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Mapping and quantifying peatlands to achieve climate change and biodiversity goals in Indonesia and Malaysia

Abstract
Tropical peatlands in Indonesia and Malaysia are globally critical ecosystems, storing substantial carbon stocks, sustaining unique biodiversity, and providing essential ecosystem services such as water regulation and support for livelihoods. Yet, these landscapes are also major sources of "haze" air pollution and greenhouse gas emissions, driven by drainage, deforestation, fire, and conversion to agriculture. Both countries rank among the world's largest emitters from peatlands, placing them at the heart of international climate and biodiversity agendas. Effective management, however, is undermined by persistent data challenges, including mapping and quantifying peatland extent, condition, impacts, and emissions. Estimates of total area vary widely between global and national datasets, while discrepancies in spatial information complicate assessments of forest loss, land use, emissions and biodiversity. These uncertainties cascade through management and governance approaches, including greenhouse gas inventories, carbon projects and markets, and conservation planning, with important implications for policy credibility and intervention effectiveness. Drawing on existing literature, plus insights obtained through a hybrid expert workshop and spatial analyses of open-access geospatial datasets, this review assesses and synthesises current knowledge, identifies seven key challenges for peatland data, and explores their policy relevance. We highlight three cross-cutting themes that emerge from the identified data challenges: (1) enhancing data practices across scales and borders, (2) constructively engaging with data uncertainty and carbon credit integrity, and (3) valuing broader sustainability benefits.

1. Introduction

Tropical peatlands are among the world's most carbon-rich and ecologically significant ecosystems (UNEP, 2022). In Southeast Asia, peatlands in Indonesia and Malaysia, account for over half of the world's tropical peatland area, notable for vast carbon stocks, high endemism, and ecosystem services such as water filtration, flood mitigation, and timber and non-timber forest products (Varkkey et al., 2024). These nations, however, have been ranked first and fourth globally in peatland-related greenhouse gas (GHG) emissions (UNEP, 2022) due to drainage, deforestation, and fire linked to oil palm, pulp, and food production. Other impacts include region-wide haze, biodiversity loss, and land subsidence that threaten livelihoods and community health. Although policy focus has shifted toward integrating peatlands into national climate and biodiversity strategies and targets within global governance frameworks (e.g. the Paris Agreement, the Global Biodiversity Framework), challenges persist in quantifying peatland extent, condition, and GHG emissions due to inconsistent definitions and methodological uncertainties, limited field validation, uneven availability of data and metadata, and divergent datasets from remote sensing and ground surveys. These challenges can hinder alignment among policymakers, scientists, land managers, and local communities.

This paper aims to review the importance of peatlands in Indonesia and Malaysia for climate mitigation and biodiversity conservation, assess the challenges of mapping and quantifying peatland extent, dynamics, impacts, and emissions, and explore the implications of data uncertainty for effective, evidence-based policy and management. The review was conducted by peatland experts representing NGOs, academia, and governmental bodies in Indonesia, Malaysia, and Singapore based on a hybrid workshop format (details in Supplementary Materials), followed by subsequent written reflections and spatial analyses. Workshop discussions were structured around four pre-determined themes: (1) Peatland Data needs, (2) Mapping peatland and its condition, (3) Calculating GHG emissions from peatlands and (4) Cross cutting challenges and opportunities for enhancing peatland data to support sustainability interventions (Table 1).

Table 1: *Themes and questions used in the workshop.*

Theme	Questions
Peatland Data needs	Q1 What are the key policy areas which need robust data? And why? Q2 What kinds of data are needed to manage peatlands? And why?
Mapping peatland and its condition	Q1 How good are peatland datasets and which are missing or restricted or low quality? (e.g. Peatland extent and physical state, Biodiversity, Haze)? Q2 What are the main sources of uncertainty? Q3 How do the above issues impact policy decisions?
Calculating GHG emissions from peatlands	Q1 What methodologies are used for calculating peatland GHG emissions? Q2 How good are the carbon stock and GHG emission datasets, and which are missing or restricted or low quality? Q3 What are the main sources of uncertainty? Q4 How do the above issues impact policy decisions?
Cross cutting challenges and opportunities for enhancing peatland data to support sustainability intervention efforts	Q1 How important is data transparency to support sustainability intervention efforts? Q2 What is the role of stakeholders, particularly communities, in enhancing peatland data to support sustainability intervention efforts? Q3 What are the scale and jurisdictional issues in enhancing peatland data to support sustainability intervention efforts? Q4 What are the opportunities for harnessing the connections between datasets on GHG emissions and other sustainability dimensions (e.g biodiversity conservation, haze reduction) to support sustainable peatland interventions?

The findings of this review are presented as follows. We begin by outlining key characteristics of peatlands in both countries, including current estimates of their extent, major impacts such as forest loss and drainage, and their role in GHG emissions. We then examine examples of uncertainty in spatial datasets used to quantify peatlands and their impacts, highlighting how these discrepancies influence estimates of GHG emissions. Finally, we discuss seven critical peatland challenges, their associated data needs, uncertainties, and policy implications, and offer recommendations for strengthening peatland data and governance for sustainability. These issues are framed within three cross-cutting themes: enhancing data practices across scales and borders, constructively engaging with data uncertainty and carbon credit integrity, and valuing broader sustainability benefits.

To complement expert perspectives obtained through the workshop we carried out a series of bespoke assessments and GIS analyses to illustrate the challenges identified. These included visualising spatial datasets across Indonesia and Malaysia, examining their distribution and potential sources of uncertainty, overlay analyses comparing peatland extent maps, and assessing error propagation from combining multiple oil palm and peatland datasets. Together, these spatial methods not only visualise discrepancies between datasets but also quantify their magnitude, showing how uncertainties may propagate into downstream assessments of emissions and biodiversity. Full details of the analysis, including GIS methods and data sources, are provided in the supplementary material.

2. The importance of peatland characteristics in Indonesia and Malaysia

As part of our workshop, we asked experts (see Table 1) to reflect on fundamental areas in which data is required for effective management of, and policymaking for, peatlands in Indonesia and Malaysia. We integrated the expert inputs with literature information to create Figure 1, which outlines key characteristics of the peatland socio-economic system, including biophysical function, anthropogenic impacts and management approaches, alongside the range of governance factors relevant to peatland management and interventions. Through further questions in our workshop we obtained views on important areas of key challenges, especially regarding peatland data characterisation, which are also listed in Figure 1, and which we explore further through the rest of this paper. In particular, in the following sections we present illustrative discussions and analyses regarding both importance and uncertainty, for key challenges 1 (extent), 4 (GHG emissions) and 5 (land use - especially oil palm). These illustrations help to support our broader discussion in the concluding section in which we return again to the full list of challenges, and offer recommendations strengthening peatland data and sustainability governance.

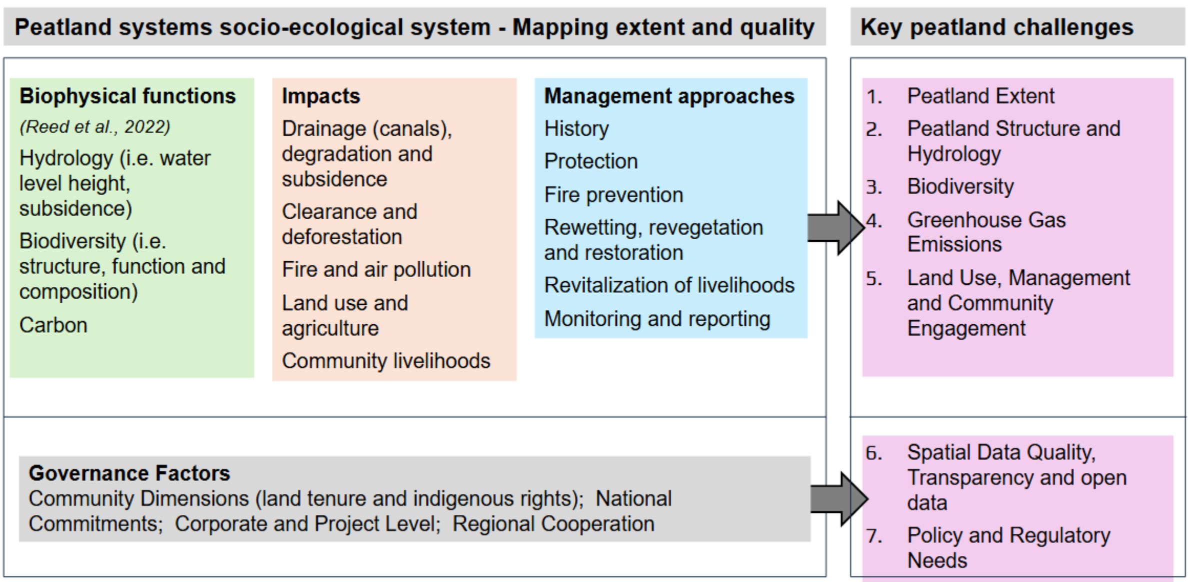

Figure 1: *Key components of peatland systems in Indonesia and Malaysia, highlighting biophysical functions, major environmental impacts, and management strategies essential for sustainable governance. The diagram also identifies priority topics requiring focused research and policy*

attention, including critical data needs for monitoring, modelling, and decision-making. These topics were derived from expert workshop inputs.

2.1 Peatland extent

Understanding the extent and location of peatlands is fundamentally important in considering their management and sustainability, and underpins further assessment of impacts, including in terms of biodiversity and GHG emission outcomes. Estimates of the total area of peatland in Indonesia and Malaysia range from 13.4–22.5 Mha and 2.2–2.9 Mha, respectively (Table 2). These estimates are derived from both global (Xu et al., 2018; Gumbricht et al., 2017; UNEP, 2022) and national or regional (Wahyunto et al., 2003; 2004; 2006; Melling, 2016; Page et al., 2011; Anda et al., 2021) assessments, which deploy varying methods and assumptions (e.g. in peat definition). Table 2 lists several spatially explicit peatland area datasets, with varying spatial resolution and definitions. The extent of peatlands is significant; to put these areas in context, UNEP (2022) estimates that the two countries combined contribute 5% of the global peatland extent. Additionally, in both countries, peatlands make up a similar and substantial fraction of the total national area, with estimates for Indonesia ranging between 7-12% of the national area (of 190.5 Mha), and for Malaysia this is 7-9% (of 33.1 Mha).

Table 2: *Comparisons of peatland area estimates for Indonesia and Malaysia.*

Source	Peatland Area (Mha)		Peat definition	Spatial Data	Extent/ Resolution	Availability
	Malaysia	Indonesia				
Page et al (2011)	2.59	20.69	Soil layer with organic content of at least 65% in minimum thickness of 30 cm.	No	Global	Tabular in source
Gumbricht et al (2017)	2.96	22.54	Soil at least 30 cm deep with at least 50% of organic content.	Yes	Global/ 232 meter	Publicly available to download
Xu et al (2018)	2.23	14.9	The definition is based on the source of data used (can vary by country).	Yes	Global/ 1:50.000 (MY) 1:250.000 (ID)	Publicly available to download
UNEP (2022)	2.56	20.9	Ecosystems with a peat soil of any thickness and peat threshold used a 30-40 cm.	Yes	Global/ 1 km	Publicly available to download

Melling (2016)	2.6	-	Classification includes "Peaty phase" for soil with a depth of less than 50 cm, and it must contain 65% organic matter.	No	National (Malaysia)	Tabular in source
Wahyunto et al., (2002 - 2006)	-	20.8	Minimum thickness of 30 cm to delineate peatland	Yes	National (Indonesia)/ 1:250.000	Upon request in PSD format
Anda et al (2021)	-	13.4	Histosol layer with minimum thickness of 50cm.	Yes	National (Indonesia)/ 1:50.000	Available for purchase or upon request, can be viewed online

In Indonesia, the Peatland map of Anda et al. (2021) is recognised as the official peatland map. The reported area of 13.4 Mha is derived from a combination of satellite images and ground-truth verification. The map is not publicly available to download as a spatial data file but can be viewed at: https://en.prims.brgm.go.id/. Notably, this dataset contains the lowest estimate of Indonesia's peatland area. Xu et al. (2018) provides a fairly similar estimate of 14.9 Mha. However, other studies (Wahyunto et al., 2003; 2004; 2006) estimate a significantly larger area of around 20.8 Mha. This larger estimate aligns more closely with some global estimates, such as the Global Peatland Map (GPM) 2.0 of UNEP (2022) at 20.9 Mha, Page et al (2011) at 20.7 Mha, and the estimate by Gumbricht et al (2017) at 22.5 Mha.

