, *148*(3), 439–452. https://doi.org/10.1016/j.agrformet.2007.10.007

Kurnianto, S., Warren, M., Talbot, J., Kauffman, B., Murdiyarso, D., & Frolking, S. (2015). Carbon accumulation of tropical peatlands over millennia: A modeling approach. *Global Change Biology*, *21*(1), 431–444. https://doi.org/10.1111/gcb.12672

Lähteenoja, O., Flores, B., & Nelson, B. (2013). Tropical peat accumulation in Central Amazonia. *Wetlands*, *33*(3), 495–503. https://doi.org/10.1007/s13157-013-0406-0

Lähteenoja, O., Reátegui, Y. R., Räsänen, M., Torres, D. D. C., Oinonen, M., & Page, S. (2012). The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland basin, Peru. *Global Change Biology*, *18*(1), 164–178. https://doi.org/10.1111/j.1365-2486.2011.02504.x

Lähteenoja, O., Ruokolainen, K., Schulman, L., & Alvarez, J. (2009). Amazonian floodplains harbour minerotrophic and ombrotrophic peatlands. *Catena*, *79*(2), 140–145. https://doi.org/10.1016/j.catena.2009.06.006

Lähteenoja, O., Ruokolainen, K., Schulman, L., & Oinonen, M. (2009). Amazonian peatlands: An ignored C sink and potential source. *Global Change Biology*, *15*(9), 2311–2320. https://doi.org/10.1111/j.1365-2486.2009.01920.x

Leifeld, J., & Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications*, *9*(1), 1071. https://doi.org/10.1038/s41467-018-03406-6

Leng, L. Y., Ahmed, O. H., & Jalloh, M. B. (2019). Brief review on climate change and tropical peatlands. *Geoscience Frontiers*, *10*(2), 373–380. https://doi.org/10.1016/j.gsf.2017.12.018

Lilleskov, E., McCullough, K., Hergoualc'h, K., del Castillo Torres, D., Chimner, R., Murdiyarso, D., Kolka, R., Bourgeau-Chavez, L., Hribljan, J., del Aguila Pasquel, J., & Wayson, C. (2019). Is Indonesian peatland loss a cautionary tale for Peru? A two-country comparison of the magnitude and causes of tropical peatland degradation. *Mitigation and Adaptation Strategies for Global Change*, *24*(4), 591–623. https://doi.org/10.1007/s11027-018-9790-3

Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., Roulet, N., Rydin, H., & Schaepman-Strub, G. (2008). Peatlands and the carbon cycle: From local processes to global implications – A synthesis. *Biogeosciences*, *5*(5), 1475–1491. https://doi.org/10.5194/bg-5-1475-2008

Lund, M., Lafleur, P. M., Roulet, N. T., Lindroth, A., Christensen, T. R., Aurela, M., Chojnicki, B. H., Flanagan, L. B., Humphreys, E. R., Laurila, T., Oechel, W. C., Olejnik, J., Rinne, J., Schubert, P., & Nilsson, M. B. (2010). Variability in exchange of CO_2 across 12 northern peatland and tundra sites. *Global Change Biology*, *16*(9), 2436–2448. https://doi.org/10.1111/j.1365-2486.2009.02104.x

Mäkiranta, P., Laiho, R., Fritze, H., Hytönen, J., Laine, J., & Minkkinen, K. (2009). Indirect regulation of heterotrophic peat soil respiration by water level via microbial community structure and temperature sensitivity. *Soil Biology and Biochemistry*, *41*(4), 695–703. https://doi.org/10.1016/j.soilbio.2009.01.004

Martikainen, P. J., Nykänen, H., Alm, J., & Silvola, J. (1995). Change in fluxes of carbon dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy. *Plant and Soil*, *168*(1), 571–577. https://doi.org/10.1007/BF00029370

McWethy, D. B., Neumann, F. H., Steinbruch, F., Ryan, C. M., & Valsecchi, V. (2016). Late Quaternary vegetation development and disturbance dynamics from a peatland on Mount Gorongosa, central Mozambique. *Quaternary Science Reviews*, *137*, 221–233. https://doi.org/10.1016/j.quascirev.2016.02.004

