



Food and Agriculture
Organization of the
United Nations



Peat-Emit

Supporting developing economies to
estimate and report greenhouse gas
emissions from organic soils



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Rome, 2026

REQUIRED CITATION:

Freeman, B., Monsen-Elvik, E., Jovani, J., Evans, C., Page, S., Rams Beltrán, E., Nuutinen, M., and Warren, M. 2026. *Peat-Emit – Supporting developing economies to estimate and report greenhouse gas emissions from organic soils*. Rome, FAO. <https://doi.org/10.4060/ce0889en>

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ISBN 978-92-5-140894-0

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Acknowledgements

The Food and Agriculture Organization of the United Nations (FAO) and the authors express their sincere appreciation to the UK Centre for Ecology & Hydrology (UKCEH) for its scientific leadership on the technical expertise of the Peat-Emit report. FAO specifically acknowledges the contributions of the project team – Ben Freeman, Elya Monsen-Elvik, Jonay Jovani, Christopher Evans (UKCEH) and Susan Page (University of Leicester) – whose collective work has been essential to the delivery and quality of the project outputs.

FAO further wishes to recognize the invaluable guidance and contributions provided by the members of the Technical Steering Committee (TSC) of the Peat-Emit project, representing expertise from five global regions with peatlands (Asia, Africa, Latin America and the Caribbean, Europe, and North America). Their engagement through consultations, workshops and peer review has significantly strengthened the scientific rigour, relevance and quality of the analysis and findings presented in this report. In particular, FAO acknowledges with appreciation the contributions of the members of the TSC: Alex Cobb – School of Earth and Environment, Nanyang Technological University, Singapore; Gusti Zakaria Anshari – Tanjungpura University, Indonesia; Aljosja Hooijer – Data for Sustainability; Erik Lilleskov – United States Forest Service (USFS); Joni Jupesta – Intergovernmental Panel on Climate Change (IPCC) Task Force on National Greenhouse Gas Inventories Bureau; Mohd Talib Latif – IPCC Task Force on National Greenhouse Gas Inventories Bureau; Jorge Hoyos-Santillan – Chile and University of Eastern Finland; Juan Carlos Benavides Duque – Universidad Javeriana, Colombia; Keiichi Igarashi – United Nations Framework Convention on Climate Change (UNFCCC); Dirk Nemitz – UNFCCC; Sandro Federici – IPCC Task Force on National Greenhouse Gas Inventories Technical Support Unit; Max Lupascu – National University of Singapore; Johannes Couwenberg – Greifswald University, Germany; Averti Ifo – Marien Ngouabi University, Republic of the Congo; Yuqi Hu – Sichuan Fire Research Institution of the Ministry of Emergency Management, China; Tom Smith – London School of Economics and Political Science (LSE); Fahmuddin Agus – National Research and Innovation Agency, Indonesia; Kristell Hergoualc’h and Erin Swails – Center for International Forestry Research (CIFOR); and Elisabet Rams Beltrán – Greifswald Mire Centre. The following are also acknowledged for their contributions from FAO: Maria Nuutinen, Matthew Warren, Adam Gerrand, Laura Villegas Mejía, Till Neeff, Marieke Sandker, Eva Ntara, Alessandro Albani, and Amy Duchelle.

Special appreciation is extended to Elisabet Rams Beltrán for her leadership in advancing the process during her time at FAO, and for her important conceptual contributions, which have helped shape the approach and overall direction of the work. FAO acknowledges the contributions of the Peatlands team within the Forestry Division for their technical oversight and coordination, as well as the following for their valuable support in finalizing and presenting this publication: the knowledge management and outreach expert, Vanessa Vertiz Larrea; the editors, Gordon Ramsar and Alex Gregor; and the graphic designer, Massimiliano Martino.

This report was developed by FAO through the Accelerating Innovative Monitoring for Forests programme (AIM4Forests), thanks to the financial support from the Department for Energy Security and Net Zero of the United Kingdom of Great Britain and Northern Ireland.

Preface

Accurate, transparent, and policy-relevant information on greenhouse gas (GHG) emissions from peatlands is essential to support countries in meeting their reporting obligations under the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. Peatlands, while covering a relatively small proportion of the Earth's surface, play a disproportionately important role in the global carbon cycle and climate system. When degraded, drained, or burned, they become significant sources of GHG emissions, contributing to climate change and undermining global emission reduction and removal efforts.

In this context, the Peat-Emit project, implemented by FAO in collaboration with the UKCEH under the Accelerating Innovative Monitoring for Forests programme (AIM4Forests), represents an important contribution to strengthening the scientific basis for emissions estimation and reporting for organic soils – particularly in developing countries.

