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INDONESIA'S TROPICAL PEATLANDS REVISITED: AREA, DEPTH, CARBON POTENTIAL, AND THEIR IMPORTANCE

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Indonesia has the largest tropical peatlands in the Asia-Pacific region and the world's second largest tropical peatlands. Growing concerns on peatland conservation and restoration emphasise the importance of these ecosystems for climate change mitigation and adaptation. Although Indonesia's peatlands are well-studied compared with other tropical countries, there are still uncertainties regarding its peat volume and carbon stock estimations, and how important it is locally and globally. To solve these uncertainties, this study estimated peat volume and carbon stock in Indonesia using the national peatlands data published by the Ministry of Agriculture, Republic of Indonesia and analysed greenhouse gas emissions among the major industrial sectors in the country and global emissions by peatland degradation. Our study posited that anthropogenic disturbance degraded Indonesian peatlands and that the country could become the largest greenhouse gas emitter in the world. Therefore, successful conservation and restoration of Indonesia's peatlands could significantly contribute to global climate change mitigation and adaptation.

Keywords: Carbon stock, climate change mitigation, greenhouse gas emissions, peatland conservation and restoration

INTRODUCTION

Peatlands are carbon-rich ecosystems formed by the accumulation of organic matter in oxygen-deprived and water-saturated environments. These ecosystems play an important role in mitigating climate change by serving as a vital carbon sink for carbon storage (Finlayson & Milton 2016, Osaki et al. 2016). Peatlands are found in 178 countries across different continents and diverse climatic conditions (FAO 2022). The global peatland area is estimated at around 185–423 mil ha, equivalent to about 2.84% of the world's land area (Xu et al. 2018). In the tropics, tropical peatland area covers around 44.1 mil ha (Page et al. 2011), which are equal to 10% of the global peatland area, and of this, 24.7 mil ha are found in South-East Asia. Tropical peatlands in South-East Asia are mainly concentrated in Indonesia, i.e. 36% of the world's tropical peatlands, making Indonesia the largest tropical peatland area in the world after Brazil (Page et al. 2011, Gumbricht et al. 2017, Xu et al. 2018).

Peatlands deposit 550–600 Gt (25%) of global soil carbon (C) stock and can store twice as much carbon as all the forests in the world combined (Joosten et al. 2016, Leifeld & Menichetti 2018). Tropical peatlands sequester more carbon compared with other terrestrial ecosystems (Page et al. 2011). In Indonesia, peatlands are estimated to store about 40.5–57.4 Gt C (Page et al. 2011, Warren et al. 2017). Aside from their importance as an immense carbon pool, tropical peatlands also provide numerous ecosystem functions such as preventing fire and flooding, providing timber and non-timber forest products, supporting biodiversity, regulating global climate change, and providing socio-cultural, recreation and education purposes.

Despite these important values, tropical peatlands have undergone significant anthropogenic disturbances. Over the past few decades, peatlands have been logged and drained for plantation and agricultural purposes, which have caused them to dry up and become vulnerable to fire (Glauber et al. 2016, Osaki et al. 2016). Consequently, due to land degradation and deforestation, peatlands can act as a source of greenhouse gas (GHG) emission (Smith et al. 2017, Astiani et al. 2018). For instance, during the period of June to October 2015, fire events especially in South Sumatra, Central Kalimantan and East Kalimantan contributed approximately 1.75 bil t CO_2 to global emissions (Field et al. 2016), resulting in an estimated cost of USD16.1 billion (Glauber 2016). In line with the global target of reducing GHG emissions towards net zero CO_2, restoring degraded peatlands is important to reverse this ecosystem as a source of GHG emissions to carbon sequestration that contribute to mitigate climate change (Leifeld & Menichetti 2018, Tanneberger et al. 2020).

Despite the increasing research on peatlands, there are still discrepancies in the extent and distribution of peatlands in Indonesia (Page et al. 2011, Warren et al. 2017, Anda et al. 2021). According to Radjagukguk (1997), there are 20.1 mil ha peatlands in Indonesia while Wahyunto et al. (2006) reported the value as 20.94 mil ha. More recently, some Indonesian government institutions published varying data on Indonesian peatlands, for example, the Ministry of Environment and Forestry (MoEF) of Indonesia reported an area of 24.6 mil ha (MoEF 2017) and the Ministry of Agriculture (MoA) reported an area of 14.9 mil ha (Ritung et al. 2011), which was then updated to 13.4 mil ha (Anda et al. 2021). The varieties of methods, assumptions and technologies used to obtain the peatland data have resulted in differences in estimates about peatlands in Indonesia (Osaki et al. 2016). Unfortunately, discrepancies in peatland data influence the inconsistent estimation of carbon storage and emissions generated from peatlands (Xu et al. 2018).

To deal with the uncertainty on information of peatland distribution, peat volume and estimation of carbon storage in Indonesia, this study was aimed at comprehensively assessing and estimating the potential carbon storage of the country's tropical peatlands. This study examined two datasets published by the MoA in 2011 and 2019 (Ritung et al. 2011, 2019 respectively). These datasets incorporated data published by the government as well as the Wetlands International Indonesia Programme (Warren et al. 2017, Anda et al. 2021), both of which adhered to national guidelines for peatland inventory that involved ground truthing methods (Anda et al. 2021). The objective of this study was to determine the volume of peat and estimate carbon content to assess the value resources of peatlands within the country. These findings are crucial for promoting sustainable peatland management, estimating carbon potential, and safeguarding ecosystem functions that contribute to mitigation of climate change and adaptation efforts.

MATERIALS AND METHODS

Study data

This study acquired principal data from the national peatlands inventory conducted by the Indonesian Center for Agricultural Land Resources Research and Development, a research agency under Indonesia's Ministry of Agriculture. The acquired datasets included a peatlands map of Indonesia at a scale of 1:250,000 published in 2011 (hereinafter referred to as MoA-2011), and the recent semi-detailed peatlands map at a scale of 1:50,000, published in 2019 (MoA-2019). These maps comprehensively present data on peatland area, distribution and peat thickness throughout Indonesia.

MoA-2011 and MoA-2019 classified Indonesia's peat thickness on an interval scale. MoA-2011 classified peat depth into four: 50–100 cm (shallow), 100–200 cm (moderately deep), 200–300 cm (deep), and > 300 cm (very deep). Meanwhile, MoA-2019 classified peat depth into six: 50–100 cm (shallow), 100–200 cm (moderately deep), 200–300 cm (deep), 300–500 cm (very deep), 500–700 cm (extra very deep), and > 700 cm (exceptionally very deep).