Melling, L., Hatano, R., & Goh, K. J. (2005). Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. *Tellus B: Chemical and Physical Meteorology*, *57*(1), 1–11. https://doi.org/10.3402/tellusb.v57i1.16772

Miettinen, J., & Liew, S. C. (2010). Status of peatland degradation and development in Sumatra and Kalimantan. *Ambio*, *39*(5–6), 394–401. https://doi.org/10.1007/s13280-010-0051-2

Miettinen, J., Shi, C., & Liew, S. C. (2012). Two decades of destruction in Southeast Asia's peat swamp forests. *Frontiers in Ecology and the Environment*, 10(3), 124–128. https://doi.org/10.1890/100236

Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation*, 6, 67–78. https://doi.org/10.1016/j.gecco.2016.02.004

Mitsch, W. J., Nahlik, A., Wolski, P., Bernal, B., Zhang, L., & Ramberg, L. (2010). Tropical wetlands: Seasonal hydrologic pulsing, carbon sequestration, and methane emissions. *Wetlands Ecology and Management*, 18(5), 573–586. https://doi.org/10.1007/s11273-009-9164-4

Moore, S., Evans, C. D., Page, S. E., Garnett, M. H., Jones, T. G., Freeman, C., Hooijer, A., Wiltshire, A. J., Limin, S. H., & Gauci, V. (2013). Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes. *Nature*, 493(7434), 660–663. https://doi.org/10.1038/nature11818

Murayama, S., & Bakar, Z. A. (1996). Decomposition of tropical peat soils, 2: Estimation of in situ decomposition by measurement of CO_2 flux. *JARQ (Japan)*, 30, 153–158. Retrieved from https://www.jircas.go.jp/sites/default/files/publication/jarq/30-3-153-158_0.pdf

Murdiyarso, D., Hergoualch, K., & Verchot, L. (2010). *Opportunities for reducing greenhouse gas emissions in tropical peatlands* (Vol. 107, pp. 19655–19660). https://doi.org/10.1073/pnas.0911966107

Netzer, M., Brown, K., & Harris, N. (2013). Projections of oil palm expansion in Indonesia, Malaysia and Papua New Guinea from 2010 to 2050. Retrieved from www.researchgate.net/publication/320024842_Projections_of_oil_palm_expansion_in_Indonesia_Malaysia_and_Papua_New_Guinea_from_2010_to_2050

Neuzil, S. G. (1997). Onset and rate of peat and carbon accumulation in four domed ombrogenous peat deposit. In R. And & S. E. Page (Eds.), *Biodiversity and sustainability of tropical peatlands – Proceedings of the international symposium on tropical peatlands* (pp. 55–72). Cardigan.

Oktarita, S., Hergoualc'h, K., Anwar, S., & Verchot, L. V. (2017). Substantial N_2O emissions from peat decomposition and N fertilization in an oil palm plantation exacerbated by hotspots. *Environmental Research Letters*, 12(10), 104007. https://doi.org/10.1088/1748-9326/aa80f1

Olefeldt, D., Roulet, N. T., Bergeron, O., Crill, P., Bäckstrand, K., & Christensen, T. R. (2012). Net carbon accumulation of a high-latitude permafrost palsa mire similar to permafrost-free peatlands. *Geophysical Research Letters*, 39(3), https://doi.org/10.1029/2011GL050355

Page, S. E., & Baird, A. J. (2016). Peatlands and global change: Response and resilience. *Annual Review of Environment and Resources*, 41(1), 35–57. https://doi.org/10.1146/annurev-environ-110615-085520

Page, S. E., Rieley, J. O., & Banks, C. J. (2011). Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*, 17(2), 798–818. https://doi.org/10.1111/j.1365-2486.2010.02279.x

Page, S. E., Rieley, J. O., Shotyk, W., & Weiss, D. (1999). Interdependence of peat and vegetation in a tropical peat swamp forest. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 354(1391), 1885–1897. https://doi.org/10.1098/rstb.1999.0529