This report responds to a critical and well-recognized challenge faced by many countries – namely the limited availability of robust, region-specific data to support GHG inventory development for peatlands and other organic soils. By systematically compiling and analysing a substantially expanded body of evidence, the publication presents proposed new/updated EFs, identifies key data gaps, and proposes methodological improvements. These outputs are directly relevant to national inventory compilers, policymakers and practitioners working to improve the transparency, accuracy and completeness of GHG emission reporting.

Importantly, the findings and datasets generated through this work are highly relevant to ongoing and future processes under the IPCC. The updated EFs and underlying database will be submitted to the IPCC Emission Factor Database (EFDB) and could make a valuable contribution to supporting its continued evolution as a global repository of scientifically credible EFs. The expanded evidence base presented in this report also has the potential to inform future refinements of the IPCC guidelines, including potential updates to the 2013 *Wetlands Supplement* and related methodological guidance. Furthermore, the report contributes to broader scientific efforts addressing short-lived climate forcers, particularly CH₄ emissions from organic soils and CO and CH₄ emissions from peatland fires. By improving the understanding of these emissions and their drivers, the work provides a relevant evidence base that can support IPCC assessments.

In line with the convention used in the 2006 *IPCC Guidelines* and the *Wetlands Supplement*, categories classified at the level of the IPCC land-use categories are capitalized throughout this report (Cropland, Forest Land, Grassland, Other Land, Plantations, Settlements, Wetlands).

The publication of this report reflects FAO's commitment to supporting countries in achieving climate goals through improved data, methodologies, and capacity development. It also illustrates the importance of collaboration across institutions, disciplines, and regions to address complex environmental challenges.

It is hoped that the Peat-Emit report will serve not only as a technical reference, but also as a catalyst for further research, collaboration, and investment in locating, monitoring and responsibly managing peatlands. Strengthening the scientific foundation for emission estimates is a critical step towards protecting these vital ecosystems and harnessing their potential for climate change mitigation.

Abbreviations

aCAR	apparent carbon accumulation rate
BACI	before–after–control–impact
C	carbon
C_f	combustion factor
CH₄	methane
CIs	confidence intervals
CO	carbon monoxide
CO₂	carbon dioxide
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
EF	emission factor (the average annual emission/removal per hectare of a given greenhouse gas for a given land-use category)
EFDB	emission factor database
ETF	Enhanced Transparency Framework
FAO	Food and Agriculture Organization of the United Nations
FMC	fuel moisture content
Frac_{oxidation}	proportion of subsidence attributed to oxidation
FTIR	fourier transform infrared
GHG	greenhouse gas
GPP	gross primary productivity (the CO ₂ uptake via photosynthesis)
IPCC	Intergovernmental Panel on Climate Change
LEAF	Lowering Emissions by Accelerating Forest finance
LiDAR	light detection and ranging

LORCA	long-term rate of carbon accumulation (equal to the total carbon stock of the peat layer, divided by the basal age)
LULUCF	land use, land-use change and forestry
MCE	modified combustion efficiency
N	nitrogen
N₂O	nitrous oxide
NDC	nationally determined contribution
NEE	net ecosystem exchange (the net exchange of CO ₂ between the land surface and the atmosphere [the balance of photosynthetic uptake by plants and respiration by plants and soil microbes])
NEP	net ecosystem production (the CO ₂ balance of the ecosystem after accounting for any carbon inputs [e.g. manure] and exports [e.g. biomass harvest]; harvested biomass is assumed to be converted to CO ₂ offsite)
PAR	photosynthetically active radiation
POC	particulate organic carbon
R_{aut}	autotrophic respiration (CO ₂ release from plants due to cellular respiration; released from both above-ground and below-ground vegetation structures)
R_{eco}	total ecosystem respiration (CO ₂ release from plants and soil microbes via autotrophic and heterotrophic respiration processes)
REDD+	Reducing Emissions from Deforestation and forest Degradation
REERCA	recent rate of carbon accumulation
R_{het}	heterotrophic respiration (CO ₂ release from microbial decomposition of soil organic matter, and above-ground and below-ground litter inputs)
R_{soil}	soil respiration (CO ₂ release from plant roots due to autotrophic respiration and from microbial decomposition of soil organic matter, as well as above-ground and below-ground litter inputs [heterotrophic respiration]).
TREES	The REDD+ Environmental Excellence Standard
TSC	technical steering committee (Peat-Emit project)
UAV	unmanned aerial vehicle
UKCEH	UK Centre for Ecology & Hydrology
UNFCCC	United Nations Framework Convention on Climate Change