As the data of peat depth was provided in interval scale, this study employed low, medium, and high estimate for each dataset as performed by Warren et al. (2017). A similar methodology and approach can also be found in the practical guidelines for peat carbon measurement published by the World Agroforestry Centre and the Indonesian Agricultural Land Resources Research and Development (Agus et al. 2011). However, it should be noted that the guidelines only calculate peat carbon based on the average peat thickness class. Therefore, medium estimate assumed the depth of peatlands within a given class at the midpoint. For instance, depth class of 50–100 cm used 75 cm as the midpoint while low estimates and high estimates of this interval used 50 and 100 cm as the low end and high end of depth class respectively. In the > 300 cm depth class, 300, 500 and 700 cm were used for low, medium and high estimates respectively. The low estimate of 300 cm was the upper end of depth reported by MoA-2011 while the high estimate of 700 cm was the upper end of depth reported by MoA-2019 and medium estimate of 500 cm was the midpoint of the 300 cm minimum and 700 cm maximum reported for the deepest depth class in the MoA-2011 and MoA-2019 respectively. Employing medium estimates assumed the depth of peatlands within a given class at the midpoint and prevented underestimates and overestimates (Warren et al. 2017).

Calculation of carbon storage

In order to estimate the volume of peat and carbon storage, we analysed the collected data by calculating the minimum, medium and maximum values. To enable comparison with MoA-2011, we merged the peat thickness classes of 300–500, 500–700, and > 700 cm from MoA-2019 into a single category of > 300 cm.

To determine the peat volume estimate, we examined data for four islands (i.e. Sumatra, Kalimantan, Sulawesi and Papua) and their respective provinces from both MoA-2011 and MoA-2019. To calculate the peat volume, we multiplied the area of peatland by the corresponding peat thickness, using the following equation:

$$V_p = A_p \times T_p$$

where, V_p, A_p, and T_p indicate peat volume (m^3), peatland area (m^2), and peat thickness (m) respectively.

To calculate the peat carbon stock estimate, the same formula used by Warren et al. (2017) was employed:

$$C_{peat} = V \times C_d$$

where, C_{peat}, V, and C_d represent carbon storage (Gt C), peat volume (m^3), and peat carbon density (kg m^{-3}) respectively. However, since there were limited sources available for peat carbon density data, we collected such information from alternative sources (Table 1).

Table 1 Peat carbon density of each province obtained from literatures

Province	Carbon density (kg m^{-3})	Reference
Aceh	55.5	*
Bangka Belitung	65.1	*
Bengkulu	65.1	*
Jambi	54.5	Warren et al. (2017)
Lampung	65.1	*
North Sumatra	65.1	*
Riau	69.8	Brady (1997), Neuzil (1997)
Riau Islands	69.8	*
South Sumatra	65.1	*
West Sumatra	65.1	*
Central Kalimantan	61.6	Page et al. (2004)
East Kalimantan	65.1	*
North Kalimantan	65.1	*
South Kalimantan	61.6	Page et al. (2004)
West Kalimantan	55.5	Warren et al. (2017)
Central Sulawesi	65.1	Neuzil (1997), Page et al. (2004)
West Sulawesi	65.1	*
Papua	65.1	*
West Papua	65.1	*

*The average of peat carbon densities suggested by Brady (1997), Neuzil (1997), Page et al. (2004), and Warren et al. (2017) was used for provinces without peat carbon density value

RESULTS

Peatland area

According to MoA-2011 (Figure 1a), the peatland area of Indonesia covers around 14,905,486 ha, distributed across 10 provinces in Sumatra (6.44 mil ha), 4 provinces in Kalimantan (4.78 mil ha), and 2 provinces in Papua (3.69 mil ha). On the other hand, MoA-2019 (Figure 1b) indicates that the peatland area in Indonesia is around 13,430,511 ha, distributed into 10 provinces in Sumatra (5.85 mil ha), 5 provinces in Kalimantan (4.54 mil ha), 2 provinces in Sulawesi (0.03 mil ha), and 2 provinces in Papua (3.01 mil ha). There are some major differences in peatland area and distribution between the MoA-2011 and MoA-2019 maps (Figure 1c). The peatland area in MoA-2019 is smaller by about 1,474,975 ha compared with the data in MoA-2011. MoA-2019 shows that peatland area in all islands have decreased except in Sulawesi, which was newly inventoried at that time. The major decrease is in Papua, which accounts for 629,008 ha, followed by Sumatra with 586,276 ha, and the lowest decrease is in Kalimantan, which accounts for 234,639 ha (Figure 1c).

Looking into the peatland area by province, data from MoA-2011 shows that Riau province in Sumatra has the biggest peatland area (3.87 mil ha), followed by Central Kalimantan province in Kalimantan (2.66 mil ha), and Papua province in Papua (2.64 mil ha) (Figure 2a). In the MoA-2019 data, the provinces with the biggest peatland area are the same, i.e. Riau province (3.57 mil ha), followed by Central Kalimantan province (2.55 mil ha), and Papua province (2.21 mil ha) (Figure 2b). There are decreases and increases in the peatland area between MoA-2019 and MoA-2011 (Figure 2c). The largest decreases are found in Papua province (424,932 ha) and Riau province (293,459 ha), while the largest increase occur in North Kalimantan province (216,994 ha). The establishment of North Kalimantan province as a new autonomous region in 2012, a year after the MoA-2011 was published, has contributed to the alteration of the peatland areas, specifically within North Kalimantan and East Kalimantan provinces, where North Kalimantan was previously part of East Kalimantan province.

Peat volume

The larger area of peatlands and deeper peat depth delineated on the maps resulted in larger estimates of peat volume. Low, medium and high estimates of the peatland volume of the MoA-2011 data are 210, 346 and 392 km^3

