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Refining greenhouse gas emission factors for Indonesian peatlands and mangroves to meet ambitious climate targets

Daniel Murdiyarso[a,b,1], Erin Swails[a], Kristell Hergoualc'h[a,c], Rupesh Bhomia[a], and Sigit D. Sasmito[a,d,e]

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For countries' emission-reduction efforts under the Paris Agreement to be effective, baseline emission/removals levels and reporting must be as transparent and accurate as possible. For Indonesia, which holds among the largest area of tropical peatlands and mangrove forest in the world, it is particularly important for these high-carbon ecosystems to produce high-accuracy greenhouse gas inventory and to improve national forest reference emissions level/forest reference level. Here, we highlight the opportunity for refining greenhouse gas emission factors (EF) of peatlands and mangroves and describe scientific challenges to support climate policy processes in Indonesia, where 55 to 59% of national emission reduction targets by 2030 depend on mitigation in Forestry and Other Land Use. Based on the stock-difference and flux change approaches, we examine higher-tier EF for drained and rewetted peatland, peatland fires, mangrove conversions, and mangrove on peatland to improve future greenhouse gas flux reporting in Indonesia. We suggest that these refinements will be essential to support Indonesia in achieving Forest and Other Land Use net sink by 2030 and net zero emissions targets by 2060 or earlier.

Nationally Determined Contributions | IPCC | nature-based climate solution | REDD+ | UNFCCC

Significance

The provision of evidence-based and high accuracy greenhouse gas inventories in wetlands could enhance confidence in climate finance schemes. This will eventually lead to best practices in nature-based climate solutions as uncertainties in greenhouse gas emission reduction estimates will be greatly reduced. In practical terms, the development of forest reference emissions level/forest reference level by which climate change mitigation actions are evaluated will be greatly improved. We propose high tiers and refined emission factors for drained peatlands, rewetted peatlands, converted mangroves, and mangrove on peatland for Indonesia. It is expected that concerned stakeholders will have a common credible reference in managing projects and programs in reducing emissions from wetlands and enhancing removals of greenhouse gases from the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) produced Guidelines for Greenhouse Gases (GHG) Inventories (1), within which peatland and mangrove ecosystems were included in the Agriculture Forestry and Other Land Use section of wetlands. Peatland and mangrove are among carbon-dense ecosystems and known as major long-term natural carbon sinks (2) and yet facing tremendous pressure from human activities (3, 4). Given the significant portion of wetlands' contribution to GHG emissions/removals, the Subsidiary Body on Scientific and Technological Advice of the United Nations Framework Convention on Climate Change (UNFCCC) requested the IPCC to establish special guidelines for wetlands GHG inventory. The 2013 IPCC Supplement to the 2006 IPCC Guidelines for GHG Inventory: Wetlands was subsequently published (5), in which peatland and mangrove are, respectively, categorized under organic soils and coastal wetlands.

Among the most important information needed by countries to conduct GHG inventories following IPCC Guidelines are the emission factors (EF) and activity data (AD) associated with human activities. These include draining, conversion, and rewetting of peatlands, while in mangrove, the activities include drainage, extraction, and rewetting. The GHG involved are CO_2 and non-CO_2 gases such as CH_4 and N_2O from human-induced fires and agriculture fertilization. The AD are expressed as the area involved in those activities (per unit area). To ensure the quality and comparability of national GHG inventory reports among countries, all reports submitted to the UNFCCC require adherence to five reporting principles: transparency, accuracy, comparability, consistency, and completeness (TACCC) (1). Therefore, high-quality GHG inventories that follow the TACCC principles may remain challenging for highly spatial and temporal dynamics of peatland and mangrove ecosystems.

As stipulated in the 2016 Cancun Agreement (UNFCCC Conference of Parties Decision 1/CP.16), forest reference emission level (FREL) and/or forest reference level (FRL) may be developed at the national and subnational levels. Therefore, the availability of high-resolution (tiers) EF and AD is crucial for land use, land-use change, and forestry activities, commonly known as the land sector. The development of FRL has been adopted to be the formal modality including for reducing emissions from deforestation and forest degradation (REDD+) mechanism (UNFCCC Conference of Parties Decision 12/CP.17 and Decision 13/CP.19). It is differentiated from the FREL which does not take into account carbon stocks enhancement through sustainable forest management.

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[1]To whom correspondence may be addressed. Email: d.murdiyarso@cifor-icraf.org.

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As one of the UNFCCC parties, Indonesia aims to reduce by 31.89% its national emissions and by 43.20% with international support by 2030. Achieving this ambitious target will require a major contribution from the land sector. This sector alone accounted for 49% of national emissions in 2010, the largest contribution compared to other sectors. While the Indonesian first FREL submitted to the UNFCCC is a laudable first effort (6), areas for technical improvement suggested by UNFCCC reviewers encompassed inclusion of peatland fires, emissions of non-CO_2 gases, and emissions following mangrove soil extraction. Emissions from peatland fires, which accounted for 27% of national emissions in 2014, emissions of non-CO_2 from drained peatlands, and oxidation of excavated mangrove soil have to be considered in the GHG inventory and reporting (6). In addition to the already adopted EF, Indonesia used its own AD derived from high-resolution land cover dynamics for important land cover categories.

High-tier EF are expected by countries like Indonesia, which holds an outsize proportion of the world's carbon-rich wetland ecosystems, including 14% of tropical peatlands (7) and 22% of global mangrove area (8). The numbers are not only relevant for the Indonesian national GHG inventory but also for the development of baseline of any kind of climate change mitigation actions that have to be based on credible and scientifically sound measurement, reporting, and verification (MRV) system. Two generic approaches are available for assessing carbon emissions of land use and land-use change, namely the carbon stock difference and the gain–loss methods (1). The carbon stock difference approach estimates the emissions by quantifying the change in ecosystem carbon stocks over time or between land uses. The gain–loss or flux change approach requires the annual rates of biomass accumulation from growth and losses associated with harvest and burning and the annual transfer into and out of dead organic matter and soil carbon pools (9). Following the 2013 IPCC Wetlands Supplement, it is good practice to apply the gain–loss approach for calculating GHG emissions/removals in organic soils such as peatland, while carbon stocks difference may be applied for mineral soils. However, the scientific challenge remains for mangrove ecosystem where some mangroves are reported to be overlapped with or contain organic soils (5).