Executive summary

The Peat-Emit report provides an updated and expanded evidence base to support the estimation and reporting of greenhouse gas (GHG) emissions from peatlands and organic soils, with a particular focus on developing economies. By compiling a substantially larger dataset than was available for the IPCC 2013 *Wetlands Supplement*, the report presents proposed new/updated Tier 1 emission factors (EFs) for carbon dioxide, methane, and nitrous oxide (N₂O), as well as updated parameters for peat fire emissions, contributing to improved consistency and accuracy of GHG inventories. The publication is based on a structured review and synthesis of peer-reviewed literature and available datasets on GHG emissions/removals from organic soils across multiple regions. Derivation of EFs followed IPCC-consistent approaches, combining flux measurements, stock-change methods, and critical assessment of study quality to ensure robustness and transparency of the estimates. The document was produced by FAO with experts from the UKCEH and University of Leicester, United Kingdom, guided by a broad steering committee from all peatland regions, and implemented under the Accelerating Innovative Monitoring for Forests programme (AIM4Forests).

The analysis shows that the availability of emissions data varies substantially between regions, with the most robust evidence available for Southeast Asia. In this region, proposed new/updated EFs confirm that drained organic soils are major sources of carbon dioxide emissions, with values strongly influenced by land use and drainage conditions. The results further show that N₂O emissions are particularly relevant in fertilized systems, where updated estimates suggest higher values than those currently reflected in Tier 1 default EFs.

In warm climate regions outside Southeast Asia – including Africa, as well as Latin America and the Caribbean – the available evidence indicates similar overall patterns, with undrained systems often acting as net carbon sinks and drained systems acting as sources. However, the limited number of data points restricts the development of robust, region-specific EFs.

In the cool climate zone, data availability remains limited outside Europe and North America. The compiled evidence indicates that undrained organic soils are generally close to neutral or act as modest carbon sinks, with variable CH₄ emissions and relatively low N₂O emissions where drainage and fertilization are absent. Given data constraints, the Tier 1 default EFs remain the most reliable basis for reporting in most cool climate regions, but the greatly increased number and expanded geographical range of studies published since the 2013 IPCC *Wetlands Supplement* would support an update of EFs for this climate zone in the future. The report highlights water table depth as a key driver of peatland GHG emissions across all regions, noting that water table-based estimation of emissions/removals could offer a robust, data-efficient solution to reporting challenges created by ongoing data limitations.

The updated analysis for peat fires shows that EFs for carbon dioxide and carbon monoxide broadly align with existing values, while methane EFs appear lower than previously assumed. However, the underlying data remain largely confined to Southeast Asia, despite evidence for fire impacts on peatlands in Africa and Latin America, limiting their wider applicability.

Despite these advances, major gaps remain. Data for developing economies are heavily concentrated in Southeast Asia, with other parts of Africa and Asia, as well as Latin America and the Caribbean, under-represented, particularly for managed and rewetted systems. Measurements of methane and especially N₂O remain limited, peat fire data are scarce outside Southeast Asia, and many EFs are derived from small sample sizes. Addressing these gaps through expanded field measurements, improved methodologies and stronger data sharing will be essential to support more accurate and comprehensive global GHG reporting.

Overall, the findings underscore the need for strengthened and more coordinated action across policy, science, and reporting communities, including increased investment in data generation and monitoring, the adoption of improved and context-specific EFs and methodologies, and greater alignment of reporting approaches with evolving scientific evidence. Decision-makers are encouraged to prioritize peatlands within national climate strategies, support sustained research and data-sharing efforts, and enhance institutional capacity for GHG inventory development, while ongoing international processes would benefit from integrating the updated evidence base to improve the consistency, representativeness, and policy relevance of future guidance and assessments.



Peat swamp forest in the Republic of the Congo

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1. Introduction

1.1 Background: *Wetlands Supplement*

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC, 2014) (hereafter referred to as the *Wetlands Supplement*), published by the IPCC, incorporates the only internationally agreed global guidelines to report on GHG emissions from and GHG removals by organic soils, including peatlands. The *Wetlands Supplement* complements the *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006) (hereafter referred to as the *2006 IPCC Guidelines*) and the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019) (hereafter referred to as the *2019 Refinement*). The *Wetlands Supplement* has also been used in other contexts, such as estimating emissions reductions for voluntary carbon (C) markets. The *Wetlands Supplement* provides a set of approaches for calculating estimates of emissions and removals, as well as default Tier 1 emission factors (EFs)¹ for different climate zones and land-use/cover categories.