For Malaysia, Melling (2016) reported a national peatland extent of 2.6 Mha, based on mapping by the Department of Agriculture, Malaysia (2002), Mutalib et al., (1991) and Department of Irrigation and Drainage, Sarawak (2014). Other estimates of Malaysia's peatland extent are more consistent among global and regional assessments than for Indonesia. For example, UNEP (2022) reports 2.56 Mha, Xu et al. (2018) reports 2.23 Mha, Gumbricht et al. (2017) estimates 2.96 Mha, and Page et al. (2011) estimates 2.59 Mha.

Given the substantial differences in total area estimates, it is important to examine how discrepancies vary spatially and agreement in specific locations. Therefore we conducted analyses to compare the spatially explicit, publicly available and commonly used peatland datasets of Gumbricht et al (2017) and Xu et al. (2018). While these are both global datasets, we focus analysis on Indonesia and Malaysia. As an initial illustrative comparison, Table S1 reports the split of peatland areas among key regions of both countries, in both the spatial datasets. Fundamental differences are revealed, such as Sumatra making the largest contribution to Indonesia's peatland area in the Xu et al. (2018) dataset, and Papua making the largest contribution in the Gumbricht et al (2017) dataset.

We also calculated the intersection between the spatial datasets (i.e. is there peatland at exactly the same location in both datasets?). Overall agreement percentages (Table S1) are low: in Indonesia, the area in which the two datasets agree peatland is located is just 6.8 Mha. In Malaysia this area of agreement is 0.83 Mha. To facilitate the spatial analyses of impacts on peatlands presented in Section 2.2, we created a combined peatland layer by merging the two datasets. Based on this, the combined peatland extent in this layer is 29.48 Mha in Indonesia, and 4.34 Mha in Malaysia (Table S1). While we recognise this combined layer is likely to significantly overestimate actual peatland area, using these values means the area of agreement between the datasets in Indonesia, the 6.8 Mha reported above, represents just 23% of the combined peatland extent. The equivalent agreement in Malaysia is 19%. Among sub-national regions, the largest agreement in Indonesia is Sumatra (26%) and in Malaysia is in East Malaysia (20%) (Table S1).

Beyond understanding total national areas, spatially explicit information regarding peatland location is also centrally important in assessing impacts and considering which areas to preserve, restore or in which to implement other peatlands management approaches (Terzano 2023; Tanneberger 2017). The causes and implications of these substantial uncertainties in peatland location are discussed further in Section 3.1.

2.2 Mapping Peatland impacts

Beyond quantifying and mapping the extent and location of peatlands, understanding anthropogenic impacts is crucial for assessing the status of peatland biophysical function and for considering potential management approaches and interventions (Figure 1). As illustrations of the range of impacts, and to support later discussion on data uncertainties, we have conducted several spatial analyses in which we overlay key “impact” datasets on the combined peatland extent layer introduced in Section 2.1. This extent layer is shown in Figure 2A, which separately indicates the peatland areas identified in only one of the Gumbricht et al. (2017) and Xu et al. (2018) datasets (labelled B and C, respectively), as well as the areas in which both datasets agree peatland is located (labelled A). In the subsequent analyses we consider the overall peatland extent (i.e. A + B + C).

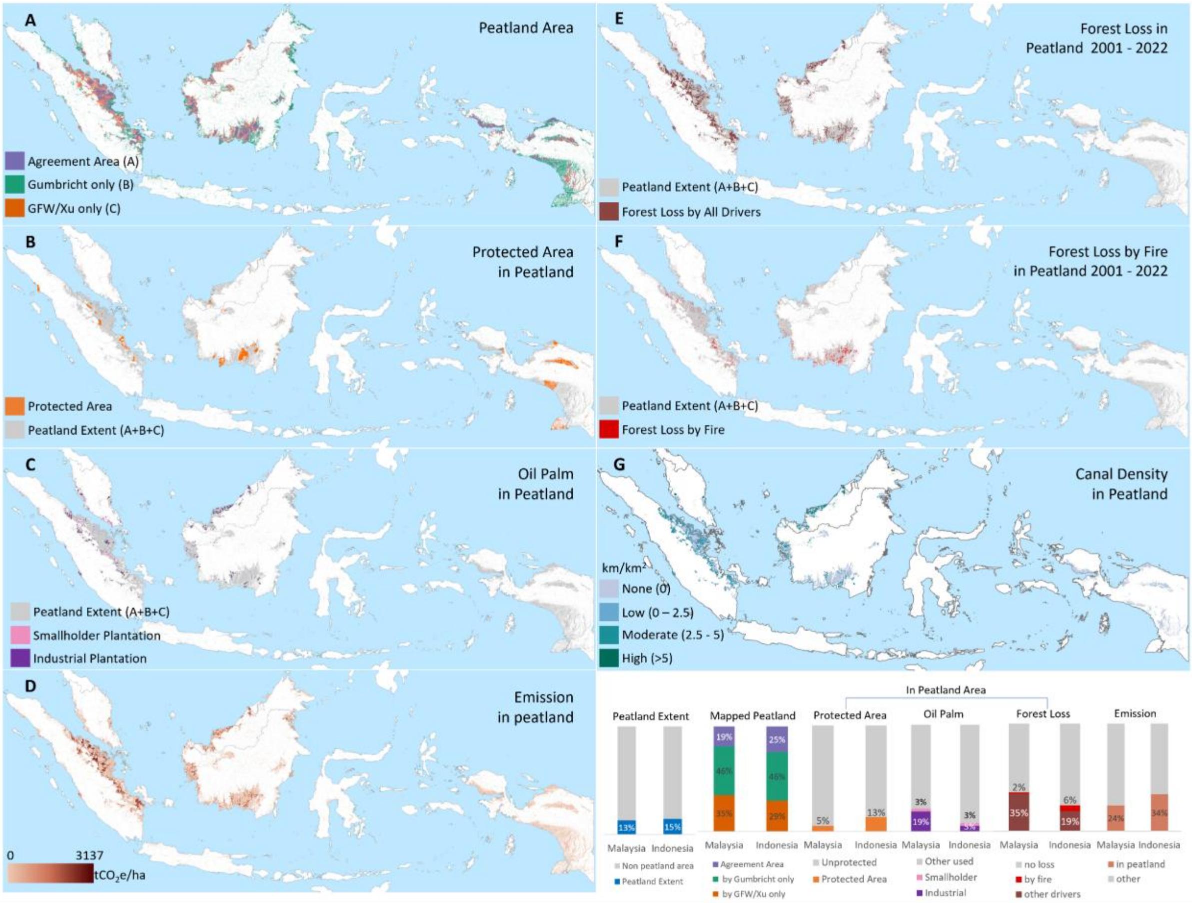

Figure 2: *Mapping of peatlands in Indonesia and Malaysia (panel A), and then within a combined peatland extent layer, mapping of protected areas (B), oil palm (C), GHG emissions (D), forest loss (E), forest loss by fire (F), and canal density (G). The bar charts in the lower right of the Figure provide comparisons between Indonesia and Malaysia of the mapped layers. Data sources are cited in the main text. The Figure is updated from Varkkey et al. (2024).*

It is well known that significant areas of native peat swamp forest in Indonesia and Malaysia have been lost (Miettinen et al. 2016; Varkkey et al., 2024). To illustrate this loss, Figure 2E shows the distribution of forest loss within our peatland extent layer, based on the dataset of Hansen et al (2013). This dataset is regularly updated, with the data we present available for 2022 (2011-2022 data was produced using an updated methodology). In this dataset loss indicates the removal or mortality of forest cover due to factors including mechanical harvesting, fire, disease, or storm damage. Forest cover is defined as vegetation greater than 5 meters in height. The forest loss within the peatland extent layer in Indonesia and Malaysia from 2001 to 2022 reached 6.9 Mha and 1.5 Mha, respectively (Table S1). This represents forest loss in this period occurring in 24% and 37% of the peatland layer. The regions in Indonesia and Malaysia with the largest fractional forest losses are, respectively, Sumatra (43%) and East Malaysia (39%) (Table S1).

In association with forest loss, Figure 2G indicates the presence of canals in peatlands, based on the dataset of Dadap et al. (2021) which is informed by satellite images from 2017. These canals have been introduced to drain peat soils and to enable use of the land for agriculture and logging. The impacts on peatland biophysical function are profound, lowering water tables, and leading to subsidence and carbon emissions (Hoyt et al., 2020). Visually comparing Figure 2E and 2G there is a close correspondence between forest loss and the presence of canals.

Figure 2F focusses on forest loss due to fire. For peatlands, fire is also closely associated with regional scale “haze” air pollution (Varkkey et al., 2024). This analysis relies on the dataset of Tyukavina et al (2022) which was mapped within the extent of Hansen et al. (2013), is updated through to 2022, and includes fire-related forest losses due to both natural causes and human activity. In Figure 2F, and the values in Table S1, we used only forest loss by fire with higher certainty (labelled “code 4” in this dataset). This analysis indicates a substantial 1.4 Mha (i.e. 23%) of peatland forest loss in Indonesia was due to fires, whereas in Malaysia fire-related losses were just 0.07 Mha (4%). Regionally, the largest fraction of fire-related loss was found in Kalimantan (31%). These calculations are consistent with past literature emphasising the association of forest loss and peatland fires in Indonesia (e.g. Adrianto et al., 2019), and indicate factors besides fire are thus the primary drivers of peatland forest loss in Malaysia.

One common land use following forest loss and drainage in peatlands is plantation agriculture, particularly oil palm (Miettinen et al., 2016). Figure 2C presents oil palm plantations within our peatland layer, using the dataset of Descals et al. (2021) which includes both smallholder and industrial plantation categories, with up-to-date data provided for 2019. This analysis suggests oil palm on peatland covers 2.2 Mha in Indonesia (9% of the peatland layer), of which 1.5 Mha is industrial plantation (Table S1). Sumatra, with a total of 1.6 Mha, is comfortably the largest contributing region, especially for the category of smallholder plantation. In Malaysia, oil palm covers 0.93 Mha (or a larger 22%) of our peatland layer, of which the majority, 0.82 Mha, is industrial plantation. East Malaysia, with a total area of 0.63 Mha, is the major contributing region. For comparison, Miettinen et al. (2016) reported areas of oil palm in peat of 1.3 Mha in Sumatra (0.3 Mha smaller than our estimate) and 0.78 Mha in East Malaysia (0.15 Mha larger). To explore the causes of such uncertainties in areas of a major commodity crop for both countries, in Section 3.2 we present a more detailed analysis.