Here, we highlight the opportunity for incorporating high-carbon ecosystems such as peatland and mangrove into GHG inventory as well as their scientific challenges in refining their EF to support climate policy processes in Indonesia where 55 to 59% of national emissions reduction targets rely on Forestry and Other Land Use (FOLU) sector mitigation. We first identified the area distribution of peatland and mangrove, and mangrove on peatland—a unique combination of two wetland ecosystems located at the same landscape and yet understudied—at the national and subnational levels. Second, we outlined the scientific gaps to improve EF for peatland (e.g., drained and rewetted peatlands and peat fires) and mangrove (e.g., deforestation, excavation, restoration). We further discussed the suitable EF and approach for mangrove on peatland and highlight the mitigation potentials provided by this unique ecosystem. By refining GHG EF for peatland and mangrove ecosystems, this assessment will be essential and directly relevant to support Indonesia's climate policy processes ahead of FOLU net sink by 2030 and net zero emissions targets by 2060 or earlier as outlined in the 2022 Enhanced Nationally Determined Contributions (10).

Results

Indonesia's Peatland and Mangrove Distributions. Housing more than 13.4 Mha of tropical peatlands (11) and nearly 3 Mha of mangrove (12), Indonesia may be considered as the wetland's powerhouse in the tropics (Fig. 1). Managing approximately 31.2 Gt of carbon of their combined peatland (28.1 GtC, ref. 13) and mangrove (3.1 GtC, ref. 14) could be significant contributions to mitigate GHG emissions, which currently is growing at an annual rate of 1.8 Gt CO_2 in 2019 of which FOLU sector contributed as much as 50.13% (10). While deforestation on peatland (peat swamp forest) and mangrove in Indonesia has slowed over the past two decades, the rates remain high with 225,000 and 7,436 ha y^{-1} for peatland and mangrove, respectively (15, 16). Therefore, avoiding more conversion and restoring these high-carbon wetland ecosystems is a significant contribution to climate change mitigation targets in Indonesia.

Summarizing peatland, mangrove, and mangrove on peatland areas across provinces in Indonesia is important for implementing mitigation actions at the subnational level. For example, identified top 10 largest total peatland and mangrove area provinces should be eligible and prioritized for jurisdictional REDD+ projects (Fig. 1). The top 10 provinces that have a minimum of 334,000 ha of combined peatland and mangrove area are Riau (22% of total national peatland and mangrove areas), Papua (19%), Central Kalimantan (16%), West Kalimantan (10%), South Sumatra (8%), West Papua (7%), Jambi (3%), East Kalimantan (2%), North Kalimantan (2%), and North Sumatra (2%) (Fig. 1). To meet the ultimate goal of emission reduction, the FREL/FRL at the national and subnational levels should be tailored in such a way to address the drivers of deforestation (5), such as agricultural development, oil palm and forest plantations for peatland, and aquaculture and agriculture for mangrove (detailed deforestation drivers on Indonesian peatland and mangrove are described in *SI Appendix*, Fig. S1).

Mangroves being peatlands in Indonesia are approximately 311,456 ha and account for 10% of the total mangrove area (Fig. 1). This unique type of wetland is mainly distributed across West Papua (74%), Papua (13%), and Riau (8%) provinces. Although mangrove and peatland coexistence was less described in the previous literature, mangrove carbon stocks across landscapes in West Papua and Papua are extremely high with more than 1,500 Mg C ha^{-1} refs. 14 and 18, or similar with carbon stocks of secondary peat swamp forests (PSF) in Central Kalimantan (19). Large carbon stocks are especially stored by mangroves located within estuarine interior hydrogeomorphic setting, where mean soil carbon content is more than 12% and this fall within organic soil definition following 2013 IPCC Wetlands Supplement (5) (see *SI Appendix*, Fig. S2 for detailed organic rich soil core obtained from Bintuni Bay, West Papua). Consequently, GHG inventory and emissions calculation of this mangrove type should be treated under organic soils rather than coastal wetlands category, in which gain–loss approach is encouraged rather than carbon stock different approach (5).

EF for Drained Peatlands. While the carbon stock difference approach is commonly used for mineral soils, it is deemed inappropriate for organic soils, including peatlands, for several reasons. First, the carbon concentration of peat soils does not necessarily decrease with depth, implying that observations of carbon stock changes should be performed over the full soil profile which can represent a major challenge. Second, peatlands typically exhibit an extreme belowground spatial variability, with peat varying up to 6 m in depth within a 5 km distance and peat substratum alternating between valleys and mounds (20). Application of the stock difference method in organic soils can therefore lead to erroneous conclusions, like an increase of soil carbon stocks following forest conversion to another land use known to stimulate carbon losses (Fig. 2*A*).

The 2013 IPCC wetlands supplement provides guidance for assessing change in soil carbon stock from on-site carbon