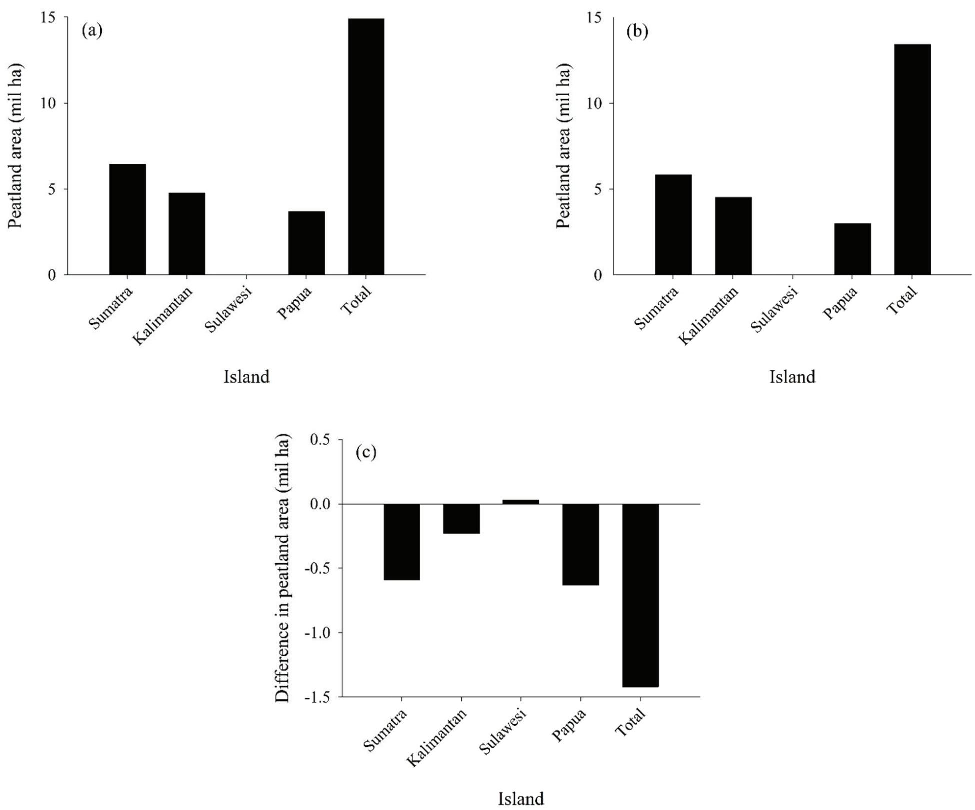

Figure 1 Peatland area by island in (a) 2011 and (b) 2019 published by the Ministry of Agriculture, Indonesian and (c) the difference in peatland areas between 2011 and 2019

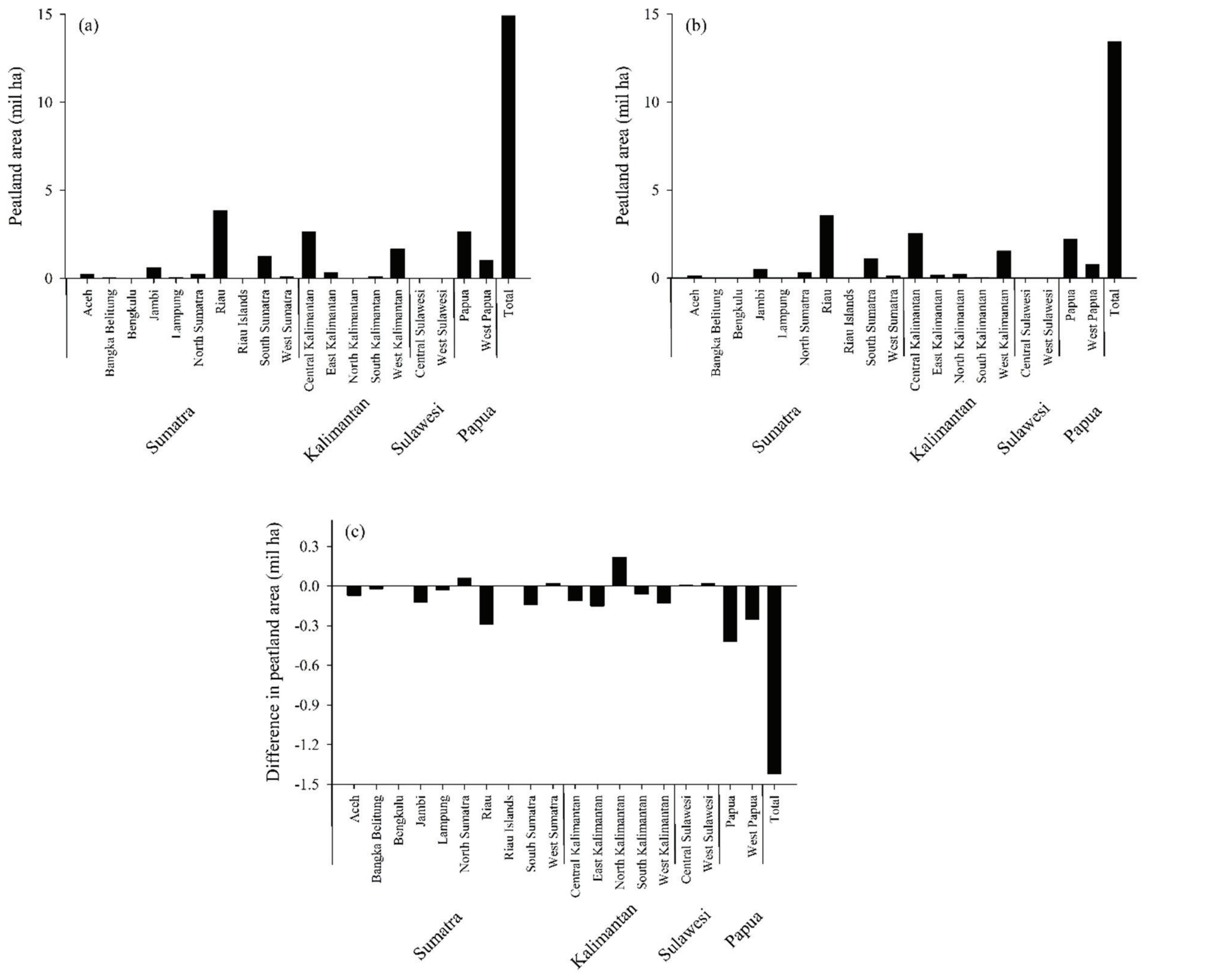

Figure 2 Peatland area by province in (a) 2011 and (b) 2019 published by the Indonesian Ministry of Agriculture and (c) the difference in peatland areas between 2011 and 2019

respectively (Figure 3a). On the other hand, the low, medium and high estimates of peat volume in the MoA-2019 data are 241.94, 393.18, and 447.91 km^3 respectively (Figure 3b). The overall difference in the medium estimates of peat volume by island between these datasets is 46.94 km^3, with the biggest gap found in Sumatra (increase of 46.89 km^3). Peat volume in Papua decreased 4.27 km^3 in 2019 compared with 2011 (Figure 3c).

The medium estimates of peat volume calculated from MoA-2011 (Figure 4a) are mostly concentrated in certain provinces, including Riau (135.08 km^3), followed by Central Kalimantan (84.46 km^3) and West Kalimantan (35.08 km^3). From the MoA-2019 data, medium estimates of peat volume by province are mostly concentrated in Riau (143.56 km^3), West Kalimantan (48.13 km^3) and South Sumatra (43.95 km^3) (Figure 4b). The overall difference in peat volume by province between MoA-2011 and MoA-2019 is concentrated in South Sumatra, West Kalimantan and Riau provinces, with increases of 29.89, 13.05 and 8.48 km^3 respectively (Figure 4c).