Page, S. E., Rieley, J. O., & Wüst, R. (2006). Chapter 7 Lowland tropical peatlands of Southeast Asia. In I. P. Martini, A. Martínez Cortizas, & W. Chesworth (Eds.), *Peatlands* (Vol. 9, pp. 145–172). https://doi.org/10.1016/S0928-2025(06)09007-9

Page, S. E., Siegert, F., Rieley, J. O., Boehm, H.-D.-V., Jaya, A., & Limin, S. (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, 420(6911), 61–65. https://doi.org/10.1038/nature01131

Page, S. E., Siegert, F., Rieley, J. O., Boehm, H. D. V., Jaya, A., Limin, S., … Limin, S. H. (n.d.). Inception, history and development of peatlands in the Amazon Basin. *Dynamics*, 19, 625–635.

Page, S. E., Wüst, R. A. J., Weiss, D., Rieley, J. O., Shotyk, W., & Limin, S. H. (2004). A record of Late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): Implications for past, present and future carbon dynamics. *Journal of Quaternary Science*, 19(7), 625–635. https://doi.org/10.1002/jqs.884

Pajunen, H. (1996). Mires as late Quaternary accumulation basins in Rwanda and Burundi, Central Africa. *Geological Survey of Finland*. Volume 384: de Bulletin. Geologian Tutkimuskeskus, 104 pp.

Ponette-González, A. G., Curran, L. M., Pittman, A. M., Carlson, K. M., Steele, B. G., Ratnasari, D., Mujiman, , & Weathers, K. C. (2016). Biomass burning drives atmospheric nutrient redistribution within forested peatlands in Borneo. *Environmental Research Letters*, 11(8), 85003. https://doi.org/10.1088/1748-9326/11/8/085003

Porporato, A., Laio, F., Ridolfi, L., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress: III. Vegetation water stress. *Advances in Water Resources*, 24(7), 725–744. https://doi.org/10.1016/S0309-1708(01)00006-9

Qiu, C., Zhu, D., Ciais, P., Guenet, B., & Peng, S. (2020). The role of northern peatlands in the global carbon cycle for the 21st century. *Global Ecology and Biogeography*, 29(5), 956–973. https://doi.org/10.1111/geb.13081

Radjagukguk, B. (1997). Peat soil of Indonesia: Location, classification and problem for sustainability. In J. O. Rieley & S. E. Page (Eds.), *Biodiversity and sustainability of tropical peatlands* (pp. 42–54). Samara Publishing Ltd.

Raupach, M., Gloor, M., Sarmiento, J., Canadell, G., Frölicher, J., Gasser, T., Houghton, R. A., Le Quéré, C., & Trudinger, C. (2013). The declining uptake rate of atmospheric CO_2 by land and ocean sinks. *Biogeosciences discussions* (Vol. 10). https://doi.org/10.5194/bgd-10-18407-2013

Reay, D., Smith, P., Christensen, T. R., James, R., & Clark, H. (2018). Methane and global environmental change. *Annual Review of Environment and Resources*, 43(1), 165–192. https://doi.org/10.1146/annurev-environ-102017-030154

Rebelo, L.-M., Finlayson, C. M., & Nagabhatla, N. (2009). Remote sensing and GIS for wetland inventory, mapping and change analysis. *Journal of Environmental Management*, 90(7), 2144–2153. https://doi.org/10.1016/j.jenvman.2007.06.027

Reiche, M., Gleixner, G., & Küsel, K. (2010). Effect of peat quality on microbial greenhouse gas formation in an acidic fen. *Biogeosciences*, 7(1), 187–198. https://doi.org/10.5194/bg-7-187-2010

Renou-Wilson, F., Moser, G., Fallon, D., Farrell, C. A., Müller, C., & Wilson, D. (2019). Rewetting degraded peatlands for climate and biodiversity benefits: Results from two raised bogs. *Ecological Engineering*, 127, 547–560. https://doi.org/10.1016/j.ecoleng.2018.02.014

Ribeiro, K., Pacheco, F. S., Ferreira, W., Sousa Neto, E. R., Ometto, J. P., Forti, M. C., Sobral, A. C., Venâncio, S., & Alvalá, P. C. (2018). Effect of land use and land cover on greenhouse gas emissions from peatlands in the Paraíba Valley, Brazil. *AGUFM*, 2018, GC21I-1213.