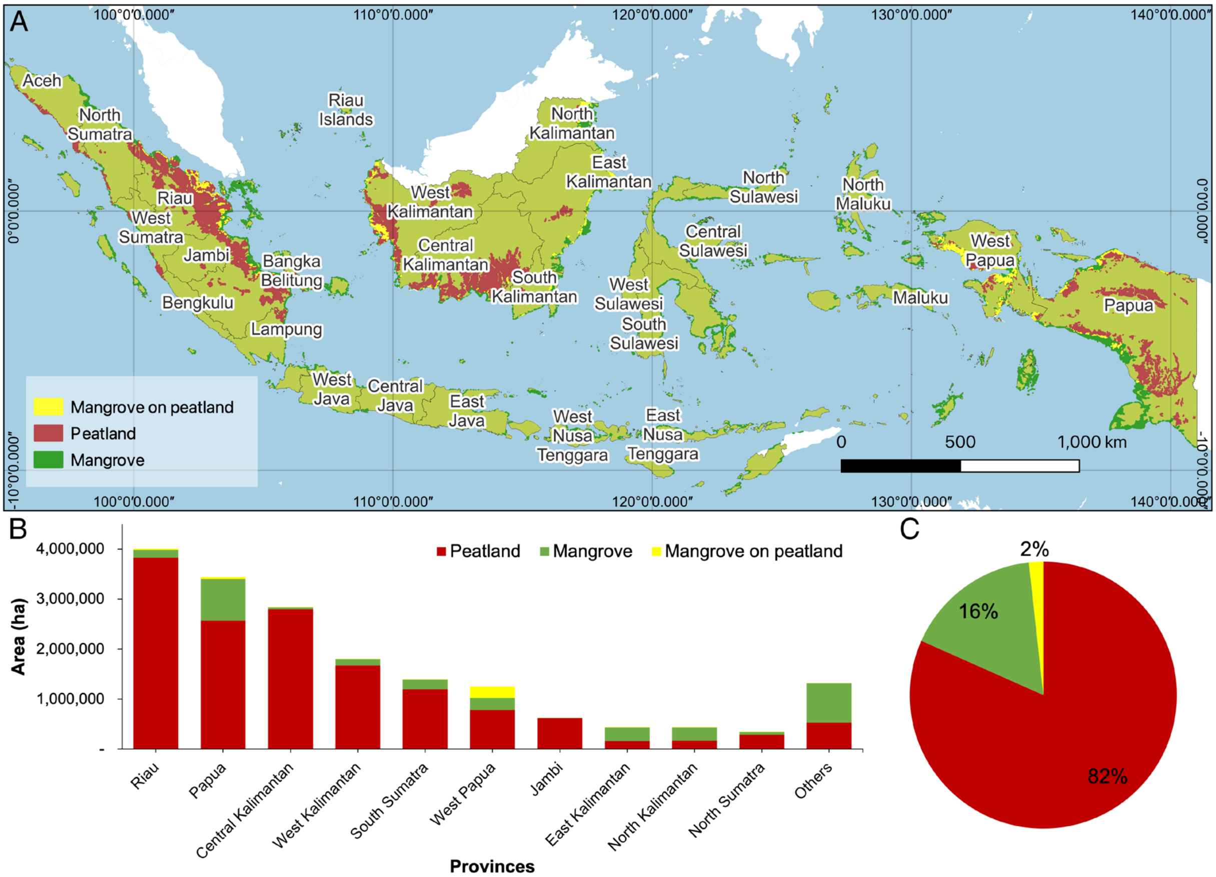


Fig. 1. (*A*) The geographical location of peatland (red), mangrove (green), and mangrove overlapping peatland (yellow) across Indonesian provinces. The bottom panel shows (*B*) the area extent of each peatland, mangrove, and mangrove overlapping peatland by province and (*C*) by national proportion. Peatland and mangrove data were, respectively, adopted from refs. 7 and 12. Administrative boundary base map was adopted from ref. 17.

emissions/removals of the soil from mineralization and sequestration processes, off-site emissions from leached carbon from the soil and anthropogenic peat fires (5) (Fig. 2*B*). Carbon loss from mineralization, also called heterotrophic soil respiration, represents only a fraction of total soil respiration which also includes root respiration. Since most measurements in tropical peatlands focus on total soil respiration, carbon mineralization is often derived by applying a ratio to total soil respiration rates. This ratio is known to vary greatly according to the land cover (24, 25). Carbon sequestration in peat soil occurs through the decomposition of

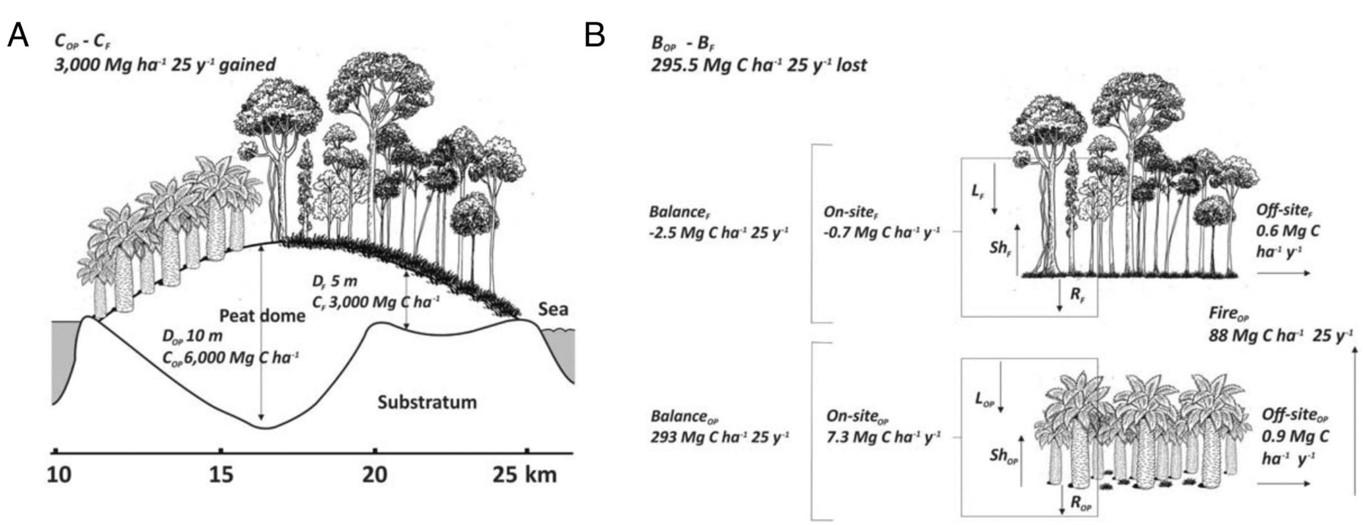


Fig. 2. Peat carbon stock in an oil palm plantation (COP) and a peat swamp forest (CF) and respective peat depth (DOP, DF) (*A*). The C stock difference method (COP—CF) which is inappropriate for organic soils suggests the erroneous conclusion that forest to oil palm conversion leads to a gain of 3,000 Mg C ha1 over 25 y. On-site, off-site, and fire C removals/emissions and their balance over 25 y in a peat swamp forest and an oil palm plantation (*B*). The flux difference method (BOP—BF) indicates a loss of 295.5 Mg C ha1 over 25 y. In (*A*), a soil C content of 40% and bulk density of 0.15 g cm^{-3} were considered, and the peat dome profile is from ref. 20. In (*B*), C fluxes were taken from ref. 21, except for the prescribed fire which is the IPCC default (5). L: litterfall, R: root mortality, Sh: heterotrophic soil respiration. The oil palm plantation and forest illustrations are from refs. 22 and 23, respectively.

above and belowground litter inputs, of which rates have been seldom studied in the tropics, especially root mortality rates.