However, at the time of the *Wetlands Supplement*'s publication, only limited data were available for some important land-use categories, especially in tropical regions, resulting in high uncertainty for some EFs. The *Wetlands Supplement* also necessarily drew heavily on data from data-rich regions, which generally tended to include developed economies. Many other regions, particularly those with developing economies, are not represented in the *Wetlands Supplement* dataset because data were not available at that time.

It has now been over 10 years since the *Wetlands Supplement* was published, and it no longer reflects the latest data or approaches adopted by countries for GHG emissions reporting, as research has progressed rapidly over the past decade. Countries have also approached the rewetting and restoration of peatlands differently based on the realities on the ground, which has created challenges with following the simplified category-based guidance provided by the *Wetlands Supplement*. Finally, the existing approach to calculating emissions from peatland fires relies on a very limited number of studies. Since the *Wetlands Supplement* was published, the number of studies relevant to peatland fires has increased, albeit with an ongoing regional bias towards Southeast Asia.

These limitations of the *Wetlands Supplement* now present a constraint for countries aiming to reduce GHG emissions from the land use, land-use change and forestry (LULUCF) sector, resulting in lower integrity in GHG emissions reporting and constraining effective decision-making on peatland management. In addition, the rapid expansion of payments for ecosystem services, including carbon markets, has created an urgent need for robust

¹ Emission factor: the average annual emission per hectare of a given GHG for a given land-use category.

information and standardized approaches to estimate GHG emissions from, and removals by, organic soils. Many countries are seeking to obtain results-based REDD+² finance in accordance with Article 5.2 of the Paris Agreement – for example, through the Lowering Emissions by Accelerating Forest finance (LEAF) coalition,³ which requires the use of The REDD+ Environmental Excellence Standard (TREES) and obliges countries to use a higher tier EF for primary carbon pools such as peatlands.

It is therefore important that organic soil EFs are updated to reflect the growing evidence base, that calculation methods are refined, and a harmonized approach is agreed, to support countries as they intensify their efforts to meet the goals of the Paris Agreement as stated in their nationally determined contributions (NDCs). This will require the development of:

- more accurate and precise organic soil GHG EF estimates for a wider range of land-management options (such as partial rewetting) and land-use/cover categories;
- regional or national level approaches (such as Tier 2 EFs); and
- robust and widely acceptable criteria for the evaluation of data quality to support dynamic updating of EFs as new data become available.

1.2 The Peat-Emit project

The Peat-Emit project was established in 2024 through a partnership among the UKCEH, FAO, and Susan Page of the University of Leicester, with support from the FAO-led programme, Accelerating Innovative Monitoring for Forests (AIM4Forests).

The ultimate objective of Peat-Emit is to provide enhanced support to countries (with a focus on developing economies) in their efforts to report GHG emissions from organic soils in alignment with the requirements of the Enhanced Transparency Framework (ETF) under the UNFCCC, as well as complement the current IPCC guidelines. Peat-Emit is also expected to contribute to higher tier assessments required by carbon standards like TREES for national and subnational carbon accounting.

The Peat-Emit project has been undertaken to make a substantial first step towards addressing the major challenges that countries face around emissions reporting, as well as developing guidance on what the most suitable next stages might be for key stakeholders. The project centred on an extensive process of literature review and data analysis for developing economies to evaluate the potential to update EFs, identify key knowledge gaps, develop criteria for study suitability assessment, and provide recommendations for key stakeholders.

The project has benefited greatly from the invaluable inputs of a TSC consisting of leading experts on peatlands and emissions reporting with a wide range of technical backgrounds and expertise, and a broad geographic representation including Africa, Latin America and Southeast Asia. Input from the TSC was incorporated through online meetings, individual consultations, and an in-person workshop held at FAO headquarters in Rome in 2024. The TSC also provided expert peer review of this report to ensure that the results of the project met the required standards.

² “REDD” stands for “Reducing emissions from deforestation and forest degradation in developing countries”. The “+” stands for additional forest-related activities that protect the climate, namely sustainable management of forests and the conservation and enhancement of forest carbon stocks.

³ LEAF website: www.leafcoalition.org

The results of the Peat-Emit project are expected to provide immediate support to end users by proposing new and updated values for Tier 1 EFs, particularly for warm climate (tropical) peatlands in Southeast Asia. The significant increase in available data for developing economies could contribute to a future update of the *Wetlands Supplement*. By highlighting the value of field measurements for EF development and revision, the work also aims to encourage additional measurements to support the development of organic soil EFs, especially for regions that remain under-represented in the current dataset.