Rieley, J., Wüst, R., Jauhiainen, J., Page, S., Wösten, H., Hooijer, A., Siegert, E., Limin, S. H., Vasander, H., & Stahlhut, M. (2008). Tropical peatlands: Carbon stores, carbon gas emissions and contribution to climate change processes. In M. Strack (Ed.), *Peatlands and climate change* (pp. 148–181). University of Calgary.

Roucoux, K. H., Lawson, I. T., Baker, T. R., Del Castillo Torres, D., Draper, F. C., Lähteenoja, O., Gilmore, M. P., Honorio Coronado, E. N., Kelly, T. J., Mitchard, E., & Vriesendorp, C. F. (2017). Threats to intact tropical peatlands and opportunities for their conservation. *Conservation Biology*, 31(6), 1283–1292. https://doi.org/10.1111/cobi.12925

Roulet, N. (2012). Peatlands, carbon storage, greenhouse gases, and the Kyoto Protocol: Prospects and significance for Canada. *Wetlands*, 20, 605–615. https://doi.org/10.1672/0277-5212(2000)020[0605:PCSGGA]2.0.CO;2

Roulet, N. T., Lafleur, P. M., Richard, P. J. H., Moore, T. I. M. R., Humphreys, E. R., & Bubier, J. (2007). Contemporary carbon

balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, 13(2), 397–411. https://doi.org/10.1111/j.1365-2486.2006.01292.x

Rudiyanto, Setiawan, B. I., Arief, C., Saptomo, S. K., Gunawan, A., Kuswarman, Sungkono, & Indriyanto, H. (2015). Estimating distribution of carbon stock in tropical peatland using a combination of an empirical peat depth model and GIS. *Procedia Environmental Sciences*, 24, 152–157. https://doi.org/10.1016/j.proenv.2015.03.020

Saleska, S. R., Miller, S. D., Matross, D. M., Goulden, M. L., Wofsy, S. C., da Rocha, H. R., De Camargo, P. B., Crill, P., Daube, B. C., De Freitas, H. C., & Silva, H. (2003). Carbon in Amazon forests: Unexpected seasonal fluxes and disturbance-induced losses. *Science*, 302(5650), 1554–1557. https://doi.org/10.1126/science.1091165

Scharlemann, J. P. W., Tanner, E. V. J., Hiederer, R., & Kapos, V. (2014). Global soil carbon: Understanding and managing the largest terrestrial carbon pool. *Carbon Management*, 5(1), 81–91. https://doi.org/10.4155/cmt.13.77

Schumann, M., & Joosten, H. (2008). Global peatland restoration manual. Retrieved from http://www.imcg.net/media/download_gallery/books/gprm_01.pdf

Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., & Martikainen, P. J. (1996). CO_2 fluxes from peat in boreal mires under varying temperature and moisture conditions. *Journal of Ecology*, 84(2), 219–228. https://doi.org/10.2307/2261357

Sjögersten, S., Black, C., Evers, S., Hoyos-Santillan, J., Wright, E., & Turner, B. (2014). Tropical wetlands: A missing link in the global carbon cycle? *Global Biogeochemical Cycles*, 28(12), 1371–1386. https://doi.org/10.1002/2014GB004844

Sorensen, K. W. (1993). Indonesian peat swamp forests and their role as a carbon sink. *Chemosphere*, 27(6), 1065–1082. https://doi.org/10.1016/0045-6535(93)90068-G

Sorribas, M. V., Paiva, R. C. D., Melack, J. M., Bravo, J. M., Jones, C., Carvalho, L., Beighley, E., Forsberg, B., & Costa, M. H. (2016). Projections of climate change effects on discharge and inundation in the Amazon basin. *Climatic Change*, 136(3), 555–570. https://doi.org/10.1007/s10584-016-1640-2