In its 2022 FRL, Indonesia considered on-site and peat fire carbon emissions but disregarded off-site losses (26). Instead of relying on IPCC Tier 1 defaults as in its 2016 FREL (6), the country used Tier 2 values for the second submission. The on-site EF per land-use class were adopted from a literature review on total and heterotrophic soil respiration (27). Regrettably, this paper omitted reviewing litter carbon inputs; therefore, the EF proposed are biased and not computed in agreement with the IPCC guidelines. An additional problem with these EF is the use of a constant value of 78% to compute heterotrophic contribution to total soil respiration from total soil respiration rates despite the well-known influence on the ratio of the land cover type. The resulting Tier 2 EF for the classes secondary forest, dry shrub, and wet shrub are far higher than the IPCC defaults used in the 2016 FREL (*SI Appendix*, Table S1). The implications are significant given that 91% of the 122,254 ha annual peat deforestation between 2006/2007 and 2019/2020 occurred in secondary forests, and 28% of the peat deforested area was converted to wet shrub (33,874 ha y^{-1}) (26).

The EF for organic soils can be improved by considering various elements and incorporating additional data and methods. Field measurements of soil heterotrophic respiration rates and litter inputs, particularly root dynamics, are necessary for enhancing the accuracy of estimates for key land uses like secondary/degraded forests, estate crops (notably oil palm plantations), forest plantations, and wet shrubs. In addition, data collection in mountain peatlands is essential since all research up to date has been conducted in lowland areas. Indonesia potentially holds a significant extent of peatlands in its mountains, for instance, in Sumatra or Papua, and there is evidence that degradation and conversion has also taken place in these areas (28). Like in other regions of the world, mountain peatlands may differ substantially from lowland peatlands, notably in their nutrient status which is typically richer than that of ombrotrophic bogs that dominate lowland peatlands of Indonesia. The nutrient status of organic soils can influence to a great extent carbon and nitrogen decomposition rates and emissions.

Considering temporal variation of emissions can also support a more accurate accounting of GHG. For example, ref. 29 found that the peat on-site CO_2 emission factor decreased over the rotation of an oil palm plantation. Conversely, the N_2O emission factor from peat decomposition and fertilizer-induced N_2O emissions increased over time (Fig. 3). These authors propose using decadal averages for these EF rather than a constant value.

Since drainage status significantly affects carbon and nitrogen dynamics and emissions, incorporating it in AD and EF could substantially improve national peat GHG estimates. Existing EF for degraded and converted lands, either IPCC defaults or Indonesian Tier 2 values, were developed from data collected in drained lands. Therefore, undrained areas like some secondary forests are being assigned emission rates of drained lands. Finally, building national technical capacities will be essential to support the collection of high-quality data and integrate these into computations following the appropriate methods recommended by the IPCC.

EF for Undrained Degraded and Rewetted Peatlands. Refined EF for undrained degraded PSF and rewetted peatlands are urgently needed to increase GHG inventory accuracy and support peatland restoration in Indonesia. A study in undrained secondary and primary PSF in Kalimantan (21) suggested that degradation without drainage enhanced CO_2 and N_2O fluxes from peat mineralization in the secondary PSF compared to undegraded conditions. Onsite CO_2 emissions from peat decomposition at

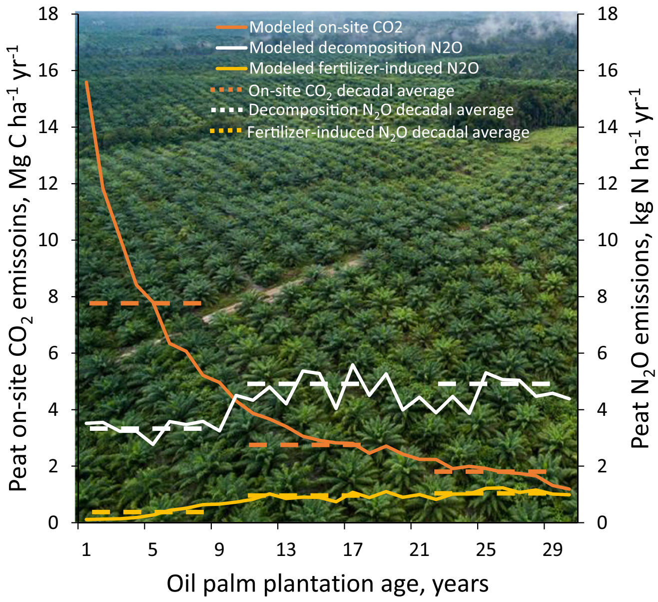


Fig. 3. Modeled annual and decadal average peat CO_2 on-site emissions (difference between carbon inputs from litterfall and root mortality and carbon outputs from soil heterotrophic respiration), N_2O emissions stemming from peat decomposition, and fertilizer-induced N_2O emissions in oil palm plantations on peat. Carbon vegetation dynamics and greenhouse gas emissions were simulated over 30 y in three plantations of Central Kalimantan, Indonesia using the DeNitrification DeComposition model. Please note differences in primary (for CO_2 emissions) and secondary (for N_2O) axis units.