Peat carbon

The difference in peat volume between the 2011 and 2019 data sets reflects the difference in peat carbon estimates. The low, medium and high estimates of peat carbon by island in the MoA-2011 are 13.55, 22.39 and 25.35 Gt C respectively (Figure 5a). The medium estimate of peat carbon in MoA-2011 shows that the largest amount of peat carbon is found in Sumatra (11.75 Gt C), followed by Kalimantan (8.09 Gt C), and Papua (2.71 Gt C). The MoA-2019 data (Figure 5b) show that the largest peat carbon amount is

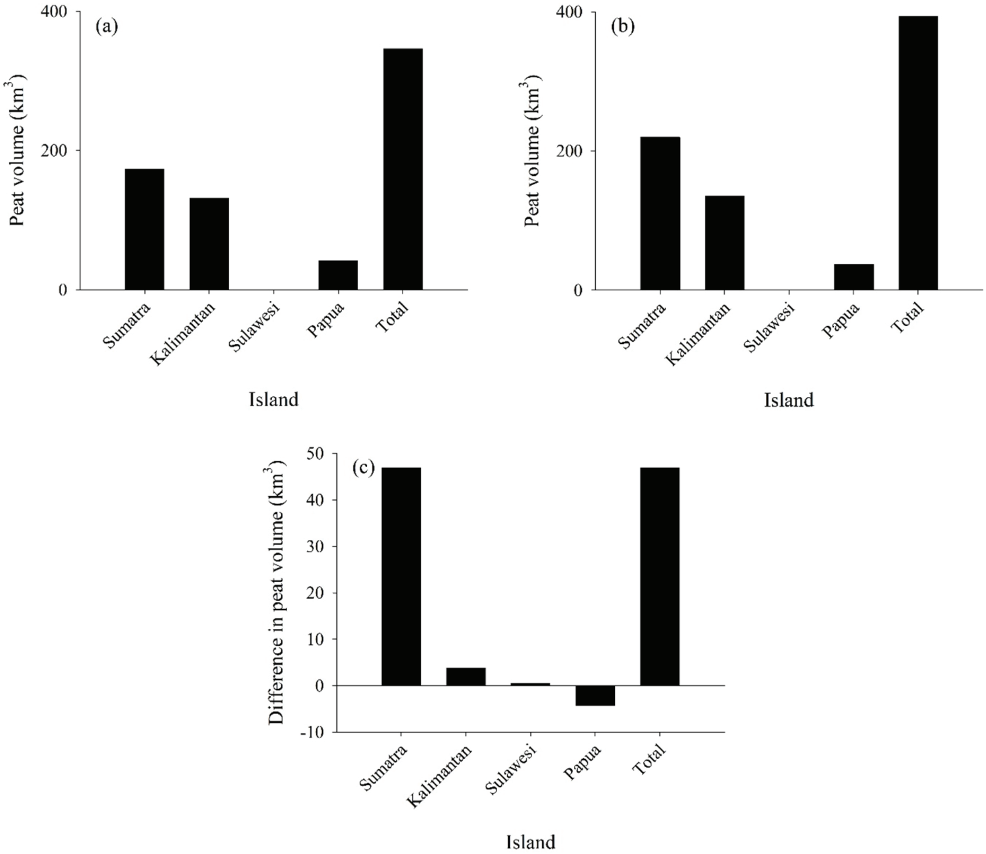

Figure 3 Peat volume by island in (a) 2011 and (b) 2019 published by the Indonesian Ministry of Agriculture and (c) the difference in peatland volume between 2011 and 2019

mostly concentrated in Sumatra (14.81 Gt C), followed by Kalimantan (8.09 Gt C) and Papua (2.43 Gt C). Overall, the medium estimates of peat carbon by island between MoA-2011 and MoA-2019 (Figure 5c) show a decrease of 1.79 Gt C. The largest decreases occur in Kalimantan (4.60 Gt C) and Papua (0.28 Gt C). Sumatra (3.05 Gt C) and Sulawesi (0.03 Gt C) experienced an increase in peat carbon between the two years.

The medium estimate of peat carbon by province in the MoA-2011 data (Figure 6a) is mostly concentrated in Riau (9.43 Gt C), Kalimantan (5.20 Gt C) and Papua (2.05 Gt C). For the MoA-2019 data (Figure 6b), the largest medium estimates of peat carbon mostly occur in Riau (10.02 Gt C), Central Kalimantan (4.55 Gt C), and South Sumatra (2.86 Gt C). The overall difference in medium estimates of peat carbon by province between MoA-2011 and MoA-2019 is a decrease of 1.79 Gt C, which mostly occur in Central Kalimantan (3.21 Gt C), West Kalimantan (1.03 Gt C) and East Kalimantan (0.42 Gt C) (Figure 6c). However, a significant increase in peat carbon estimate is recorded in Riau (1.35 Gt C).

DISCUSSION

The data of Indonesia's peatland areas published in the MoA-2019 show that the peatland areas cover 13.4 mil ha (Ritung et al. 2019), which are lower than the previous dataset of the 1:250,000 scale map covering an area of 14.9 mil ha (Ritung et al. 2011). The values of peatland areas published on these datasets are lower than the estimates reported in the last two decades varying from 20.94 mil ha (Wahyunto et al. 2003, 2004, 2006) to 20.6 mil ha (Page et al. 2011). An assessment conducted through meta-analysis by Xu et al. (2018) found that the Indonesian peatlands cover an area of 14.8 mil ha, which is close to the data in MoA-2011.

The fundamental issue in mapping peatlands is the lack of a standardised criteria by which peatlands are defined and identified, and the