Spahni, R., Joos, F., Stocker, B. D., Steinacher, M., & Yu, Z. C. (2013). Transient simulations of the carbon and nitrogen dynamics in northern peatlands: From the Last Glacial Maximum to the 21st century. *Climate of the Past*, 9(3), 1287–1308. https://doi.org/10.5194/cp-9-1287-2013

Swindles, G. T., Morris, P. J., Whitney, B., Galloway, J. M., Gałka, M., Gallego-Sala, A., Macumber, A. L., Mullan, D., Smith, M. W., Amesbury, M. J., Roland, T. P., Sanei, H., Patterson, R. T., Sanderson, N., Parry, L., Charman, D. J., Lopez, O., Valderamma, E., Watson, E. J., … Lähteenoja, O. (2018). Ecosystem state shifts during long-term development of an Amazonian peatland. *Global Change Biology*, 24(2), 738–757. https://doi.org/10.1111/gcb.13950

Takada, M., Shimada, S., & Takahashi, H. (2016). *Tropical peat formation BT – Tropical peatland ecosystems* (M. Osaki & N. Tsuji, Eds.). https://doi.org/10.1007/978-4-431-55681-7_8

Tian, H., Chen, G., Lu, C., Xu, X., Ren, W., Zhang, B., Banger, K., Tao, B. O., Pan, S., Liu, M., Zhang, C., Bruhwiler, L., & Wofsy, S. (2015). Global methane and nitrous oxide emissions from terrestrial ecosystems due to multiple environmental changes. *Ecosystem Health and Sustainability*, 1(1), 1–20. https://doi.org/10.1890/EHS14-0015.1

Treat, C. C., Kleinen, T., Broothaerts, N., Dalton, A. S., Dommain, R., Douglas, T. A., Drexler, J. Z., Finkelstein, S. A., Grosse, G., Hope, G., Hutchings, J., Jones, M. C., Kuhry, P., Lacourse, T., Lähteenoja, O., Loisel, J., Notebaert, B., Payne, R. J., Peteet, D. M., … Brovkin, V. (2019). Widespread global peatland establishment and persistence over the last 130,000 y. *Proceedings of the National Academy of Sciences of the United States of America*, 116(11), 4822–4827. https://doi.org/10.1073/pnas.1813305116

Turetsky, M. R., Kotowska, A., Bubier, J., Dise, N. B., Crill, P., Hornibrook, E. R. C., Minkkinen, K., Moore, T. R., Myers-Smith, I. H., Nykänen, H., Olefeldt, D., Rinne, J., Saarnio, S., Shurpali, N., Tuittila, E.-S., Waddington, J. M., White, J. R., Wickland, K. P., & Wilmking, M. (2014). A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands. *Global Change Biology*, 20(7), 2183–2197. https://doi.org/10.1111/gcb.12580

Ueda, S., Go, C.-S.- U., Yoshioka, T., Yoshida, N., Wada, E., Miyajima, T., Sugimoto, A., Boontanon, N., Vijarnsorn, P., & Boonprakub, S. (2000). Dynamics of dissolved O_2, CO_2, CH_4, and N_2O in a tropical coastal swamp in southern Thailand. *Biogeochemistry*, 49(3), 191–215. https://doi.org/10.1023/A:1006393214432

Vitt, D. H. (2013). Peatlands. In *Encyclopedia of ecology* (Vol. 2, 2nd ed., pp. 557–566). https://doi.org/10.1016/B978-0-12-409548-9.00741-7

Wang, H., Richardson, C. J., & Ho, M. (2015). Dual controls on carbon loss during drought in peatlands. *Nature Climate Change*, 5, 584. https://doi.org/10.1038/nclimate2643

Wang, S., Zhuang, Q., Lähteenoja, O., Draper, F. C., & Cadillo-Quiroz, H. (2018). Potential shift from a carbon sink to a source in Amazonian peatlands under a changing climate. *Proceedings of the National Academy of Sciences of the United States of America*, 115(49), 12407–12412. https://doi.org/10.1073/pnas.1801317115

Warner, B. G., & Rubec, C. D. A. (1997). *The Canadian wetland classification system* (2nd ed.). National Wetlands Working Group.