the degraded site (4.6 Mg CO_2 ha^{-1} y^{-1}) (21) were 87% of the IPCC defaults for drained organic soils. The limited available measurements in rewetted Indonesian PSF indicate the mean heterotrophic respiration rate (24.8 ± 2.6 Mg CO_2 ha^{-1} y^{-1}, n = 3) comparable to the degraded undrained Kalimantan PSF (30.1 ± 2.6 Mg CO_2 ha^{-1} y^{-1}) (21). By contrast, with 20 y global warming potential substantial differences, peat CH_4 emissions were observed in paired rewetted (−0.1 ± 0.0 Mg CO_2 equivalent ha^{-1} y^{-1}) and undrained degraded PSF (6.4 ± 0.0 Mg CO_2 equivalent ha^{-1} y^{-1}) in Kalimantan, though heterotrophic respiration rates were similar at the two sites (15.0 ± 0.0 and 14.7 ± 0.7 Mg CO_2 ha^{-1} y^{-1} in rewetted and undrained PSF, respectively) (30). Peat GHG emissions at these sites are influenced by variables such as water table level, soil moisture, and soil temperature, in addition to soil chemistry and previous land use. It is likely that several decades are required for rewetted peatlands to display peat GHG uptake and emissions similar to undrained sites. While onsite CO_2 emissions from rewetted peat are likely not zero, as indicated in the 2013 IPCC Supplement, increased information on C inputs from aboveground and root litter in addition to measurements of C outputs from heterotrophic respiration to determine onsite CO_2 EF for rewetted as well as undrained degraded peatlands. Additionally, the impact of degradation without drainage and rewetting of drained peatlands on dissolved organic carbon export is highly uncertain. Measurements of CH_4 and N_2O are also scarce and critically needed to generate robust EF for non-CO_2 emissions from undrained degraded and rewetted peatlands in Indonesia. Table 1 shows CO_2 emissions from different land-use, peat depth, and ground water table.

Emissions from Peatland Fires. Understanding the nature of peat fires and quantifying their emissions are crucial for assessing their contribution to national and global GHG budgets. In Indonesia, peat fires are a key category in the 2022 FRL with 41.1 ± 2.7 thousand hectares of peat forest burnt per year between 2006/2007

Table 1. Varying EF from rewetted/drained versus drained peatland derived from measurement of total respiration in converted peat swamp forest in Indonesia (modified from ref. 30)

	Rewetted/Undrained		Drained	
Land cover	Ground water table/ peat depth (cm)	CO_2 emission ($Mg\ CO_2\ ha^{-1}\ y^{-1}$) (Mean ± SD)	CO_2 emission ($Mg\ CO_2\ ha^{-1}\ y^{-1}$) (Mean ± SD)	Peat depth (cm)
Shrubland	43/520	52.4 ± 4.1	80.77 ± 17.40	360
Oil palm (1 to 4 y)	60/200	8.13 ± 5.73	43.3 ± 1.5	46
Secondary forest	30/300	33.98 ± 11.54	43.4 ± 2.1	380

and 2019/2020 releasing 20.9 Tg CO_2e annually solely from the soil (26). The vast majority of these deforestation peat fires occur in secondary PSF (93%).

Following the IPCC guidelines (5), emissions from fires on drained peat are calculated based on several components including the area burnt, the mass of peat available for combustion (i.e., mass burnt), a combustion completeness factor, and EF for CO_2, CO, and CH_4. The mass of peat burnt is expected to vary according to the nature of the fire, either wildfire or prescribed fire (5), and depends on the depth of peat burnt and its bulk density. Peat burn depth is highly variable spatially (31, 32) and temporally (31), and this variability contributes greatly to uncertainty in estimates of emissions from peat fires (33). Combustion completeness refers to the degree to which the peat fuel is consumed during the fire and is influenced by peat properties notably its moisture content and fire intensity.

The IPCC Tier 1 combustion factor is set at 1, with the assumption that all fuel is combusted. Peat ignition and the quantity of organic matter consumed by fires in tropical peatlands are influenced by a number of factors including peat decomposition status (34) and peat moisture (35) which are themselves closely related to management and climate. For instance, ref. 34 observed that the fuel consumption was greater in sapric (highly decomposed) than hemic (less decomposed) tropical peat, with no consumption of fibric (least decomposed) peat. Peat moisture content plays a critical role in the combustion and emission processes with drier peatlands being more prone to intense smoldering combustion. The mass of peat burnt should be computed from studies which monitored concomitantly peat burn depth and bulk density instead of combining a regional average bulk density with on-site peat burn depth measurements which may result in inaccurate estimates (e.g., ref. 36).

However, such studies are scarce, with three for each type of fire (wildfires, prescribed fires) (31, 32, 34, 37–39) and geographically limited (Central Kalimantan and Jambi and Riau in Sumatra). GHG EF allow determination of the mass of CO_2, CO, and CH_4 emitted per unit mass of peat combusted. CO which is a very weak direct greenhouse gas is typically excluded from GHG inventories. The IPCC default EF for CO_2 and CH_4 for tropical peat is based on one study by ref. 40. Since then, nine additional studies have been published for the tropics (e.g., ref. 41); however, geographic representation is limited to the islands of Kalimantan and Sumatra.

In its 2022 FRL, Indonesia adopted a combustion factor of 0.54 following findings by ref. 42 (*SI Appendix*, Table S2). This combustion factor is the average of values measured in three secondary forests of Central Kalimantan by comparing mass of peat after fires to a primary forest reference site over a range of 10 to 40 cm peat depth. The FRL approach for computation of peat mass burnt used a single average burn depth regardless of fire type and a single average bulk density from various land uses and unrelated to fire activity. The lack of disaggregation by fire category is due to the absence of related fire AD. Given intersite variability in burn depth and bulk density the approach employed increases peat mass burnt uncertainty. Furthermore, given that the FRL assesses forest fires, values from other land uses should be discarded. The Tier 2 EF for CO_2 and CH_4 incorporate latest data not included in the IPCC Wetland Supplement which are based on measurements in *Acacia* plantations, primary and secondary forests, and fern and scrub dominated peatlands, predominantly located on the island of Kalimantan. Inclusion of new data supported a more robust emission factor for CH_4 (*SI Appendix*, Table S2).