The loss of forest, drainage and conversion to plantation agriculture in peatlands are strongly associated with disturbance of carbon stores, and thus with GHG emissions. While this topic is discussed in greater detail in the subsequent Section 2.3, we refer here to the spatially explicit forest emissions dataset of Harris et al. (2021), presented only within our peatland layer in Figure 2D. Based on this dataset, and on average between 2001-2022, 322 of a total 961 MtCO2e (i.e. 34%) that was emitted from Indonesia’s forests occurred within our peatland layer. In Malaysia, 57 of a total 234 MtCO2e (i.e. 24%) of emissions occurred within the peatland layer (further details in Table S1). The contribution of peatlands to GHG emissions in both countries is thus apparently substantial, and we discuss this importance later, in Section 2.3. Nevertheless, estimating emissions from land (including peatland) is challenging, and fraught with uncertainty - this issue is developed in Section 3.3, through comparison of the Harris et al. (2021) dataset with others.

As well as affecting biophysical functions of water and carbon, the various impacts on peatlands also threaten their unique biodiversity (Yule, 2010; Azhar et al., 2011; Sasidhran et al., 2016; Shuhada et al., 2017; Grover et al. 2024; Struebig et al., 2025). Peatlands of Indonesia and Malaysia host a range of plants, animals, and microbes and serve as vital sanctuaries for threatened species such as orangutans (Yule, 2010). Protection is one existing strategy to conserve peatland areas, their biodiversity and their wider biophysical function

(Novita et al, 2022). The World Database of Protected Areas (WDPA; IUCN and UNEP-WCMC, 2024) is a widely-used global dataset of protected areas, both marine and terrestrial, and both national and international. Following topology analysis to merge overlapping areas in the WDPA dataset, Figure 2B suggests 3.6 Mha (or 13%) of our peatland layer for Indonesia is protected, whereas only 0.22 Mha (5%) of the peatland layer in Malaysia is protected (Table S1). While just one perspective, the modest fractions of protected peatland in both countries presented in this analysis indicate the great potential to enhance interventions to support peatland sustainability. We return to this topic, and associated considerations related to data and uncertainty in Section 4.

2.3 Peatland Greenhouse Gas emissions

Multiple studies have emphasised the critical importance of peatlands in contributing to GHG emissions in both Indonesia and Malaysia (e.g. Miettinen et al., 2016; UNEP, 2022; Varkkey et al., 2024; Sasmito et al., 2025). As one example, the UNEP Peatland Assessment ranked these two countries as first and fourth largest contributors to estimated global emissions of 2,000 Mt CO2e per year due to peatland decomposition, with estimated annual emissions of 668 Mt CO2e in Indonesia and 90 Mt CO2e in Malaysia.

The importance of peatlands can also be assessed through the key official source of national GHG emissions data, which is the regular reporting by countries to the United Nations Framework Convention on Climate Change (UNFCCC). Provisions under the Paris Agreement now stipulate the submission of biennial transparency reports (BTRs), which follow a common reporting format. Developing countries, including Indonesia and Malaysia, submitted their first BTR at the end of 2024. These BTRs either include, or are accompanied by, a national (GHG emissions) inventory document (NID) and a range of reporting tables, also following standardised formats.

Table 3 helps to quantify the importance of peatlands within reported national emissions in Indonesia and Malaysia. In both countries the Energy and “Land Use, Land Use Change, and Forestry” (LULUCF) categories are the two largest contributors. Considering reported trends in Indonesia, Energy has been the largest emitting category only in recent years - 2018, 2020, 2021 and 2022 - in which reported LULUCF emissions are lower than in most earlier years. Both countries report a substantial net sink (i.e. carbon removals are larger than emissions) in the Forest Land category. Emissions of CO_2 from peatland decomposition (or oxidation) are inferred as resulting from loss of carbon from organic soil, which is reported across various land categories. For Indonesia, losses of organic soil (i.e. peat decomposition emissions) contribute substantially to the overall net emissions from the LULUCF category, and are equivalent to 65% of Energy emissions. In Malaysia, the large Forest Land removals outweigh peatland emissions (predominantly occurring in Cropland), resulting in a net sink in the LULUCF category. Nevertheless, at 54 MtCO_2, peat decomposition emissions are 21% of Energy emissions, and are larger than emissions in the Industry (37 MtCO_2e), Agriculture (9 MtCO_2e), and Waste (24 MtCO_2e) categories (not shown in Table 3).

Table 3: *National reported GHG emissions, for selected key categories rounded to nearest MtCO2e, from the latest available year in the common reporting tables in BTRs of Indonesia and Malaysia (Republic of Indonesia, 2024; Government of Malaysia, 2024).*

Emissions category	Indonesia (2022)	Malaysia (2021)
Total net GHG emissions	1383	107
Energy (Category 1)	739	260
LULUCF (Category 4)	312	-222
LULUCF Forest Land (Category 4A)	-267	-258
Emissions from loss of organic soil*	479	54

**For Indonesia, loss of carbon from organic soil is reported in categories 4A, 4B, 4C, 4F (respectively Forest Land, Cropland, Grassland, Other Land). For Malaysia, losses are reported in categories 4A and 4B. The values in this table are the sum of these carbon losses, converted to CO_2 emissions.*

Peat fires are widely recognised for their substantial emissions of air pollutants, notably particulate matter, which periodically degrade regional air quality. GHG emissions from peat fires are also historically substantial, especially in Indonesia (e.g. Huijnen et al., 2016), but more variable year-to-year than the continual emissions from peatland decomposition. Unlike in Indonesia's previous Biennial Update Report, the standardised BTR format does not yield a standalone value for peat fire GHG emissions. Nevertheless, recent years of well documented peat fires - 2015 and 2019 - are years with higher emissions in Indonesia's latest BTR inventory, and the reported lower LULUCF emissions in 2022 can in part be attributed to relatively low levels of peat fires. Indeed, even considering the "low" recent year of 2022, Indonesia's BTR states "The leading emitter in the LULUCF sector was cropland … primarily due to peat decomposition and fires."

From the above discussion, peatlands' importance is clear, but uncertainties also begin to emerge. In the case of both countries, the peatland decomposition emissions estimated by UNEP are higher than those presented in the BTRs, by 39% for Indonesia and by 66% for Malaysia. Put differently, if the UNEP values replaced the values contained in the national emission inventories (bottom row of Table 3), total national net emissions (top row in Table 3) would increase by 14% in Indonesia and by 34% in Malaysia. These kinds of differences between peatland emission estimates are thus critical to understand in interpreting progress in national climate mitigation, and lead to important questions regarding data uncertainties and the varying methodologies used to estimate emissions. These issues are developed later, in Section 3.3.

3. Analysis of key sources of uncertainty

Having highlighted the importance of peatlands in Indonesia and Malaysia across a range of sustainability dimensions, in this section we present further illustrative analyses that provide insights into peatland data uncertainties, on 1) peatland extent, 2) peatland impacts (via an oil palm example), and 3) peatland GHG emissions. As shown in Figure 3, through the ways these datasets are used together in calculations (e.g. of GHG emissions), uncertainties can increase and errors propagate and magnify. Broadly the same analysis steps also need to be considered for uncertainties in biodiversity assessments.

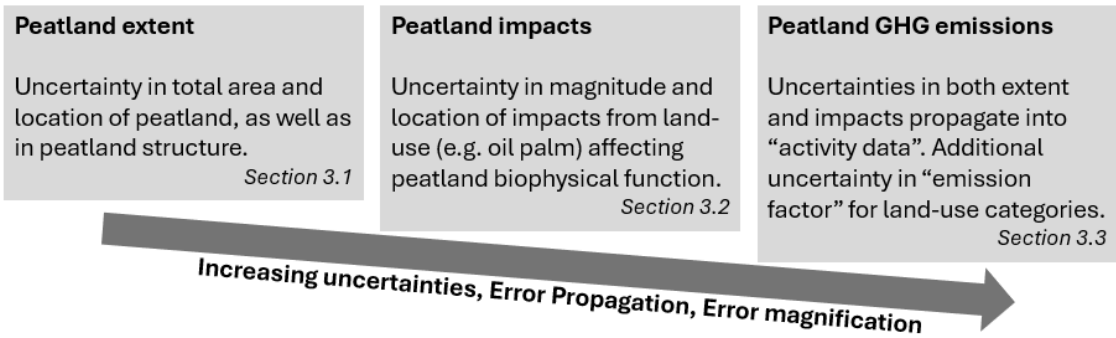

Figure 3: *flow chart diagram to show links between the illustrative analyses presented in this section.*

3.1 Uncertainties in Peatland Extent

While overall areal estimates area can be similar for certain datasets, the actual location of peatlands can vary greatly. For example, in Figure 4 we present a comparison between the peatland data of Gumbricht et al. (2017), Xu et al. (2018) and UNEP (2022) (see Table 2) which reveals where there is a lack of consensus on the location of peatlands. In Section 2.1, we already highlighted substantial disagreements between the former two datasets, which agree on peatland location in a minority of their mapped peatland areas. Here, for visualisation, we also include the UNEP (2022) dataset, which is publicly available. However, this dataset was excluded from our earlier quantitative comparisons due to inconsistencies between its spatial datafile and statistics presented within the UNEP (2022) report.

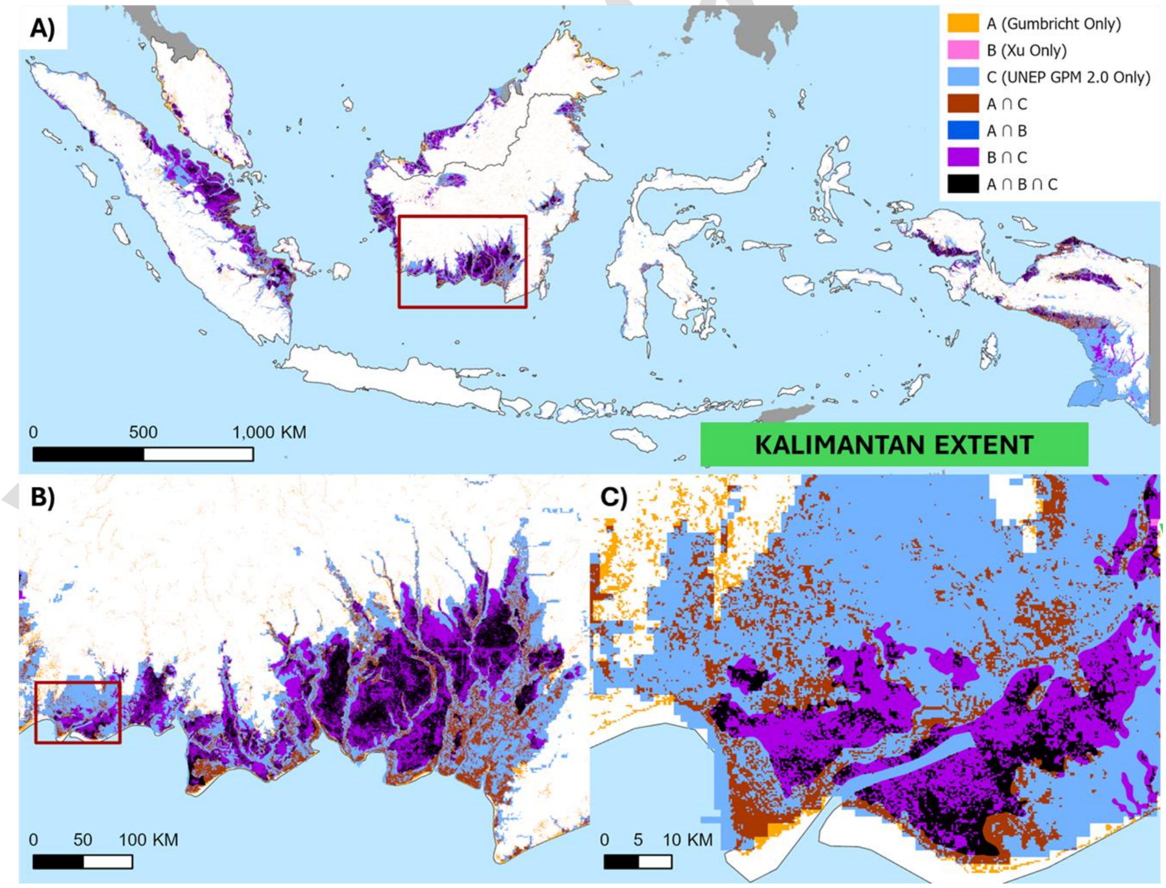

Figure 4: *Mapping discrepancies in peatland areas. (A) Shows areas of agreement and disagreement between peatland datasets across Indonesia and Malaysia. (B) Provides a detailed view of a region in Kalimantan (red box in A), showing that different sources generally identify a peatland area, but the actual extent and precision of the mapping varies between datasets. (C) At a finer spatial resolution, the differences driven by pixel size and the data structure—raster versus vector—become evident.*