Warren, M., Hergoualc'h, K., Kauffman, J. B., Murdiyarso, D., & Kolka, R. (2017). An appraisal of Indonesia's immense peat carbon stock using national peatland maps: Uncertainties and potential losses from conversion. *Carbon Balance and Management*, 12(1), 12. https://doi.org/10.1186/s13021-017-0080-2

Wilson, S., Griffiths, M., & Anielski, M. (2001). *The Alberta GPI accounts: Wetlands and peatlands*. Retrieved from http://www.pembina.org/reports/23_wetlands_and_peatlands.pdf

Wong, G. X., Hirata, R., Hirano, T., Kiew, F., Aeries, E. B., Musin, K. K., Waili, J. W., Lo, K. S., & Melling, L. (2020). How do land use practices affect methane emissions from tropical peat ecosystems? *Agricultural and Forest Meteorology*, 282–283, 107869. https://doi.org/10.1016/j.agrformet.2019.107869

Worrall, F., Chapman, P., Holden, J., Evans, C., Artz, R., Smith, P., & Grayson, R. (2011). *A review of current evidence on carbon fluxes and greenhouse gas emissions from UK peatlands*. https://doi.org/10.1016/j.catena.2007.07.010

Wösten, J. H. M., Clymans, E., Page, S. E., Rieley, J. O., & Limin, S. H. (2008). Peat–water interrelationships in a tropical peatland ecosystem in Southeast Asia. *CATENA*, 73(2), 212–224. https://doi.org/10.1016/j.catena.2007.07.010

Wright, E. L., Black, C. R., Cheesman, A. W., Drage, T., Large, D., Turner, B. L., & Sjögersten, S. (2011). Contribution of subsurface peat to CO_2 and CH_4 fluxes in a neotropical peatland. *Global Change Biology*, 17(9), 2867–2881. https://doi.org/10.1111/j.1365-2486.2011.02448.x

Wu, J., & Roulet, N. T. (2014). Climate change reduces the capacity of northern peatlands to absorb the atmospheric carbon dioxide: The different responses of bogs and fens. *Global Biogeochemical Cycles*, 28(10), 1005–1024. https://doi.org/10.1002/2014GB004845

Xu, J., Morris, P. J., Liu, J., & Holden, J. (2018). PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *CATENA*, 160, 134–140. https://doi.org/10.1016/j.catena.2017.09.010

Yu, G. R., Fang, H. J., Cheng, S. L., Zhu, T. H., Wang, Y. S., Yan, J. H., Wang, M., Cao, M., & Zhou, M. (2010). Effects of multiple environmental factors on CO(2) emission and CH(4) uptake from old-growth forest soils. *Biogeosciences*, 7(1), 395–407.

Yu, Z. (2011). Holocene carbon flux histories of the world's peatlands: Global carbon-cycle implications. *The Holocene*, 21(5), 761–774. https://doi.org/10.1177/0959683610386982

Yu, Z. C. (2012). Northern peatland carbon stocks and dynamics: A review. *Biogeosciences*, *9*, 4071–4085. https://doi.org/10.5194/bg-9-4071-2012

Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., & Hunt, S. J. (2010). Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, *37*(13), https://doi.org/10.1029/2010GL043584

Yule, C. M., Lim, Y. Y., & Lim, T. Y. (2016). Degradation of tropical malaysian peatlands decreases levels of phenolics in soil and in leaves of *Macaranga pruinosa*. *Frontiers in Earth Science*, *4*, 45. https://doi.org/10.3389/feart.2016.00045

Zoltai, S. C., & Martikainen, P. J. (1996). In M. J. Apps & D. T. Price (Eds.), *Estimated extent of forested peatlands and their role in the global carbon cycle BT – Forest ecosystems, forest management and the global carbon cycle*. Springer. https://doi.org/10.1007/978-3-642-61111-7_5

Zulkafli, Z., Buytaert, W., Manz, B., Rosas, C. V., Willems, P., Lavado-Casimiro, W., Guyot, J.-L., & Santini, W. (2016). Projected increases in the annual flood pulse of the Western Amazon. *Environmental Research Letters*, *11*(1), 14013. https://doi.org/10.1088/1748-9326/11/1/014013