Improving factors that influence fire emissions entails collecting additional data, enhancing methodological aspects, and getting a better understanding of fire behavior. Concomitant measurements of burn depth and soil bulk density are needed across different geographies and forest conditions (especially secondary drained and undrained forests) to refine estimates of peat mass burnt and reduce their uncertainty (43). In addition, fire frequency has been observed to significantly impact the burnt depth (31), the peat bulk density and its carbon content (33). The more often the area burns the less deep it burns, the more compact it becomes with higher C concentrations. Since moisture is a key factor influencing combustion, there is a strong interdependence between burnt depth and distance to drainage canals (31); a factor which could also be included in fire monitoring. Combustion completeness data are critically lacking and should be investigated according to soil moisture, water table depth, or distance to drainage canals (43). Higher tier reporting could also consider variation in fire intensity with different proportions of smoldering versus flaming combustion (5). Finally, efforts to refine peat fire EF for Indonesia should strategically focus on secondary forests where most peat forest fires occur.

EF for Mangrove Deforestation, Conversion, and Restoration. While it is clear that peatland is considered as organic soils category according to the 2013 IPCC Wetlands Supplement, mangrove forest is considered as coastal wetlands category. However, 2013 IPCC Wetlands Supplement also suggested that particularly soil carbon EF for mangrove can be considered as mineral or organic soils. Therefore, refining mangrove EF requires careful assessment of soil organic carbon content, with further implication and requirement of the use of gain–loss approach instead of stock-different approach for mangrove forests with organic soils (further section describing EF for mangrove on peatland is provided). This precaution is particularly important not only to improve EF accuracy and credibility between mineral and organic soils, but also provide challenges to derive high accuracy of AD due to limited approach to spatially differentiate which mangroves contain mineral or organic soils. One of the proxies that can be used to solve this issue is by considering hydrogeomorphic setting dataset, where estuarine interior mangroves are commonly have high soil carbon content compared to other mangrove settings such as open coast and fringe (18).

In the FREL 2016 (6) and FRL 2022 (26), GHG emissions following mangrove deforestation were calculated by using Tier 2 above- and below-ground biomass covering variation of Indonesia's main islands and mangrove stratification classes, namely primary and secondary mangrove forests. While variation of biomass carbon stocks between islands are well documented through the extensive database of National Forest Inventory (NFI) combined with independent assessments obtained from literature, the EF of primary and secondary mangrove classes stratification remains inconsistent. For example, some of the NFI data show greater biomass carbon stocks at secondary compared to primary mangroves at almost across all islands except Papua and Sumatra (26). This inconsistency may be due to different assessment time between EF and AD data collection, in which EF is always time sensitive as mangroves are deforested, converted, and regenerated (44). Further improvement to minimize mangrove stratification bias should be refined through the incorporation of hydrogeomorphic settings, where spatial variation of macroecology mangrove structure and carbon sinks are greatly driven coastal hydrogeomorphic processes (18, 45–47).

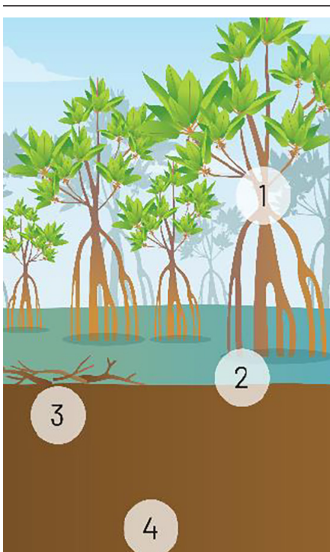
In the Indonesian FREL 2016 (6), GHG emissions from mangroves were calculated using defaults EF from the 2006 IPCC Guidelines, and soil carbon was not accounted as a pool. However, in the FRL 2022 (26), loss of soil carbon was accounted for mangrove conversion into fishponds with an emission factor of 90.06 Mg CO_2-eq ha^{-1} based on field measurements done in the Mahakam Delta (48). However, the depth of soil excavation was not clearly described despite the study mentioned that the mass difference between mangrove and fishpond in the original study was approximately 1 m (48). Clarifying excavated soil depth is crucial to calculate GHG emissions following mangrove conversion to aquaculture ponds. It is described in the 2013 Wetlands Supplement that soil excavation can vary between 0.5 and 2.5 m, and top 1 m soil carbon for both mineral and organic soils in mangrove is normally more than 200 MgC ha^{-1} (see Table 2 for carbon stocks comparison between carbon pools across land uses). Given the aquaculture land use type is among top (48%) mangrove loss drivers in Indonesia (*SI Appendix*, Fig. S1) (49), the availability of soil excavation depth data is critical in the future update and significant to improve GHG inventory credibility.

Regenerated mangrove was included in the FRL 2022 (26), and carbon removal was the product of biomass carbon stocks and area of transition from nonforest to forests with annual regenerated primary mangrove forest alone was 2,247 ha. While rates of biomass carbon stocks recovery are strongly controlled by time since regeneration, it is unclear whether carbon removals following mangrove regeneration were calculated by using carbon stock difference or loss–gain approach. For example, it is clear that mangrove biomass carbon stocks are increased from 0 to 25 y following regeneration growth curve with rates of 3.6 to 7.0 MgC ha^{-1} y^{-1} (18, 51). Future FREL/FRL improvement for mangrove biomass carbon stocks enhancement should be focused on the incorporation of annual biomass growth, in which multiple assessments have been done from West Papua province (18, 51, 52). Therefore, carbon removals through carbon stocks enhancement may be appropriate to be calculated by using carbon stocks difference if only annual biomass growth and ages of regenerated mangroves are known.

Following the 2013 IPCC Supplement, we proposed that higher tiers of mangrove EF should be determined based on the trajectory of coastal land-use change. Fig. 4 shows the possible starting points of intervention that are categorized into two clusters, degrading and restoring. Programs and project attempt to reverse degrading trajectory and at the same time to enhance the restoring trajectory. Each management regime have its unique benefits and costs depending on the objectives that the managers are trying to achieve.