The spatial differences between datasets become more apparent when zooming into specific areas (Figure 4, Panels B and C). Panel B shows that while these maps agree on the general areas of peatland, the exact boundaries vary significantly among the data sources. Panel C further illustrates how finer spatial resolutions expose the influence of pixel size and data structures, whether raster or vector, which drive differences between datasets. For example, raster data can include many small patches of peatland, unlike vector data. While the fine-scale data from Gumbricht et al. (2017), with a pixel size of 232 m, offers highly detailed mapping, the other two datasets provide coarser resolution.

Differences in peatland mapping arise through varying practices in defining peat, difficulties in measuring peatland systems accurately and comprehensively, differences in methodological approaches, the dynamic nature of peatland landscapes (Wahyunto and Suryadiputra, 2008; Lourenco et al., 2022), as well as misclassification of remote sensing data. For example, peat thickness plays a critical role in defining peat (see Table 2), in assessing functions such as carbon storage, and in understanding peatland development and land-use management decisions (Parry et al., 2014; Minasny et al., 2019). While deep peat stores significant carbon through the accumulation of organic material, shallow peat still holds substantial carbon stocks and contributes to hydrological and biodiversity functions that should not be excluded from consideration (IUCN, 2023).

Peat thickness varies significantly in tropical peatlands (Page et al., 2011) and mapping thickness is challenging. Ground-based methods like probing and ground-penetrating radar (GPR) are resource-intensive, while remote sensing techniques struggle to measure peat depth directly due to subsurface variability and face challenges in tropical regions where extensive cloud cover frequently obstructs satellite imagery (Minasny et al., 2024; Fiantis et al., 2023; Parry et al., 2014). Only a few studies have mapped the spatial distribution of peat and its thickness in Indonesia and Malaysia (Anda et al., 2021; Gumbricht et al., 2017). Anda et al. (2021) determined peat depth by measuring along transect lines then refined it using satellite image feature, categorizing depth into six classes from shallow (50 - 100 cm) to exceptionally very deep (>700 cm). Gumbricht et al, (2017) used a model-based approach, incorporating biophysical indicators and terrain data to estimate peat depth and distribution across tropical regions, ranging from less than 1 m depth to over 9 m. Comparisons between these available peatland depth datasets in Indonesia would be informative, but are inhibited by the free availability of data (Table 2).

Peatland extent and depth are two key indicators of peatland quantity, and crucial for characterising its condition and contribution to carbon storage. Many other physical, spatial, and temporal properties of peatlands are equally or even more challenging to assess. For example, historical remote sensing imagery, which is essential for evaluating changes over time and is required for certification by the Roundtable on Sustainable Palm Oil (RSPO), is often scarce and of poor quality or resolution, particularly before the 2010s. The presence of peat soil, a critical indicator of peatland ecosystems, cannot be directly mapped using remote sensing. Instead, mapping depends on proxies and correlations, due to obstructions from ground cover and tree canopy (UNEP, 2022). Thus an overall major challenge in peatland mapping and quantification is the diversity of disciplines required, from remote sensing to soil science and chemistry.

3.2 Uncertainties in oil palm extent and error propagation

As discussed in the previous section, differences between (and thus errors in) fundamental datasets, such as for peatland extent, can be significant. However, the data challenge is larger still because many applications of peatland management require combining multiple spatial datasets. Combining multiple datasets can potentially compound uncertainty (Goldstein, 2022, Lechner et al. 2012), which we illustrate here using an example focussed on oil palm.

In Section 2.2 we highlighted conversion to oil palm agriculture as one of the most significant pressures on peatlands in Indonesia and Malaysia. As with peatland extent, there are numerous maps of oil palm extent, covering different time periods, which are compiled (for all soil types) in Figure 5, S1, S2. Some datasets provide continuous records beginning in 1987, while most are available only for a single year, with greater coverage after 2015. Overall, the various maps show a well-known trend, that oil palm coverage has expanded across Indonesia and Malaysia. However, these comparisons of eight major datasets reveal large discrepancies in both area and time series trends. Considering Indonesia and Malaysia combined (Figure 5A), the greatest divergence occurs in 2015, with estimates ranging from 19.5 Mha (Petersen et al., 2016, oil palm and oil palm mix) to 11.1 Mha (Miettinen et al., 2015). Regional discrepancies are also pronounced. For example, estimates for West Malaysia (Figure 5D) vary far more than those for Sumatra (Figure 5F) , and whether a dataset contains a high or a low estimate of oil palm area can also depend on the region. In Borneo, Danylo's estimate is nearly 2.5 times higher than Miettinen (Figure 5E), whereas in Malaysia, Miettinen's estimate is only 13.8% higher than Danylo (Figure 5B). Some datasets explicitly acknowledge this uncertainty such as Xu et al. (2020), which reports upper and lower bounds, while Petersen distinguishes between oil palm only and oil palm mix to capture semantic uncertainty.

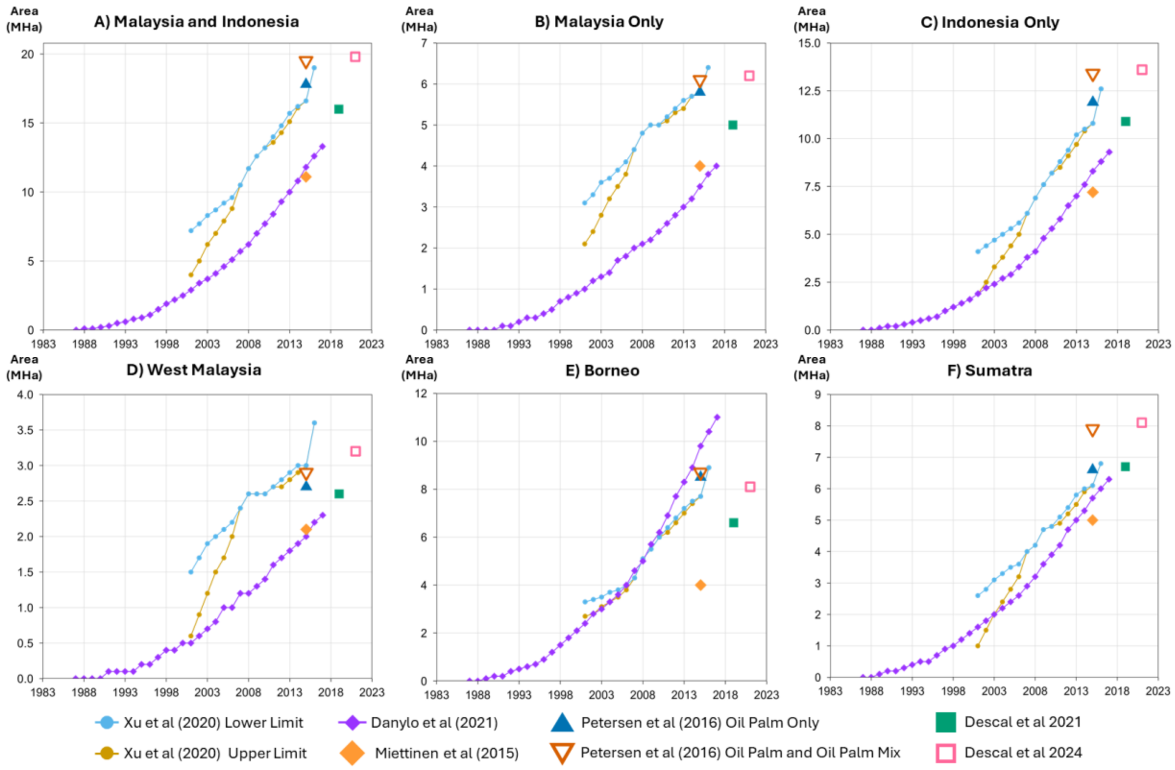

Figure 5: *Timeseries of the oil palm datasets area (MHa) for A) Malaysia and Indonesia (Sumatra and Kalimantan), B) Malaysia only, C) Indonesia only, D) West Malaysia (Peninsular Malaysia), E) Borneo (Kalimantan and East Malaysia) and F) Sumatra, from 2000 to 2019. The data nodes are labelled with the source reference and publication dates.*

Uncertainty then becomes even more pronounced when oil palm datasets are combined with peatland extent datasets, for example in answering the fundamental question: “how much oil palm is on peatland?”. Figure 6 shows four estimates of oil palm area within peatlands, derived from calculating the area of overlap between the four possible combinations of two oil palm datasets with two peatland datasets. Depending on the combination, total oil palm areas of overlap in Indonesia and Malaysia combined range from 1.5 Mha to 2.2 Mha. When considering the areas of overlap across all four datasets (i.e. a conservative estimate), the area calculated is just 0.4 Mha. In contrast, for a much less conservative estimate if both oil palm datasets are merged and both peatland datasets are merged, the intersection is nearly 3.8 Mha. These large discrepancies underscore how strongly results depend on dataset selection and treatment, and highlight the difficulty of reliably quantifying land-use disturbances. This, of course, has direct implications for GHG emission estimates, a challenge examined further in the next section.