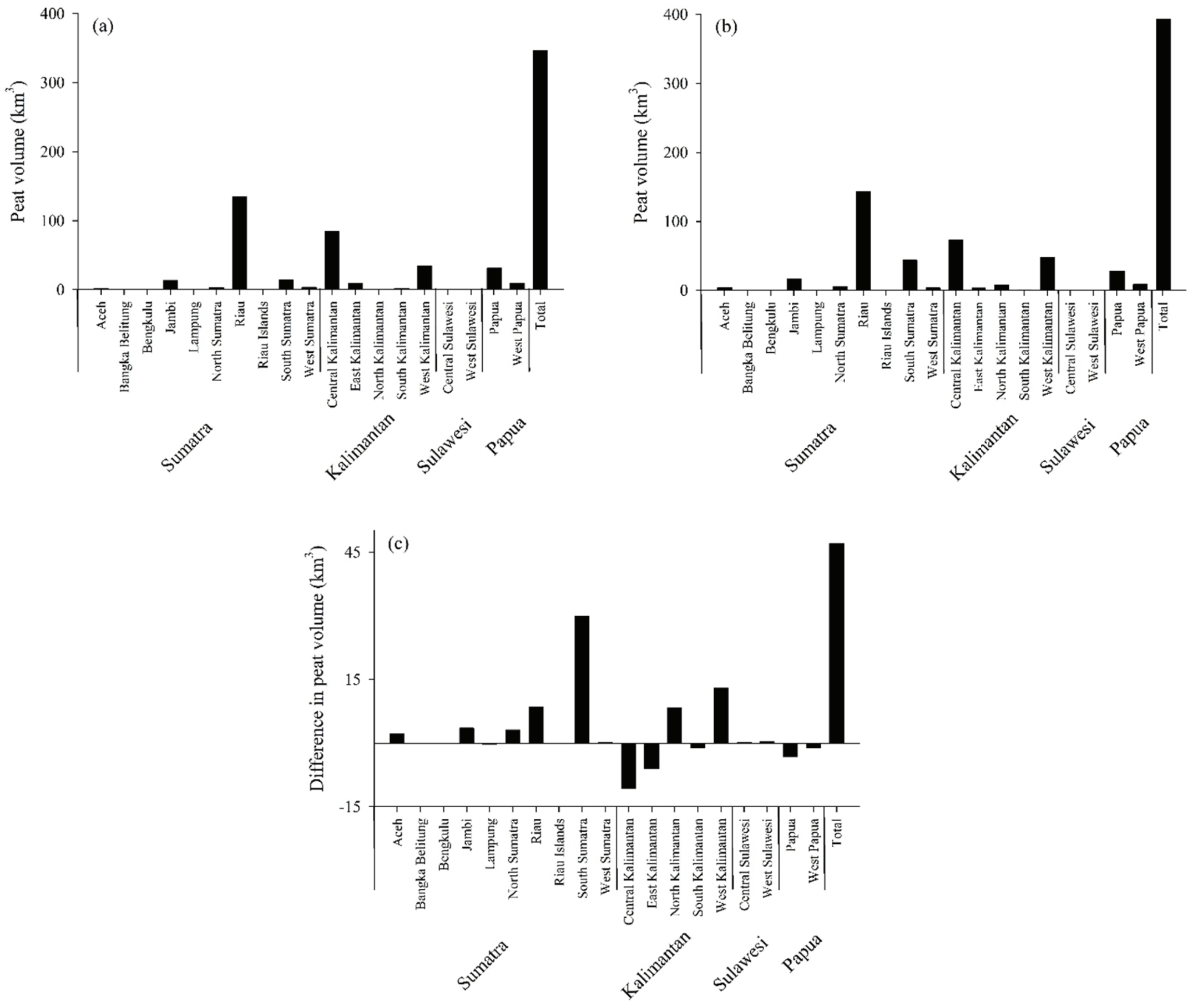

Figure 4 Peat volume by province in (a) 2011 and (b) 2019 published by the Indonesian Ministry of Agriculture and (c) the difference peatland volume between 2011 and 2019

lack of classification systems that consider specific hydrological conditions and respective plant communities (Junk et al. 2011, 2014). As evidence, Indonesia was cited as having the largest tropical peatland area in the world (Page et al. 2011, Joosten et al. 2016). However, in other studies, Brazil was listed as having the largest tropical peatlands in the world, followed by Indonesia (Gumbricht et al. 2017, Ribeiro et al. 2021). The aim of this study was not to criticise these discrepancies but to highlight the range of values used to define peatlands; therefore, future research on carbon cycle and landuse management on this ecosystem should consider this issue.

In the process of compilation of the MoA-2019 dataset, previously published government and organisation's data were included as reference for ground truthing and verification (Anda et al. 2021). The process of data compilation and ground truthing follow the official Indonesian guidelines published by the National Standardization Agency (2013, 2019), which potentially cause changes in peatland area across Indonesia. In this study, we found decreases in the peatland areas in Sumatra (586,276 ha), Kalimantan (234,639 ha) and Papua (629,008 ha). On the other hand, Sulawesi experienced an increase of 25,052 ha, even though it was not accounted for in MoA-2011 inventories. According to Anda et al. (2021) the MoA-2019 data on peatlands are more accurate because mineral soil has been subtracted from the values but was previously included in the inventory of 2011. The improvement in accuracy in inventory methods also affected the

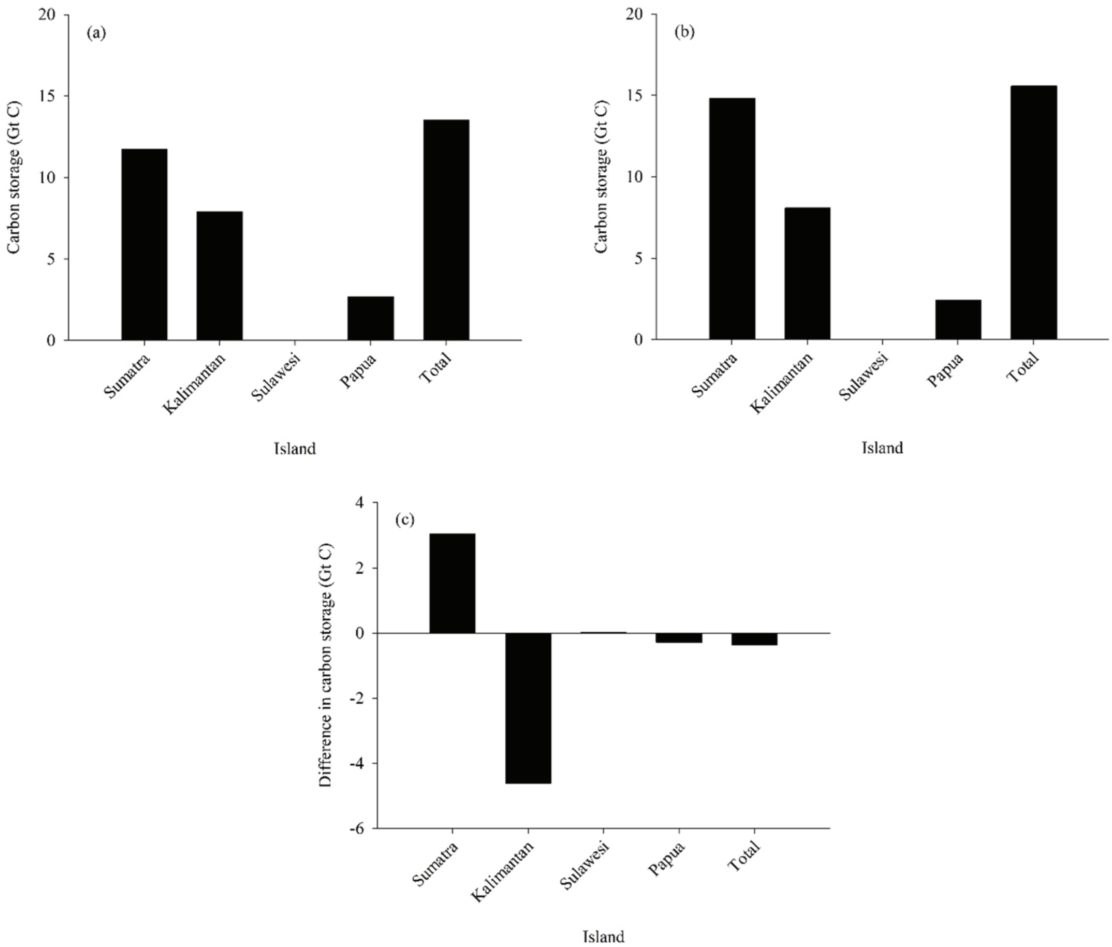

Figure 5 Peatland carbon estimate by island in (a) 2011 and (b) 2019 published by the Indonesian Ministry of Agriculture and (c) the difference in peatland carbon storage between 2011 and 2019

determination of peat thickness in MoA-2019.