While pressure from land-use change is rampant and the overall carbon dynamic occurs in biomass, soil carbon pool usually remains stable if soil excavation does not take place (51). Unlike the rest of

Table 2. Comparison of ① aboveground biomass carbon (AGBC), ② belowground biomass carbon (BGBC), ③ dead organic matter (DOM), and ④ soil organic carbon (SOC) from the IPCC default values (5) and most recent measurements in Indonesia involving four different activities or land uses (49)



	IPCC default value	Undisturbed mangrove	Regenerated mangrove	Degraded mangrove	Aquaculture (fishpond)
	94.1 (4.3-188) [187, 204]	101.67 (4.79) [92, 111]	58.06 (8.17) [41, 75]	20.98 (6.05) [7, 35]	11.01 (3.86) [2, 20]
	46.1 (2.1-92.4)	28.70 (1.65) [25, 32]	15.80 (3.77) [8, 24]	6.01 (1.43) [2, 10]	2.64 (1.30) [−0.5, 6]
	10.7 [7, 15]	14.47 (1.22) [12, 17]	13.49 (2.52) [8, 19]	24.34 (6.67) [8, 41]	3.39 (2.72) [−31, 38]
	286 (55-1376) [247, 330]	258.44 (32.40) [193, 324]	296.41 (20.11) [255, 338]	215.66 (38.07) [133, 299]	259.08 (90.53) [26, 492]

All units are in Mg C ha^{-1}. Note: Numbers in brackets are range of the IPCC default values and the SEs for other columns; numbers in square brackets are the 95% CIs.

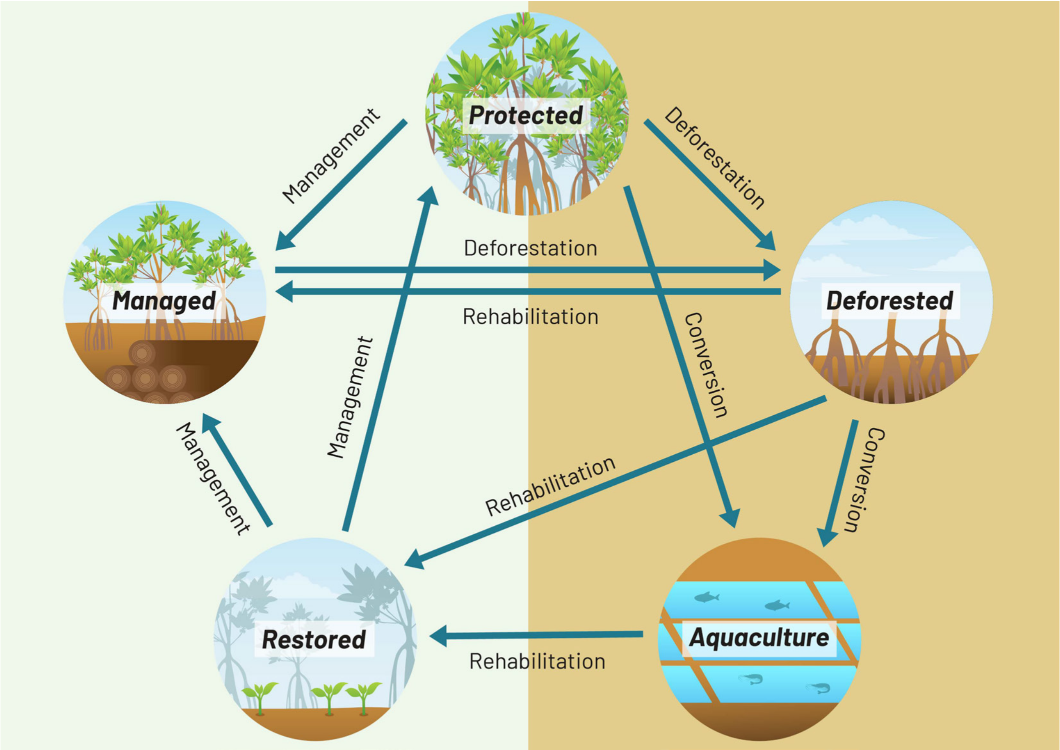


Fig. 4. Trajectories of mangrove land-use change. The circles signify the current use with different management regimes and arrows indicate the direction of change. The brown shaded area represents degrading phase or depleted carbon stocks, and the green-shaded area represents restoring phase or enhanced carbon stocks.

terrestrial forests, mangrove forests and coastal blue carbon ecosystems experience wide tidal range and provide other ecosystem services co-benefits, particularly in coping with sea level rise (53). At the same time, carbon burial in the sediment also takes place allowing soil carbon pool to replenish (51, 54, 55). The complexity of carbon fluxes direction in coastal ecosystems may create complication as well as refinement opportunities for GHG emissions and removals calculation under the gain–loss approach.

Natural inundation and drainage in the intertidal zones also affect the release and removal of GHG particularly for non-CO_2 gases such as methane and nitrous oxide (56), and therefore, the gain–loss approach may be offered to estimate long-term dynamic of GHG fluxes and particularly for mangroves that contain organic soils. Table 3 shows the summary of soil carbon burial and GHG fluxes obtained from mangroves and other land uses across Indonesia that can be used for GHG emissions/removals calculation by using the gain–loss approach. The use of gain-loss approach may be the alternative in the absent of carbon stocks data in the country or any mitigation projects and reporting.

Mangrove on Peatland Distribution and Their EF. Approximately two-third of mangrove on peatland in Indonesia are distributed across estuarine interior mangrove setting in Bintuni Bay, Teminabuan, Arguni Bay, and Etna Bay of West Papua province (Fig. 5*A*). While

Table 3. Greenhouse gas fluxes and soil carbon burial across Indonesian mangrove ecosystems under different management regimes

Carbon fluxes	Unit	Mean	n	SE	95% CI
Aquaculture					
Soil CO_2 effluxes	Mg CO_2 ha^{-1} y^{-1}	23.81	30	1.40	−0.40 to 48.02
Soil CH_4 effluxes	Mg CO_2 ha^{-1} y^{-1}	2.02	20	0.68	−1.11 to 5.16
Degraded mangrove					
Soil CH_4 effluxes	Mg CO_2 ha^{-1} y^{-1}	4.18	3	0.73	−0.63 to 8.99
Soil carbon burial	Mg C ha^{-1} y^{-1}	1.22	na	na	0.39 to 2.05
Regenerated mangrove					
Soil CO_2 effluxes	Mg CO_2 ha^{-1} y^{-1}	13.49	na	na	2.39 to 24.6
Soil carbon burial	Mg C ha^{-1} y^{-1}	1.67	8	0.35	0.87 to 2.46
Undisturbed mangrove					
Soil CO_2 effluxes	Mg CO_2 ha^{-1} y^{-1}	7.87	7	4.54	5.00 to 10.74
Soil CH_4 effluxes	Mg CO_2 ha^{-1} y^{-1}	0.98	na	na	−0.44 to 2.4
Soil N_2O effluxes	kg CO_2 ha^{-1} y^{-1}	−0.12	na	na	−0.48 to 0.25
Soil carbon burial	Mg C ha^{-1} y^{-1}	3.20	5	0.29	−2.28 to 8.69

Note: na= data are not available.