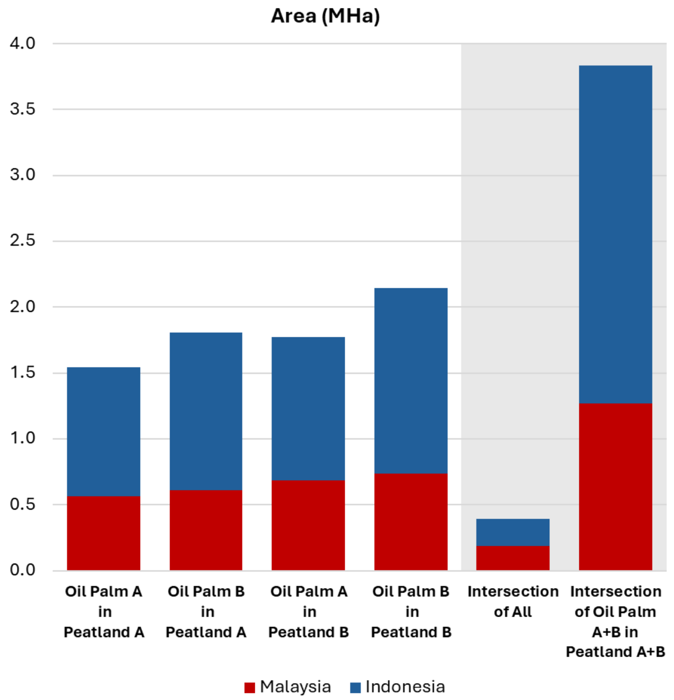

Figure 6: *The first four bars compares the combinations of coverage (MHa) of the two oil palm datasets – (A) Danylo et al (2021) and (B) Descal et al (2021) - within the two peatland datasets - (A) Gumbricht et al (2017) and (B) Xu et al (2018) - for Malaysia against Indonesia. The fifth bar shows a conservative intersection coverage across all 4 dataset which indicates areas where authors have observed that both peatland and oil palm are present. And finally, the sixth (rightmost) bar shows the intersection of all oil palm areas (Union of oil palm A+B) within both peatland datasets (Union of peatland A+B), reflecting a more generous coverage.*

3.3 Uncertainties in Peatland Greenhouse Gas Emissions

Estimates of GHG emissions from peatlands can be obtained using a range of methods (e.g. Hoyt et al., 2020; Desmukh et al. 2023; Basri et al., 2024), yet are faced with multiple challenges and uncertainties. Varying and poorly mapped peat depth and density lead to uncertainty in peatland extent and carbon stocks. Further, the natural spatial heterogeneity within peatlands means uncertainty is introduced by the common approach of extrapolating local-scale emission measurements across large areas, or applying those data at other unmeasured sites. Similarly, emissions fluctuate temporally, for example with hydrology, vegetation, and land-use changes (such as due to oil palm), leading to further uncertainties when relying on short-term measurements. There are also different accounting practices (i.e. stock difference and gain-loss methods), not all measurement approaches will include the full range of carbon fluxes, and additional GHGs such as methane and nitrous oxide are not always measured (Murdiyarso et al., 2024).

In this section we focus on comparing national-scale peatland GHG emission estimates, but emphasise that sub-national (e.g. project scale) estimates are increasingly important. As a major element of national reporting to the UNFCCC (e.g. in the BTRs discussed in Section 2.3), national emission inventories are expected to be developed using a standardised methodology, which is described in Intergovernmental Panel on Climate Change (IPCC)

Guidelines. For peatlands, both the general guidelines for National GHG Inventories (IPCC, 2006) and the Wetlands Supplement (IPCC, 2013) are key methodological references. In essence, these guidelines require calculating emissions based on the product of an *emitting activity* (e.g. an area of land with a particular status) and an *emission factor* (an emission rate, per unit activity). However, calculations can be conducted with varying levels of detail and complexity, within the tiered approach of the guidelines.

In brief, the simplest approach is Tier 1, which relies on default emission factors and basic activity data. Tier 2 employs country-specific emissions factors, typically informed by local field (i.e. peatland) measurements. Tier 3 may involve more detailed models, spatial data, and long-term flux monitoring to simulate emissions under varying conditions; this approach should result in more accurate estimates, but requires significant technical resources. Both Indonesia and Malaysia largely rely on Tier 1 approaches for the estimates of LULUCF emissions presented in recent BTRs (Table 3), but reflecting their importance, Indonesia has developed a Tier 2 approach to estimate peatland emissions. These country specific peatland emission factors are based on measurements from multiple field studies in Indonesia (Novita et al., 2021). They have also been applied in Indonesia's latest, second Forest Reference Level for the UNFCCC (Republic of Indonesia, 2022), and considerations for improvements have been suggested by Murdiyarso et al. (2024).

To illustrate the importance of assumptions regarding peatland areas and land uses (i.e. activity data) and emission factors, we present various estimates of peatland GHG emissions for Indonesia and Malaysia (including those mentioned in Section 2). These estimates are shown in Figure 7, in which emissions are plotted as a function of the peatland area reported in the study. This arrangement means lines of constant emission factor (i.e. emitted mass per unit area) radiate from the origin, with three such lines (for 20, 30 and 40 tCO_2e/ha) plotted for reference. From Figure 7 we can identify differences in estimated emissions that are likely to be caused by the assumed area of peatland, the emission factors employed, the range of emitting processes included in the calculation, as well as from the year of emission being considered.

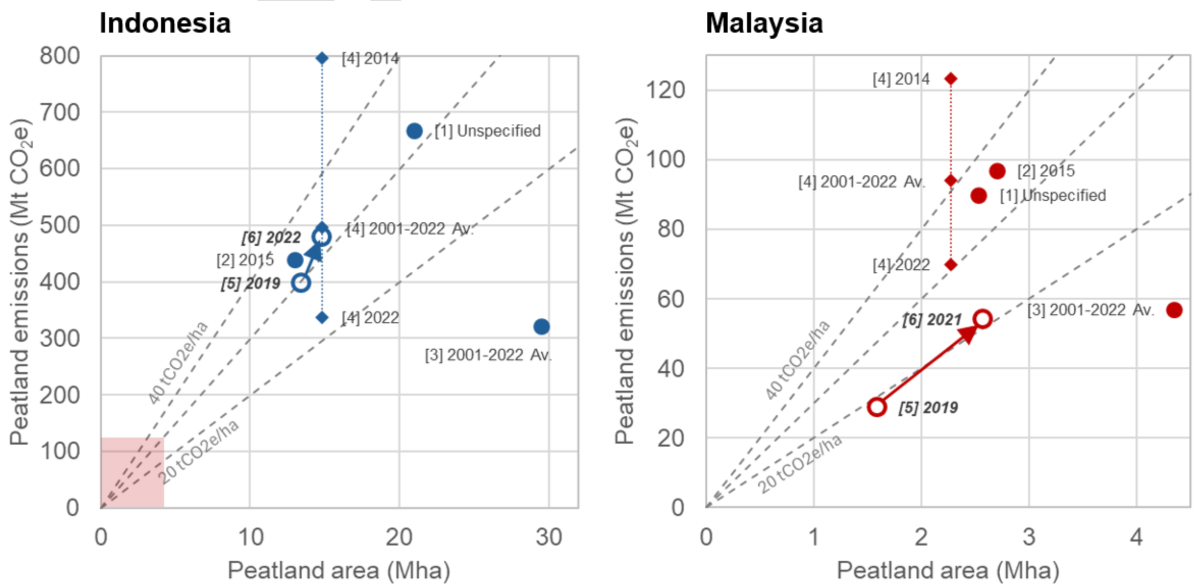

Figure 7: *Multiple estimates of peatland GHG emissions and areas in Indonesia (left) and Malaysia (right). The year for which the estimate is made is indicated. The red shading in the lower corner of the Indonesia plot indicates the emission-area space in the Malaysia plot. The sources of the estimates are: [1] UNEP (2022); [2] Miettinen et al. (2017); [3] Harris et al. (2021), as in Figure 2; [4] Sasmito et al. (2025); [5] Previous national BURs; [6] Latest national BTRs, as in Table 3. Note that studies can use multiple emission factors for peatland in different states. The final effective emission factor for a study, and thus the positioning of the marker relative to the dashed grey lines in the Figure, will reflect the proportion of peatland areas in differing state categories (e.g. forest, cropland, oil palm, fire, drained, deforested etc.) and the specific emission factor used for each category.*

We first compare the estimates of UNEP (2022) and Miettinen et al. (2017), labelled [1] and [2] in Figure 7. Both estimates focus on emissions from peat oxidation (or decomposition), and deploy IPCC (2014) default (i.e. Tier 1) emission factors for non-pristine peatland areas. For Malaysia, the total peatland areas assumed in these two studies are similar (2.5 and 2.7 Mha, respectively). While not all details of peatland state are available in the UNEP (2022) report, the effective emission factors (that emerge from the emission calculation weighted by the sizes of areas in different states) are also similar, and thus the calculated emissions are similar (90 and 97 tCO_2e). In the case of Indonesia, the larger difference in the estimated emissions (668 and 440 tCO_2e) likely arises due to the smaller area in the Miettinen et al. (2017) study, which did not map and calculate emissions for all Provinces.

We can also compare, for both countries, emissions reported to the UNFCCC in the latest BTR and in the previous Biennial Update Report (BUR; Republic of Indonesia, 2021; Government of Malaysia, 2022). These estimates are labelled [6] and [5] respectively in Figure 7, and the update in the reported emission is indicated by the arrow pointing from [5] to [6]. For Malaysia, in both the BUR and the BTR, emissions are reported as loss of carbon from drained organic soil. In the latest BTR, the reported emission (54 tCO_2) is larger than in the BUR (29 tCO_2). This difference appears to be predominantly due to the larger area of organic soil in the cropland category in the BTR (1.8 Mha, out of the total reported 2.6 Mha of organic soil) than in the BUR (1.1 Mha of a total 1.6 Mha). The implied emission factor in both the BUR and the BTR is very similar, with the arrow running close to parallel to the 20 tCO_2e/ha reference line. For Indonesia, we focus this comparison between BUR and BTR on the estimates related to peatland decomposition/oxidation (i.e. loss of organic soil), and ignore separately reported emissions from peatland fires. While changes in reporting approach hinder detailed comparison, both a more modest increase in total peatland area, and a slightly higher implied emission factor, contribute to somewhat higher emissions in the later BTR (479 tCO_2e) than in the previous BUR (398 tCO_2e).

Continuing comparisons related to differing peatland areas, we refer again to the spatially explicit GHG emissions dataset of Harris et al. (2021), which was presented in our mapped peatland layer in Figure 2D. Recall this peatland layer was constructed by combining two peatland area datasets which disagree substantially in spatial detail and thus in combination likely yield an exaggerated peatland area. In Figure 7, the Harris et al. (2021) emissions in our peatland layer are labelled [3]. Here, despite the larger area considered, the emissions are relatively low, due to a lower effective emission factor. The Harris et al. (2021) emissions are calculated using multiple spatial datasets and, as shown in Section 3.2, substantial uncertainties arise through spatial overlaps and dataset selection.

We next present emissions estimates from the study of Sasmito et al. (2025), labelled [4] in Figure 7. Using peatland areas from Xu et al. (2018), this study provides more detailed emissions estimates, by year and by emitting process. The connected markers in Figure 7 show the effect of selecting different years to estimate emissions, comparing the average emissions of 22 years with emissions in two specific years: 2014 (with high emissions), and 2022 (with low emissions). Earlier years in the record of Sasmito et al. (2025) had larger emission contributions from the processes of peatland drainage, deforestation and fire (71% and 59% in 2014, in Indonesia and Malaysia respectively). By 2022, these emitting processes are less important, leaving peat decomposition as the major (close to 80%) contributor in both countries, and the total emissions reported are lower.

Finally, we compare the emissions reported by both countries in their latest BTRs and associated data tables, which are now presented in a common format. The reporting documents include areas of organic soil in specific land categories, alongside “implied carbon stock change factors”, which are equivalent to emission factors if carbon is lost to the atmosphere as CO_2. The reported values for organic soils in croplands are -7.53 and -11.53 tC/ha for Malaysia and Indonesia, respectively. These values are equivalent to emission factors of 27.6 and 42.3 tCO_2/ha. There are similar differences for other land categories, with the factors for organic soils in forest land also greater in Indonesia’s report. These inter-country differences are reflected in the positioning of the markers labelled [6] in Figure 7, relative to the reference emission factor dashed lines.