The peat volume estimate of this study is lower compared with estimations by Warren et al. (2017) (391.03 km^3) and Page et al. (2011) (1138.23 km^3). Subsequently, the values of peat volume were used to calculate the amount of carbon stored in peatlands, multiplied by the appropriate carbon density. Due to limited data, selected published papers were used to obtain the value of peat density for each province. Nevertheless, the most reliable data are derived from the field, but require more time to obtain (Page et al. 2007). By estimating the peat carbon storage using peatland area and thickness from the MoA-2011 data (Ritung et al. 2011), this study revealed that the peat carbon storage ranged from 13.55 to 25.35 Gt C, with the best estimate of 22.9 Gt C. The estimation of this study is relatively lower than the peat carbon estimated by Warren et al. (2017) (25.33 Gt C) in the MoA-2011 map. Furthermore, compared with the earlier estimation of Indonesia's peat carbon storage, which varied from 53.367 Gt C (Page et al. 2011) to 30 Gt C (Rudiyanto et al. 2015) and 23.2 Gt C (Dommain et al. 2014), our recent estimates are considerably low. The variation in the values of estimated peatland carbon stock occurred as a result of different methodological approaches used for estimating peatland areas as well as the variety source of data as reference (Gumbricht et al. 2017, Anda et al. 2021). The wide range of peat carbon estimates are mainly caused by differences in estimations of peat area, thickness and volume among studies (Warren et al. 2017).

Although the MoA-2019 dataset has undergone significant improvements, this dataset is still lacking in comprehensive coverage of landuse in peatlands across Indonesia. Thus, additional field data particularly for provinces

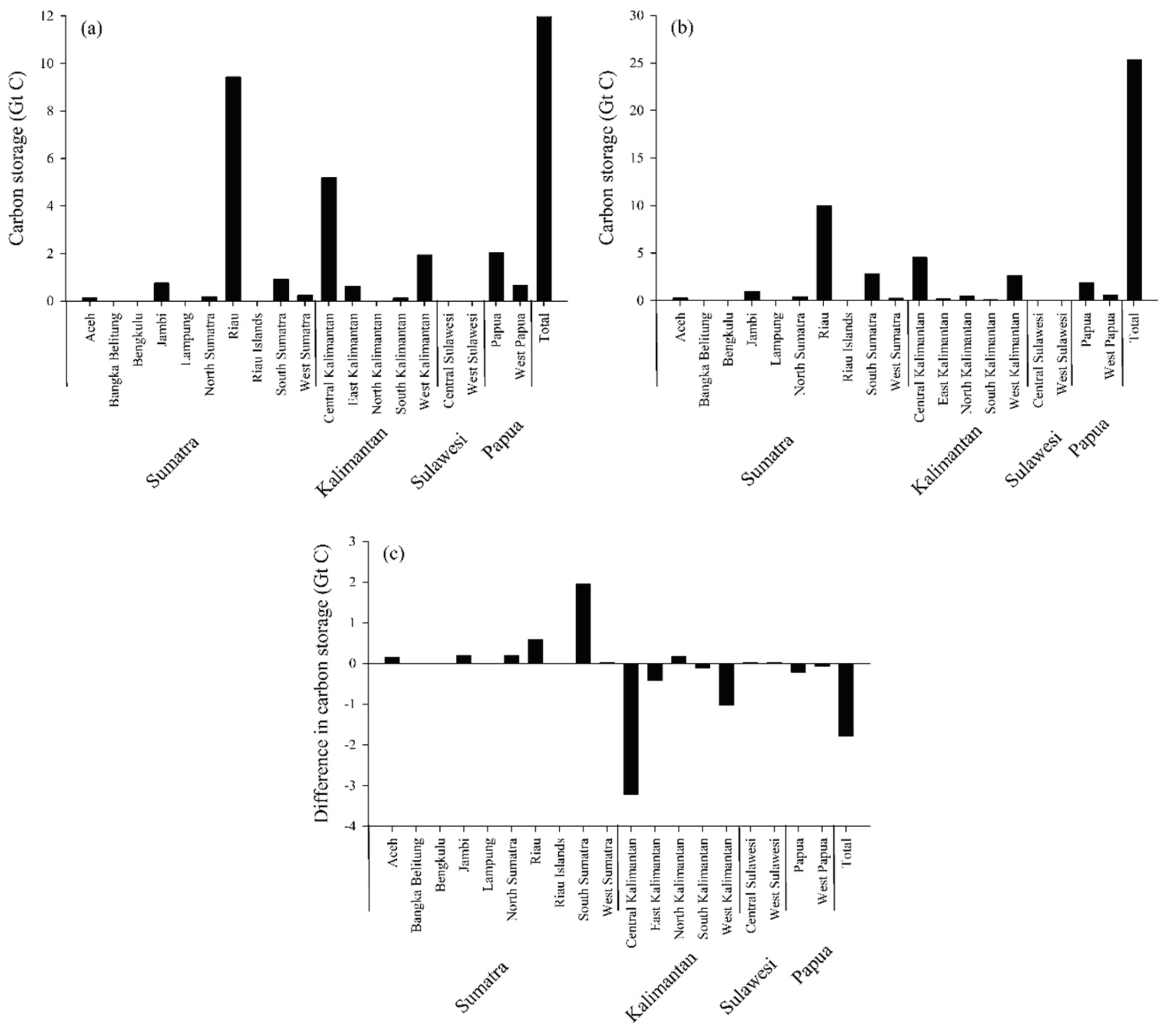

Figure 6 Peatland carbon estimate by province in (a) 2011 and (b) 2019 published by the Indonesian Ministry of Agriculture and (c) the difference in peatland storage between 2011 and 2019

in Papua is needed to better constrain the estimate of Indonesia's total peat carbon store (Warren et al. 2017). Acquiring information on landuse of peatlands is crucial for accurately estimating potential emissions from peatlands and is considered a prerequisite for effective peatlands restoration and management (Osaki et al. 2016).

Major emissions of Indonesia's peatlands from fires mainly occurred in 1997, 2015, and 2019, which burnt large areas of Indonesia's peatlands (Field et al. 2016, Cole et al. 2022). As a result, between 2000 and 2020, peat fires have emerged as the second largest contributor to GHG emissions in the country, ranking right after energy sector, and followed by forestry and other landuses (Figure 7). Indonesia is the largest contributor of emissions generated from degraded peatlands globally (Joosten 2009). In addition, Indonesia alone contributed the most GHG from degraded peatlands, excluding peat fires, which accounted for 666.7 mil t CO_2e year^{-1} followed by the Russian Federation, China, Malaysia, and Mongolia (Figure 8).