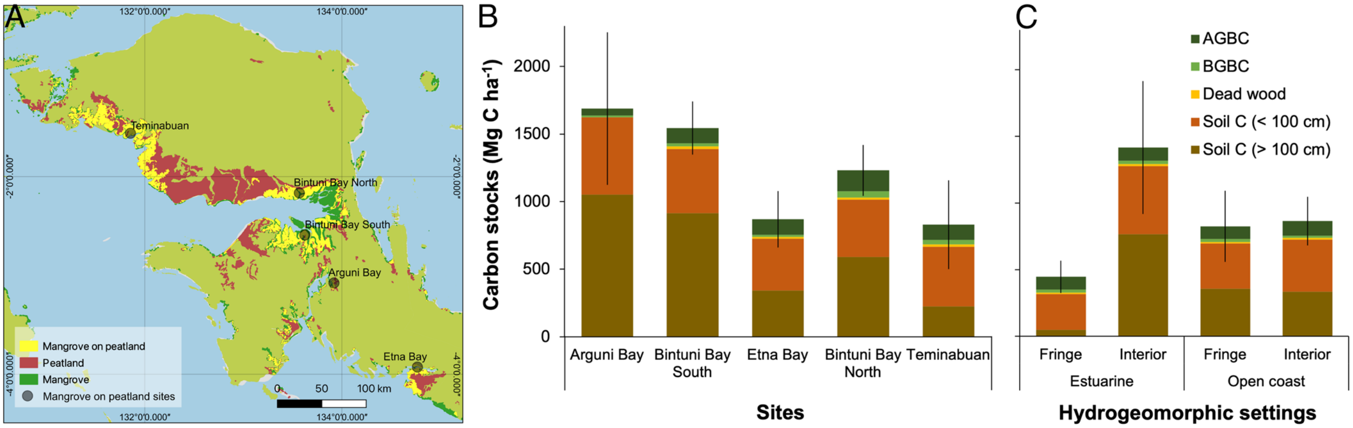


Fig. 5. (*A*) The distribution of mangrove on peatland in West Papua province and (*B* and *C*) their respective carbon stocks. Carbon stocks data were adopted from refs. 18 and 51.

mangrove provides much more direct ecosystem service cobenefits to the local communities compared to peatland, mangroves on peatlands such as in this region will be substantially important for both climate change mitigation and adaptation. This typical mangrove can store exceptional soil carbon stocks in addition to providing fishery products that can be directly beneficial for the coastal communities. Mangroves across this region are mostly pristine and dominated by tall mature stands, some activities that are expected and threaten this region with possible future land-use change implications include settlement, mining, and forest management (57).

Total ecosystem carbon stocks of mangrove on peatland in this region are extremely high and ranging from 830 to 1,689 with mean of 1,233 MgC ha^{-1} (previously assessed by refs. 18 and 51) or 28% more than global mangrove carbon stocks assessment (58). High-carbon stocks are supported by large biomass and soil carbon stocks up to 300 cm depth. Soil carbon contents were between 7 and 20% with relatively low bulk density (0.36 to 0.54 g cm^{-3}) (18), and thus, their emissions and removals calculation should be categorized under organic soils where the gain–loss approach is encouraged. With the total distribution area of mangrove on peatland in West Papua are approximately 231,909 ha (Fig. 1*B*), their total carbon stocks are estimated up to 0.28 MtC or 9% of national mangrove carbon stocks. Avoiding deforestation and conversion in this region can contribute significant mitigation potential for Net FOLU sink targets by 2030.

General Discussions and Conclusions

Indonesia has updated their FREL/FRL through second FRL submission in 2022 by including REDD+ activities and emissions from deforestation, forest degradation and carbon stocks enhancement, peat decomposition and fires, and soil excavation following mangrove conversion, as well as non-CO2 gases inclusion and uncertainty improvements. All of these improvements, particularly peat fires and soil excavation following mangrove conversion are among key categories that were not reported in the first FREL submitted in 2016. Peat fires contributed to approximately 20.93% of annual net emissions (267.7 Mt CO_2 y^{-1}) following deforestation, forest degradation, and carbon stocks enhancement, while mangrove soil emissions contributed less than 1%.

Although the EF and AD improvements between categories in the second FRL, there are still gaps for future refinement highlighted by our study, particularly through i) the application of gain–loss approach to calculate GHG emissions/removals in peatlands and mangroves on peat soils, ii) improving EF and AD for peat fires, peat rewetting and mangrove conversion. It is obvious that more detailed and refined EF and AD will eventually be needed for mitigation activities at the subnational and project levels.

The FREL/FRL is a crucial part of the MRV processes suggested by UNFCCC and should be developed by considering historical forest cover change under particular national circumstances. The FREL/FRL reporting is used to assess the performance of emission reduction through mitigation strategies and mechanisms, including REDD+ programs or projects. Hence, FREL/FRL may be used as the quantitative and credible basis for rewarding and payment resulted from policy interventions at the national level and mitigation actions on the ground as projects are implemented at the subnational and project levels. Consequently, the FREL/FRL should be carefully developed following TACCC principles with possible minimum uncertainty.

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*.

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Author affiliations: [a]Center for International Forestry Research–World Agroforestry, Situgede, Bogor 16115, Indonesia; [b]Department of Geophysics and Meteorology, IPB University, Bogor 16680, Indonesia; [c]Centre de coopération International en Recherche Agronomique pour le Développement, 34398 Montpellier Cedex 5, France; [d]NUS Environmental Research Institute (NERI), National University of Singapore, Singapore 117411, Singapore; and [e]Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), College of Science and Engineering, James Cook University, Douglas, QLD 4811, Australia

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