Overall, these comparisons show the value of reporting transparency in understanding differences between datasets. For Malaysia, while the peatland (organic soil) area used in the BTR is broadly consistent with other studies, the use of a lower implied emission factor results in a lower reported emission. This could potentially be reconciled with a more detailed description of emitting processes, as in Sasmito et al. (2025). For Indonesia, the estimates of area and emissions from decomposition in the BTR, and in Miettinen et al. (2017) and Siswento et al. (2025), are broadly similar. The UNEP (2022) estimate is affected by a much larger assumed peatland area. Importantly, the peatland areas considered here have been aggregated to the national scale. The uncertainties and locational disagreement in peatland extent and status shown in the preceding sections would potentially translate into bigger uncertainties in smaller, sub-national, areas such as might be considered in project-scale estimates of GHG emissions.

4. Conclusion: Cross cutting challenges and opportunities for peatland data to support sustainability intervention efforts

Despite the wide-ranging uncertainties in mapping and quantifying activities in peatlands and their impacts, it is clear that interventions to reduce emissions and prevent further degradation offer substantial promise for climate mitigation (Sasmito et al., 2025) and to achieve additional sustainability goals. In turn, this means addressing the challenges of data quality and uncertainty across different scales is essential for credible sustainability outcomes in peatlands. Accordingly, in Table 4 of this concluding section, for each of the seven key challenges identified in Figure 1, we summarise data needs, data uncertainties and data recommendations. We then highlight cross-cutting opportunities to 1) enhance data practices, 2) engage constructively with uncertainty, and 3) value broader sustainability benefits.

Table 4: *Seven key peatland challenges are presented alongside their importance and data needs, associated uncertainties and consequences, and recommendations for improving peatland data and sustainability policy in Indonesia and Malaysia. These challenges are underpinned by three cross-cutting themes: (1) enhancing data practices across scales and borders, (2) constructively engaging with data uncertainty and carbon credit integrity, and (3) valuing broader sustainability benefits. The cross-cutting themes are cited in the rightmost column.*

Key Data Challenge	**Importance of Peatlands and Data Needs**	**Peatland Data Uncertainties and consequences**	**Recommendations for Peatland Data and Better Sustainability Policy**
1. Peatland Extent	Mapping peatland boundaries and hydrological and ecological units to identify and prioritize areas for management and interventions.	Disagreements on extent definitions, mapping methods, and limited large-scale or historical field data. Leading to fundamental uncertainties in characterisation of peatland extent and location to support assessments of GHG emissions and conservation.	Improved spatial data, with quantification of uncertainty and transparency, are needed to address extent mismatches, as these affect error propagation and all peatland quantification and management efforts (1,2)
2. Peatland Structure, Hydrology and Condition	Essential for understanding peatland health in terms of characteristics (i.e. dome and depth), water management (i.e. canals), fire susceptibility, flood risks and soil condition.	Lack of data on peatland structure, hydrology and condition, with limited field measurements in space and time (e.g., water depth), and modelling. Lead to uncertainty in characterisation of peatland conditions, particularly problematic for restoration initiatives.	Accurate data on peatland structure and hydrology are critical inputs for all aspects of peatland quantification (e.g. GHG emissions), and effective management. Extensive fieldwork required as well as developments of novel remote sensing methods (1,2).
3. Biodiversity	Supports biodiversity conservation, ecosystem health assessments.	Lack of detailed, accurate mapping of peatland biodiversity and ecosystem health, with limited data on many species, especially non-mammals and birds. Hinder effective conservation planning, overlooking critical habitats, contribute to local species declines and potential extinctions.	Parallel assessments of carbon stock and flora diversity, and greater research on link between peatland condition and biodiversity loss (or conservation). (3)
4. Carbon and Greenhouse Gas Emissions	Quantify emissions, support climate change mitigation efforts, and evaluate carbon storage capacity, particularly important for reporting to	Limited spatially-explicit belowground carbon stock data; outdated carbon stock datasets; high variability in GHG emissions; poor data on CH_4 and N_2O emissions; high uncertainty in emission factors	Transparent and detailed reporting of peatland emission methodologies can clarify contribution to national or corporate targets and support data harmonization at the regional scale. Carbon credit

	UNFCCC and for carbon credit schemes.	and lack of adequate baseline data. Lowers confidence in peatland's role in GHG reduction targets and leads to carbon credit integrity risks.	approaches that foreground uncertainty are likely to reduce risks to integrity of outcomes. (1, 2)
5. Land Use, Management and Community Engagement	Identifies drivers of degradation such as agriculture, key stakeholders (i.e.the local community) to inform and support restoration efforts, and evaluates management effectiveness.	Missing spatial data on restored peatlands; lack of accessible site-level data; outdated land-use change data. Mismatches in administrative/jurisdictional boundaries and biophysical boundaries and lack of clear land tenure can result in policies that do not support the natural hydrology of peatlands.	Engaging local communities in peatland data collection, management, and translation fosters ground-truthing, ownership, advocacy, and culturally appropriate, accessible information, ensuring data-driven, context-specific interventions, sustainable stewardship, and informed policy influence. (1,2,3)
6. Spatial Data Quality, Transparency and open data	Systematic and transparent assessment of spatial data quality supports fitness-for-use evaluations and understanding of error propagation, while open data enables broader stakeholder access, use, and contribution to peatland information.	Lack of systematic assessment and transparency in spatial data quality and uncertainty, leads to error propagation and poor management decisions. Lack of available “official” spatial data and/or limited open data access results in stakeholders using a variety of inconsistent and non-standard datasets.	Formal recognition of uncertainty through spatial data quality metrics, transparent metadata, and modelling methods for assessing fitness-for-use and error propagation, alongside open data, are essential for robust and consistent analysis. (1,2)
7. Policy and Regulatory Needs	Evidence-based, data-driven approaches guide effective conservation and restoration strategies, promote equitable management, and embed transparency and spatial data quality into decision-making processes.	Policies that ignore data uncertainty and lack evidence-based approaches risk leading to poor and potentially biased and/or harmful decisions.	Integrate quantitative approaches and uncertainty assessment into decision-making processes, grounded in the precautionary principle. (1,2,3)

Overall, a productive path forward in addressing these data challenges would incorporate opportunities across the three cross-cutting themes identified. For example, this review’s assessment of Challenge 5 in Table 4 on land use management recommends engaging local communities in peatland data collection, management, and translation as a way to enhance data practices (theme 1) while improving relevance and trust at all scales. Community-led ground-truthing exercises and data verification can provide a trusted, on-the-ground audit of management practices and their climate impacts, to address data uncertainty through context-specific policy interventions supported by culturally appropriate information (Varkkey et al., forthcoming) (2). Ultimately, such processes can incorporate multiple metrics alongside qualitative indicators to fully value broader sustainability benefits (3), ensuring that land management decisions support not just carbon targets but also community livelihoods, cultural values, and biodiversity, thereby fostering true stewardship and long-term resilience. Experiences with community fire management and peatland restoration in Ogan Komering Ilir district in South Sumatra and Pulang Pisau district in Central Kalimantan show how communities can be effectively engaged to address peatland data issues. In this case, contributions from the community played an essential role in developing Indonesia's Peat Fire Danger Rating System (Robins et al, 2022). Exploratory surveys among peat communities in Perak and Selangor in Malaysia furthermore revealed that 74% of community members sincerely wanted to contribute to peat conservation through participation in community-based management (Nath et al., 2016).

At a systemic level, evidence-based, data-driven approaches can guide effective peatland conservation and restoration strategies, promote equitable peatland management through participatory engagement with local communities, and embed transparency and spatial data quality into decision-making processes across scales and borders (1). Policies that ignore data uncertainty and lack robust quantitative assessment methods risk leading to poor decisions that compromise desired outcomes (e.g. carbon credit integrity) (2) and undermine broader sustainability benefits including community livelihoods, biodiversity conservation, and haze prevention (3). Moving forward, although a wide range of datasets relevant peatlands are now available, their fitness for use remains unclear. Incorporating quantitative approaches to evaluate this fitness and to assess uncertainty, including error propagation, into decision-making processes will be beneficial. Grounded in the precautionary principle, this ensures data limitations are addressed conservatively while recognizing both carbon and non-carbon outcomes. Such integration will be critical for advancing equitable peatland governance that upholds data quality, market integrity, and broad sustainability benefits.

This review has provided a comprehensive assessment of the persistent data challenges undermining peatland management in Indonesia and Malaysia. By integrating a structured expert workshop with spatial analyses designed to quantify and visualize key uncertainties, our interdisciplinary synthesis has characterized seven critical data issues and demonstrated how their associated errors can propagate into downstream policy mechanisms. The framework presented here offers a robust pathway for transforming complex data into actionable evidence. Our conclusions provide a critical foundation for shaping future research and evidence-based policy. Ultimately, this work delivers a coherent strategy with direct societal relevance, offering stakeholders across sectors a credible approach for achieving equitable outcomes in these critically important ecosystems.

Acknowledgments
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Supplementary materials

***Table S1**: Statistical summary of mapped quantities in Figure 2, by country and region.*

Region / Country	Peatland extent (1,000 km2)				Forest Loss in Peatland (1,000 km2)		Oil Palm in Peatland (1,000 km2)				Protected Peatland (1,000 km2)		Forest Emission (MtCO2ey-1)			Forest Removal (MtCO2ey-1)		
	Xu et al	Gumbricht et al	Agreement Area	Extent	All driver	by Fire	Industrial	Small-holder	Total				Total	in Peatland		Total	in Peatland	
Sumatra	64.0	59.9	25.9	97.6	41.8	5.7	9.6	6.3	15.9	(16%)	6.6	7%	444	201	45%	213	67	31%
Kalimantan	49.2	64.7	23.2	90.7	24.9	7.6	5.2	0.8	6.0	(7%)	12.8	14%	385	112	29%	188	40	21%
Papua	36.4	72.3	18.9	89.8	1.6	0.2	0.2	0.0	0.2	(0%)	16.9	19%	36	6.5	18%	85	36	43%
Sulawesi	-	7.8	-	7.8	0.8	0.1	0.1	0.2	0.3	(4%)	0.4	6%	66	2.6	4%	49	4	9%
Maluku	-	2.5	-	2.5	0.1	0.0	-	-	-	(0%)	0.2	6%	18	0.6	3%	27	3	12%
Jawa Bali	-	5.8	-	5.8	0.0	0.0	0.0	0.0	0.0	(0%)	-	0%	8.1	0.1	1%	39	1	3%
Nusa Tenggara	-	0.3	-	0.3	0.0	0.0	-	-	-	(0%)	0.0	3%	5.2	0.01	0%	12	0	1%
Indonesia	**149.6**	**213.3**	**68.0**	**294.8**	**69.3**	**13.6**	**15.0**	**7.4**	**22.4**	**(8%)**	**36.4**	**13%**	**961**	**322**	**34%**	**612**	**152**	**25%**
West Malaysia	7.5	11.3	2.9	15.8	5.0	0.2	2.3	0.8	3.1	(20%)	0.3	2%	84	12	14%	42	6	15%
East Malaysia	15.8	17.2	5.4	27.6	10.9	0.4	5.9	0.4	6.3	(23%)	1.9	7%	151	45	30%	63	12	20%
Malaysia	**23.3**	**28.4**	**8.3**	**43.4**	**15.9**	**0.7**	**8.2**	**1.2**	**9.3**	**(22%)**	**2.2**	**5%**	**234**	**57**	**24%**	**105**	**19**	**18%**

Methodological approaches to the review

Expert workshop

Our hybrid workshop involved participants from Indonesia, Malaysia, and Singapore, followed by subsequent discussions and spatial analyses. The workshop conducted on August 7, 2024, brought together 22 experts: 14 from Indonesian institutions, 6 from Malaysian institutions, and 2 from Singaporean institutions, representing NGOs, academia, and governmental bodies. 16 of the participants joined in person and 6 online. Prior to the workshop we identified four themes: 1) Peatland Data needs, 2) Mapping peatland and its condition, 3) Calculating GHG emissions from peatlands and 4) Cross cutting challenges and opportunities for enhancing peatland data to support sustainability interventions (presented in Table 1). For each of the four themes we held group discussions both online and in small breakout tables, focusing on questions relevant to Indonesia and Malaysia. Discussion points from the workshop were compiled in an Excel spreadsheet, and participants were subsequently invited to submit further written reflections and supporting evidence. A smaller working group then consolidated and refined these contributions. As part of the consolidation exercise, an artificial intelligence (AI) tool (Microsoft Copilot) was used to summarise the workshop notes contained in an anonymised version of the Excel spreadsheet and to generate initial outlines for Figure 1 and for Table 4. The AI outputs were cross-checked against the workshop notes, and were refined over multiple iterations by the authors to create the final versions.