According to this study, MoA-2019 reported that approximately 70% of the peatland areas in Indonesia have less than 300 cm depth, which potentially led to their legal conversion of landuse (Warren et al. 2017). According to the Presidential Decree number 39 of 1990 and Government Regulation number 26 of 2008, conversion of landuse is allowable on

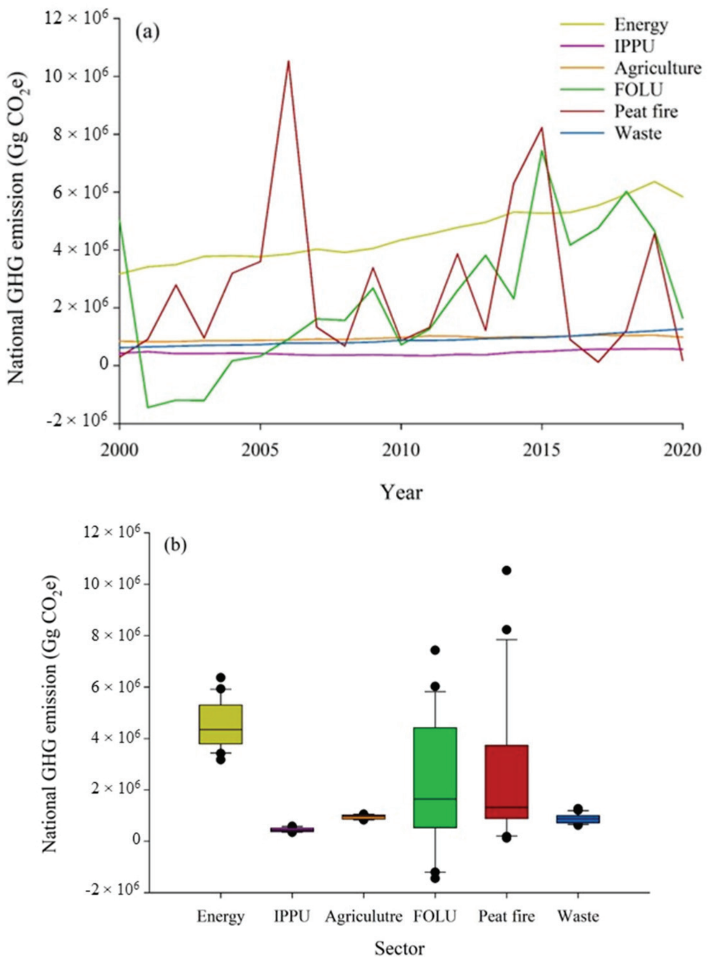

Figure 7 Indonesia's national greenhouse gas (GHG) emissions from major sectors for the period 2000–2021: (a) annual trends and (b) mean annual emissions of six sectors; IPPU = industrial processes and product use, FOLU = forest and other landuse

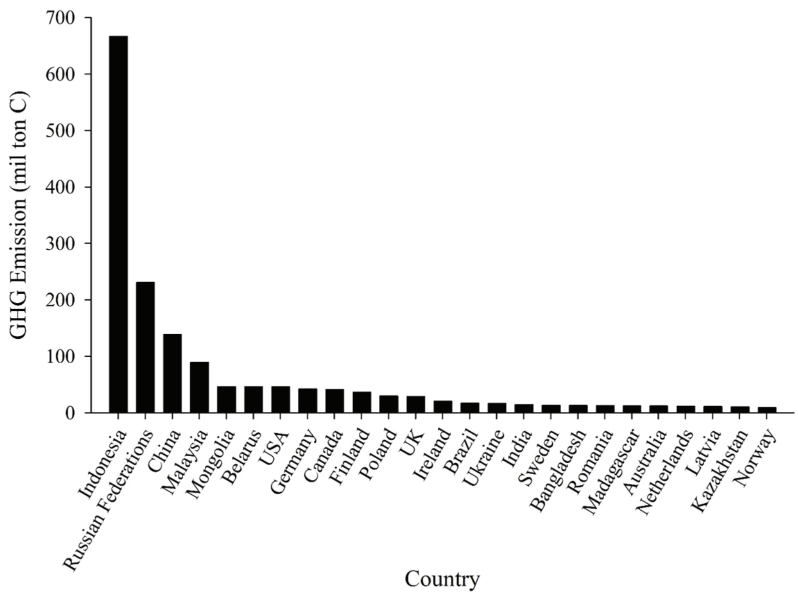

Figure 8 Estimations of greenhouse gas emissions (GHG) from the 25 largest peat-emitting countries in the world; data was taken from UNEP (2022)

peatlands up to 300 cm deep. Implementing stringent control measures such as supportive policy and regulation will effectively safeguard an area encompassing approximately 9.2 ha of peatlands from land conversion, thereby mitigating the potential exacerbation of national GHG emissions.

CONCLUSION

The estimation of Indonesia's tropical peatland area and depth has varied widely between studies, leading to uncertainties when determining peat volume and carbon storage. The result of this study highlighted the range of values for the estimated peatland carbon storage. Based on our study, the medium estimate of carbon storage in the peatlands of Indonesia is 22.39 Gt C. The latest survey of Indonesia's peatland area has significantly improved accuracy by subtracting mineral soil from the peatland survey, although some uncertainties remain. Conducting a systematic and comprehensive inventory could improve the data on national peatland distribution, thickness and carbon storage estimates. The uncertainties of peatland inventory and mapping could be addressed by using advanced earth observation technologies and comprehensive ground truthing. There is an urgent need to develop a comprehensive national peatland map that includes information on the degradation status of peatlands and artificial canal networks of each landscape, so that it can be a reliable and accurate data that can be used for national and international reference.

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REFERENCES

Agus F, Hairiah K & Mulyani A. 2011. *Measuring Carbon Stock in Peat Soils: Practical Guidelines*. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program and Indonesian Centre for Agricultural Land Resources Research and Development, Bogor.

Anda M, Ritung S, Suryani E et al. 2021. Revisiting tropical peatlands in Indonesia: semi-detailed mapping, extent and depth distribution assessment. *Geoderma* 402: 115235. https://doi.org/10.1016/j.geoderma.2021.115235

Astiani D, Curran LM, Burhanuddin et al. 2018. Fire-driven biomass and peat carbon losses and post-fire soil CO_2 emission in a West Kalimantan peatland forest. *Journal of Tropical Forest Science* 30: 570–575. https://doi.org/10.26525/jtfs2018.30.4.570575

Brady MA. 1997. Organic matter dynamics of coastal peat deposits in Sumatra, Indonesia. Doctoral dissertation, University of British Columbia, Vancouver.