GIS methods

Overlay analyses were conducted in ArcGIS Pro (version 3.5.3) using standard GIS techniques to quantify spatial overlap, as well as areas of agreement and disagreement among datasets. All spatial datasets employed in the analysis were publicly accessible and are documented in the corresponding sections where they are examined.

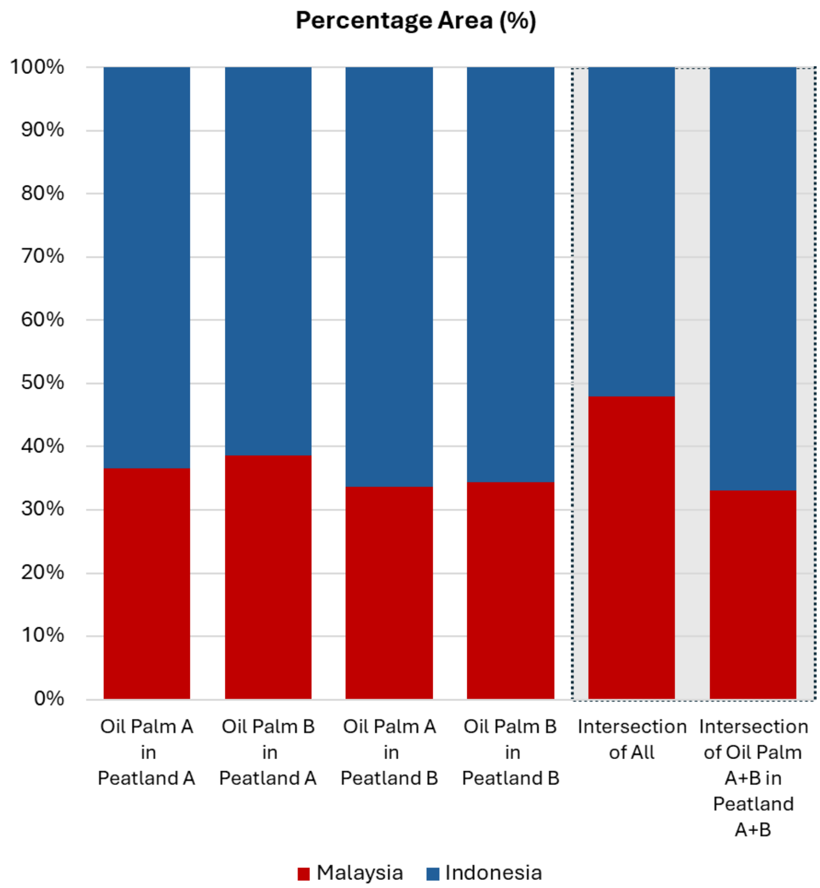

Figure S1*: The first four bars compares the combinations of coverage in percentage (%) of the two oil palm datasets – (A) Danylo et al (2021) and (B) Descal et al (2021) - within the two peatland datasets - (A) Gumbricht et al (2017) and (B) Xu et al (2018) - for Malaysia against Indonesia. The fifth bar shows a conservative intersection coverage across all 4 dataset which indicates areas where authors have observed that both peatland and oil palm are present. And finally, the sixth (rightmost) bar shows the intersection of all oil palm areas (Union of oil palm A+B) within both peatlands datasets (Union of peatland A+B), reflecting a more generous coverage.*

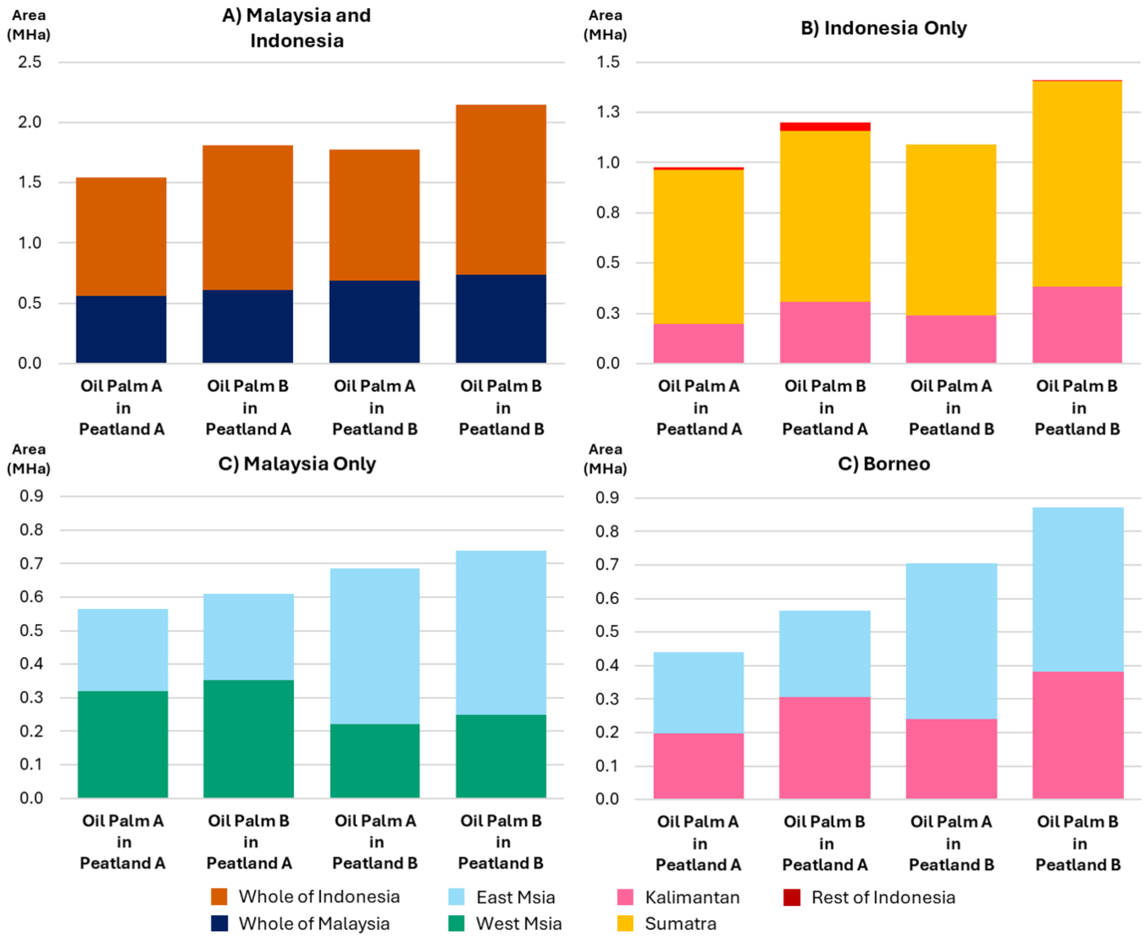

Figure S2: *The first four bars compares the combinations of coverage (MHa) of the two oil palm datasets – (A) Danylo et al (2021) and (B) Descal et al (2021) within the two peatland datasets - (A) Gumbricht et al (2017) and (B) Xu et al (2018) - for the following extents: A) Malaysia and Indonesia, B) Indonesia only, C) Malaysia only, and D) Borneo (Kalimantan and East Malaysia). These differences in areas further illustrate spatial discrepancies that are regionally diverse and inconsistent between both oil palm and peatland datasets.*

References

Adrianto, H. A., Spracklen, D. V., & Arnold, S. R. (2019). Relationship between fire and forest cover loss in Riau Province, Indonesia between 2001 and 2012. Forests, 10(10), 889. https://doi.org/10.3390/f10100889.

Anda, M., Dariah, A., Wulandari, D., Sulaeman, Y., & Subiksa, I. G. M. (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.

Azhar, B., Lindenmayer, D. B., Wood, J., Fischer, J., Manning, A., McElhinny, C., Zakaria, & M. 2011). The conservation value of oil palm plantation estates, smallholdings and logged peat swamp forest for birds. Forest Ecology and Management, 262(12), 2306-2315. https://doi.org/10.1016/j.foreco.2011.08.026.

Basri, M. H. A., McCalmont, J., Kho, L. K., Hartley, I. P., Teh, Y. A., Rumpang, E., Signori-Müller, C., & Hill, T. (2024). Reducing bias on soil surface CO2 flux emission measurements: Case study on a mature oil palm (Elaeis guineensis) plantation on tropical peatland in Southeast Asia. Agricultural and Forest Meteorology, 350, 110002. https://doi.org/10.1016/j.agrformet.2024.110002.

Dadap, N. C., Hoyt, A. M., Cobb, A. R., Oner, D., Kozinski, M., Fua, P. V., & Konings, A. G. (2021). Drainage canals in Southeast Asian peatlands increase carbon emissions. AGU Advances, 2(1), e2020AV000321. https://doi.org/10.1029/2020AV000321.

Danylo, O., Pirker, J., Lemoine, G., & others. (2021). A map of the extent and year of detection of oil palm plantations in Indonesia, Malaysia and Thailand. Scientific Data, 8, 96. https://doi.org/10.1038/s41597-021-00867-1.

Department of Agriculture Malaysia. (2002). Reconnaissance soil map of Peninsular Malaysia [Map] (Scale 1:750,000).

Department of Irrigation and Drainage Sarawak. (2014). Distribution of peat soils in Sarawak. http://www.did.sarawak.gov.my/modules/web/page.php?id=97&menu_id=0&sub_id=117.

Descals, A., Wich, S., Meijaard, E., Gaveau, D. L. A., & Peedell, S. (2021). High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. Earth System Science Data, 13, 1211–1231. https://doi.org/10.5194/essd-13-1211-2021.

Descals, A., Gaveau, D. L. A., Wich, S., Szantoi, Z., & Meijaard, E. (2024). Global mapping of oil palm planting year from 1990 to 2021. Earth System Science Data, 16, 5111–5129. https://doi.org/10.5194/essd-16-5111-2024.

Deshmukh, C. S., Susanto, A. P., Nardi, N. et al. (2023). Net greenhouse gas balance of fibre wood plantation on peat in Indonesia. Nature 616, 740–746. https://doi.org/10.1038/s41586-023-05860-9.

Devillers, R., Stein, A., Bédard, Y., Chrisman, N., Fisher, P., & Shi, W. (2010). Thirty years of research on spatial data quality: Achievements, failures, and opportunities. Transactions in GIS, 14(4), 387–400. https://doi.org/10.1111/j.1467-9671.2010.01212.x.

Fiantis, D., Rudiyanto, Gusnidar, Ginting, F. I., Padrikal, R., Prayoga, D., & Nelson, M. (2023). Carbon and phosphorus in volcanic soils of Mt. Kerinci (Sumatra) after long-term tea and paddy cultivation. Communications in Soil Science and Plant Analysis, 54(22), 3169–3184. https://doi.org/10.1080/00103624.2023.2253843.

Goldstein, Jenny E. 2022. "More Data, More Problems? Incompatible Uncertainty in Indonesia's Climate Change Mitigation Projects". Geoforum 132 (June): 195–204. https://doi.org/10.1016/j. Geoforum.2021.11.007

Government of Malaysia. (2022). Biennial Update Report (BTR4). https://unfccc.int/documents/624776.

Government of Malaysia. (2024). Biennial Transparency Report (BTR1). https://unfccc.int/documents/645171.
Grover, S., Treby, S., Mendham, D. S., & Rawluk, A. (2024). Social and ecological dimensions of tropical peatland restoration. Mires and Peat. https://doi.org/10.19189/MaP.2023.OMB.Sc.2114019.
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.
Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. R. G. (2013). High-resolution global maps of 21st-century forest cover change. Science, 342(6160), 850–853. https://doi.org/10.1126/science.1244693.
Harris, N. L., Gibbs, D. A., Baccini, A., Birdsey, R. A., de Bruin, S., Farina, M., Fatoyinbo, T., Hansen, M. C., Herold, M., Houghton, R. A., Potapov, P. V., Suarez, D. R., Roman-Cuesta, R. M., Saatchi, S. S., Slay, C. M., Turubanova, S. A., & Tyukavina, A. (2021). Global maps of twenty-first century forest carbon fluxes. Nature Climate Change, 11, 234–240. https://doi.org/10.1038/s41558-020-00976-6.
Huijnen, V., Wooster, M., Kaiser, J., 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, 26886. https://doi.org/10.1038/srep26886.
Hoyt, A. M., Chaussard, E., Seppalainen, S. S., Harvey, C. F., Cobb, A. R., & Konings, A. G. (2020). Widespread subsidence and carbon emissions across Southeast Asian peatlands. Nature Geoscience, 13, 435–440. https://doi.org/10.1038/s41561-020-0575-4.
Intergovernmental Panel on Climate Change. (2006). 2006 IPCC guidelines for national greenhouse gas inventories. IPCC-TFI/NGGIP. https://www.ipcc-nggip.iges.or.jp/public/2006gl/.
Intergovernmental Panel on Climate Change (Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., & Troxler, T. G., Eds.). (2014). 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. IPCC-TFI/NGGIP. https://www.ipcc-nggip.iges.or.jp/public/wetlands/.
International Union for Conservation of Nature. (2023). IUCN 2023 annual report. Access at: https://iucn.org/resources/annual-reports/iucn-2023-international-union-conservation-nature-annual-report.
Lechner, Alex M., William T. Langford, Sarah A. Bekessy, and Simon D. Jones. 2012. “Are Landscape Ecologists Addressing Uncertainty in Their Remote Sensing Data?”. Landscape Ecology. https://doi. org/10.1007/s10980-012-9791-7
Lourenco, M., Fitchett, J. M., & Woodborne, S. (2022). Peat definitions: A critical review. Progress in Physical Geography: Earth and Environment, 47(4), 506-520. https://doi.org/10.1177/03091333221118353.
Melling, L. (2016). Peatland in Malaysia. In M. Osaki & N. Tsuji (Eds.), Tropical peatland ecosystems (pp. 59–74). Springer. https://doi.org/10.1007/978-4-431-55681-7_4
Miettinen, J., Shi, C., & Liew, S. C. (2016). 2015 land cover map of Southeast Asia at 250 m spatial resolution. Remote Sensing Letters, 7(7), 701–710. https://doi.org/10.1080/2150704X.2016.1182659.
Miettinen, J., Hooijer, A., Vernimmen, R., Liew, S. C., & Page, S. E. (2017). From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environmental Research Letters, 12, 024014, 1–10. https://doi.org/10.1088/1748-9326/aa5b6f.

Minasny, B., Adetsu, D. V., Aitkenhead, M., & others. (2024). Mapping and monitoring peatland conditions from global to field scale. Biogeochemistry, 167, 383–425. https://doi.org/10.1007/s10533-023-01084-1.
Murdiyarso, D., Swails, E., Hergoualc'h, K., Bhomia, R., & Sasmito, S. D. (2024). Refining greenhouse gas emission factors for Indonesian peatlands and mangroves to meet ambitious climate targets. Proceedings of the National Academy of Sciences of the United States of America, 121(17), e2307219121. https://doi.org/10.1073/pnas.2307219121.
Mutalib, A. A., Lim, J. S., Wong, M. H., & Koonvai, I. (1991, March 8–10). Characterization, distribution and utilization of peat in Malaysia. Symposium on Tropical Peat Land, Kuching, Sarawak.
Nath, T. K., Dahalan, M. P. B., Parish, F., & others. (2017). Local peoples' appreciation on and contribution to conservation of peatland swamp forests: Experience from Peninsular Malaysia. Wetlands, 37, 1067–1077. https://doi.org/10.1007/s13157-017-0941-1.
Novita, N., Lestari, N. S., Lugina, M., Tiryana, T., Basuki, I., & Jupesta, J. (2021). Geographic setting and groundwater table control carbon emission from Indonesian peatland: A meta-analysis. Forests, 12(7), 832. https://doi.org/10.3390/f12070832.
Novita, N., Lestari, N. S., Anshari, G. Z., Lugina, M., Yeo, S., Malik, A., & Ellis, P. (2022). Natural climate solutions in Indonesia: Wetlands are the key to achieve Indonesia's national climate commitment. Environmental Research Letters, 17(11), 114045. https://doi.org/10.1088/1748-9326/ac9e0a.
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.
Parry, L. E., Holden, J., & Chapman, P. J. (2014). Restoration of blanket peatlands. Journal of Environmental Management, 133, 193–205. https://doi.org/10.1016/j.jenvman.2013.11.033.
Petersen, R., & others. (2016). Mapping tree plantations with multispectral imagery: Preliminary results for seven tropical countries (Technical Note). World Resources Institute. https://www.wri.org/publication/mapping-treeplantations.
Reed, S. E., Korfanta, N. M., Rochefort, R. M., & Cooper, D. J. (2022). Restoring function: Positive responses of carbon and nitrogen to 20 years of hydrologic restoration in montane meadows. Ecological Applications, 32(7), e2677. https://doi.org/10.1002/eap.2677.
Republic of Indonesia. (2021). Biennial Update Report (BUR3). https://unfccc.int/documents/403577
Republic of Indonesia. (2022). National forest reference level for deforestation, forest degradation and enhancement of forest carbon stock in the context of decision 12/CP.17 para 12 UNFCCC. Jakarta, Indonesia.
Republic of Indonesia. (2024). Biennial Transparency Report (BTR1). https://unfccc.int/documents/645082
Robins, L., van Kerkhoff, L., Rochmayanto, Y., & others. (2022). Knowledge systems approaches for enhancing project impacts in complex settings: Community fire management and peatland restoration in Indonesia. Regional Environmental Change, 22, 100. https://doi.org/10.1007/s10113-022-01960-w.
Sasidhran, S., Adila, N., Hamdan, M. S., Samantha, L. D., Aziz, N., Kamarudin, N., Puan, C. L., Turner, E., & Azhar, B. (2016). Habitat occupancy patterns and activity rate of native mammals in tropical fragmented peat swamp reserves in Peninsular Malaysia. Forest Ecology and Management, 363, 140-148. https://doi.org/10.1016/j.foreco.2015.12.037.
Sasmito, S. D., Taillardat, P., Adinugroho, W. C., & others. (2025). Half of land use carbon emissions in Southeast Asia can be mitigated through peat swamp forest and mangrove conservation and restoration. Nature Communications, 16, 740. https://doi.org/10.1038/s41467-025-55892-0.

Shuhada, S. N., Sabiha, S., Nobilly, F., Zubaid, A., & Azhar, B. (2017). Logged peat swamp forest supports greater macrofungal biodiversity than large-scale oil palm plantations and smallholdings. Ecology and Evolution, 7(18), 7187-7200. https://doi.org/10.1002/ece3.3273.
Struebig, M. J., Lee, J. S. H., Deere, N. J., & others. (2025). Drivers and solutions to Southeast Asia's biodiversity crisis. Nature Reviews Biodiversity, 1, 497–514. https://doi.org/10.1038/s44358-025-00064-7.
Tanneberger, F., & Belous, T. (2017). The peatland map of Europe. Mires and Peat, 19, 1–17. https://doi.org/10.19189/MaP.2016.OMB.264.
Terzano, D., Trezza, F. R., Rezende, M., Malatesta, L., Yan, S. L. S., Parish, F., & Attorre, F. (2023). Prioritization of peatland restoration and conservation interventions in Sumatra, Kalimantan and Papua. Journal for Nature Conservation, 73, 126388. https://doi.org/10.1016/j.jnc.2023.126388.
Tyukavina, A., Potapov, P., Hansen, M. C., Pickens, A. H., Stehman, S. V., Turubanova, S., Parker, D., Zalles, V., Lima, A., Kommareddy, I., Song, X.-P., Wang, L., & Harris, N. (2022). Global trends of forest loss due to fire from 2001 to 2019. Frontiers in Remote Sensing, 3, 825190. https://doi.org/10.3389/frsen.2022.825190.
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. https://doi.org/10.59117/20.500.11822/41222.
Varkkey, H., Ashfold, M., Anshari, G., & Lechner, A. M. (2024). Mitigating carbon emissions and haze in Southeast Asia's peatlands: Opportunities and challenges in integrating policy and governance. ISEAS–Yusof Ishak Institute. https://www.iseas.edu.sg/articles-commentaries/trends-in-southeast-asia/mitigating-carbon-emissions-and-haze-in-southeast-asias-peatlands/.
Varkkey, H., Ashfold, M. J., Anshari, G. Z., Lechner, A. M., Seah, S., Alkaf, F. T., & Wijayanti, N. (forthcoming). Participatory Methods to Inform Policy and Governance in Southeat Asia's Peatlands, in D. Miteva (Ed.), Research Handbook for Ecosystem Services. Edward Elgar Publishing.
Wahyunto, S. I., & Suryadiputra, I. N. N. (2008). Peatland distribution in Sumatra and Kalimantan: Explanation of its data sets including source of information, data constraints, and gaps. Wetlands International–Indonesia Programme.
Wahyunto, Suparto, B., Heryanto, B., & Bekti, H. (2006). Sebaran lahan gambut, luas dan cadangan C bawah permukaan di Papua (Peatland distribution, area extent, and C stock of peat in Papua). Wetlands International–Indonesia Programme.
Wahyunto, R. S., & Suparto, S. H. (2004). Maps of area of peatland distribution and carbon content in Kalimantan, 2000–2002. Wetlands International–Indonesia Programme and Wildlife Habitat Canada.
Wahyunto, S., Ritung, S., Suparto, & Subagjo, H. (2003). Map of peatland distribution and its C content in Sumatera. Wetlands International–Indonesia Programme and Wildlife Habitat Canada.
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.
Xu, Y., et al. (2020). Annual oil palm plantation maps in Malaysia and Indonesia from 2001 to 2016. Earth System Science Data, 12, 847–867. https://doi.org/10.5194/essd-12-847-2020.
Yule, C. M. (2010). Loss of biodiversity and ecosystem functioning in Indo-Malayan peat swamp forests. Biodiversity and Conservation, 19(2), 393–409. https://doi.org/10.1007/s10531-008-9510-5.