Cole LES, Åkesson CM, Hapsari KA et al. 2022. Tropical peatlands in the anthropocene: lessons from the past. *Anthropocene* 37: 100324. https://doi.org/10.1016/j.ancene.2022.100324

Dommain R, Couwenberg J, Glaser PH, Joosten H & Suryadiputra INN. 2014. Carbon storage and release in Indonesian peatlands since the last deglaciation. *Quaternary Science Reviews* 97: 1–32. https://doi.org/10.1016/j.quascirev.2014.05.002

FAO. 2022. *Peatlands and Climate Planning—Part 1: Peatlands and Climate Commitments*. FAO, Rome. https://doi.org/10.4060/cc2895en

Field RD, Van Der Werf GR, Fanin T et al. 2016. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. *Proceedings of the National Academy of Sciences of the United States of America* 113: 9204–9209. https://doi.org/10.1073/pnas.1524888113

Finlayson CM & Milton GR. 2016. Peatlands. Pp 1–18 in Finlayson C et al. (eds) *The Wetland Book*. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6173-5_202-1

Glauber AJM, Moyer S, Adriani M & Gunawan I. 2016. *The Cost of Fire: An Economic Analysis of Indonesia's 2015 Fire Crisis*. World Bank, Jakarta.

Gumbricht T, Roman-Cuesta RM, Verchot L et al. 2017. An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. *Global Change Biology* 23: 3581–3599. https://doi.org/10.1111/gcb.13689

Joosten H. 2009. *The Global Peatland CO_2 Picture: Peatland Status and Drainage Related Emissions in All Countries of the World*. Wetlands International, Ede.

Joosten H, Sirin A, Couwenberg J, Laine J & Smith P. 2016. The role of peatlands in climate regulation. Pp 63–67 in Bonn A et al. (eds) *Peatland Restoration and Ecosystem Services*. Cambridge University Press, Cambridge. https://doi.org/10.1017/cbo9781139177788.005

Junk WJ, Piedade MTF, Lourival R et al. 2014. Brazilian wetlands: their definition, delineation, and classification for research, sustainable management, and protection. *Aquatic Conservation:*

Marine and Freshwater Ecosystem 24: 5–22. https://doi.org/10.1002/aqc.2386

Junk WJ, Piedade MTF, Schöngart J, Cohn-Haft M, Adeney Jm & Wittmann F. 2011. A classification of major naturally-occurring Amazonian lowland wetlands. *Wetlands* 31: 623–640. https://doi.org/10.1007/s13157-011-0190-7

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

MoEF (Ministry of Environment and Forestry). 2017. *Decree of the Minister of Environment and Forestry Number SK.129/MENLHK/SETJEN/PKL.0/2/2017 on Determination of Peat Hydrological Unit.* Indonesian Ministry of Environment and Forestry, Jakarta. (In Indonesian)

National Standardization Agency. 2013. *Peatlands Mapping at the Scale of 1:50,000 based on Remote Sensing Imagery.* National Standardization Agency of Indonesia, Jakarta. (In Indonesian)

National Standardization Agency. 2019. *Peatlands Mapping at the Scale of 1:50,000.* National Standardization Agency of Indonesia, Jakarta. (In Indonesian)

Neuzil SG. 1997. Onset and rate of peat and carbon accumulation in four domed ombrogenous peat deposits, Indonesia. Pp 55–72 in Rieley JO & Page SE (eds) *Proceedings of the International Symposium on Biodiversity, Environmental Importance, and Sustainability of Tropical Peat and Peatlands.* 4–8 September 1995, Palangka Raya.

Osaki M, Hirose K, Segah H & Helmy F. 2016. Tropical peat and peatland definition in Indonesia. Pp 137–147 in Osaki M & Tsuji N (eds) *Tropical Peatland Ecosystems.* Springer, Tokyo. https://doi.org/10.1007/978-4-431-55681-7_9

Page SE, Banks CJ & Rieley JO. 2007. Tropical peatlands: distribution, extent and carbon storage: uncertainties and knowledge gaps. In Rieley JO et al. (eds) *Carbon-Climate-Human Interaction on Tropical Peatland. Proceedings of the International Symposium and Workshop on Tropical Peatland.* 27–29 August 2007, Yogyakarta.

Page SE, Rieley JO & Banks CJ. 2011. Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* 17: 798–818. https://doi.org/10.1111/j.1365-2486.2010.02279.x

Page SE, Wust RAJ, Weiss D, Rieley JO, Shotyk W & Limin SH. 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: 625–635. https://doi.org/10.1002/jqs.884

Radjagukguk B. 1997. Peat soil of Indonesia: location, classification and problems for sustainability. Pp 45–53 in Rieley JO & Page SE (eds) *Biodiversity and Sustainability of Tropical Peatlands. Proceedings of the International Symposium on Biodiversity, Environmental Importance, and Sustainability of Tropical Peat and Peatlands.* 4–8 September 1995, Palangka Raya.

Ribeiro K, Pacheco FS, Ferreira JW et al. 2021. Tropical peatlands and their contribution to the global carbon cycle and climate change. *Global Change Biology* 27: 489–505. https://doi.org/10.1111/gcb.15408

Ritung S, Suryani E, Yatno et al. 2019. *Map of the Indonesian Peatlands at the Scale of 1:50,000.* Indonesian Center for Agricultural Land Resources Research and Development, Bogor.

Ritung S, Wahyunto, Nugroho K, Sukarman, Hikmatullah, Suparto CT. 2011. *Map of the Indonesian Peatlands at the Scale of 1:250,000.* Indonesian Center for Agricultural Land Resources Research and Development, Bogor.

Rudiyanto, Setiawan BI, Arief C et al. 2015. Estimating distribution of carbon stock in tropical peatland using a combination of an empirical peat depth model and GIS. *Procedia Environmental Science* 24: 152–157. https://doi.org/10.1016/j.proenv.2015.03.020

Smith TEL, Evers S, Yule CM & Gan JY. 2017. *In situ* tropical peatland fire emission factors and their variability, as determined by field measurements in peninsula Malaysia. *Global Biochemical Cycles* 32: 18–31. https://doi.org/10.1002/2017GB005709

Tanneberger F, Schröder C, Hohlbein M et al. 2020. Climate change mitigation through land use on rewetted peatlands—cross-sectoral spatial planning for paludiculture in northeast Germany. *Wetlands* 40: 2309–2320. https://doi.org/10.1007/s13157-020-01310-8

UNEP. 2022. *Global Peatlands Assessment: The State of the World's Peatlands–Evidence for Action Toward the Conservation, Restoration, and Sustainable Management of Peatlands.* United Nations Environment Programme, Nairobi.

Wahyunto, Bambang H, Hasyim B & Fitri W. 2006. *Maps of Peatland Distribution, Area and Carbon Content in Papua 2000–2001.* Wetlands International—Indonesia Programme & Wildlife Habitat Canada, Bogor.

Wahyunto, Ritung S & Subagjo H. 2003. *Maps of Peatland Distribution, Area and Carbon Content in Sumatera 1990–2002.* Wetlands International—Indonesia Programme & Wildlife Habitat Canada, Bogor.

Wahyunto, Ritung S & Subagjo H. 2004. *Maps of Peatland Distribution, Area and Carbon Content in Kalimantan 2000–2002.* Wetlands International—Indonesia Programme & Wildlife Habitat Canada, Bogor.

Warren MW, Hergoualc'h K, Kauffman JB, 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 Management* 12: 12. https://doi.org/10.1186/s13021-017-0080-2

Xu J, Morris PJ, 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