1.3 Project scope

This report details work to identify organic soil GHG emissions data and develop potential new/updated organic soil GHG EFs for developing economies. Broadly, this includes:

- a review of relevant emissions data and EFs for terrestrial GHG emissions; and
- a review of relevant emissions data and EFs for peatland fires and fire emissions.

Terrestrial emissions of carbon dioxide (CO₂), CH₄ and N₂O were the main outcomes of interest. In all cases, the focus was on quantifying direct terrestrial net emissions from, or net sequestration into, the soil carbon or nitrogen (N) pools. GHG emissions can also occur via aquatic pathways, including direct (“onsite”) CH₄ emissions from drainage ditches located within areas of organic soil, and indirect (“offsite”) GHG emissions resulting from the waterborne export of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC), nitrate, and dissolved GHGs, all of which can lead to GHG emissions remote from their original source. However, there are currently not sufficient data to support an update of existing methods and EFs for these aquatic emissions pathways (beyond very limited refinements). The project team therefore prioritized a review of terrestrial organic soil GHG EFs. The geographic scope of this study was limited to developing economies as defined by the *World Economic Situation and Prospects 2023* report (United Nations, 2023). Consequently, the major focus of the work centres on East and Southeast Asia, Latin America and the Caribbean, and Africa. A small number of data points from tropical locations in the United States of America were also included to provide analogues for similar sites in Latin America and the Caribbean. Emissions data from cool climate organic soils within these regions (tropical high-altitude and southern temperate regions) were also included, but at this stage were not merged with the much larger (and ecologically distinct) emissions data from the northern temperate and boreal regions.

The main outcomes of interest regarding peatland fires were fire-derived GHG emissions and the mass of peat combusted (fuel consumption). Fire-derived emissions of CO₂, carbon monoxide (CO) and CH₄ were included. The recommended combustion factor (C_f), a measure of combustion completeness, value of 1.0 was also evaluated based on data obtained. Finally, an indicative record was built of peatland fire occurrences to illustrate the prevalence of contemporary (as opposed to palaeo) peatland fires within the regions of interest. Given patterns of data availability, this work constituted a review and update of tropical peatland fire emissions. However, data from non-tropical regions were evaluated where these provided relevant information.



Turmeric crop in Malaysia

© Jonay Jovani

2. Methodology

This section details the approach taken for aggregating, analysing and presenting information on GHG emissions and removals for organic soils. The EF calculation approach is presented first, as the required input data for this process are the primary drivers of the data collection approach.

2.1 Emission factor derivation

2.1.1 Carbon dioxide emissions

According to the *Wetlands Supplement*, total emissions and removals of CO₂ expressed in terms of carbon (measured in CO₂-C; in t CO₂-C ha⁻¹ yr⁻¹) from inland organic soils should be calculated using Equation 1.

Equation 1

$$CO_2 - C_{organic} = CO_2 - C_{on-site} + CO_2 - C_{DOC} + L_{fire} - CO_2 - C$$

Equation components include:

- CO₂-C_{on-site} represents the net direct (“onsite”) terrestrial CO₂-C emissions from and removals by ecosystems on organic soil.
- CO₂-C_{DOC} represents the indirect (“offsite”) aquatic net CO₂-C emissions due to export of DOC from organic soil.
- L_{fire}-CO₂-C represents the CO₂-C emissions from combustion of organic soil due to fires.

Estimation of direct CO₂-C emissions from organic soil due to organic matter decomposition (CO₂-C_{on-site}) is possible using several different methods that are described and discussed in more detail in this section. Estimation of CO₂-C emissions from combustion of organic soil due to fires (L_{fire}-CO₂-C) is discussed in Section 2.1.4, along with emissions of other GHGs that result from the combustion of organic soil. As mentioned previously, aquatic emissions fall outside the scope of this report, and thus a discussion of the methods for estimating aquatic indirect net CO₂-C emissions due to transport of DOC for organic soil (CO₂-C_{DOC}) is not included.

Soil flux carbon balance

This approach (often referred to as the gain–loss method) centres on the use of opaque chambers to measure the CO₂ flux from the surface of bare soil, along with measurements of carbon inputs to the soil from vegetation. The net CO₂-C fluxes are expressed as the balance of outputs (positive sign) and inputs (negative sign) as shown in Figure 1. These fluxes, which are calculated using Equation 2, are presented from the atmospheric perspective, whereby negative values indicate net accumulation of carbon.

Equation 2

$$CO_2 - C_{on-site} = R_{het} - Litter_{AG} - Litter_{BG}$$

Equation components include:

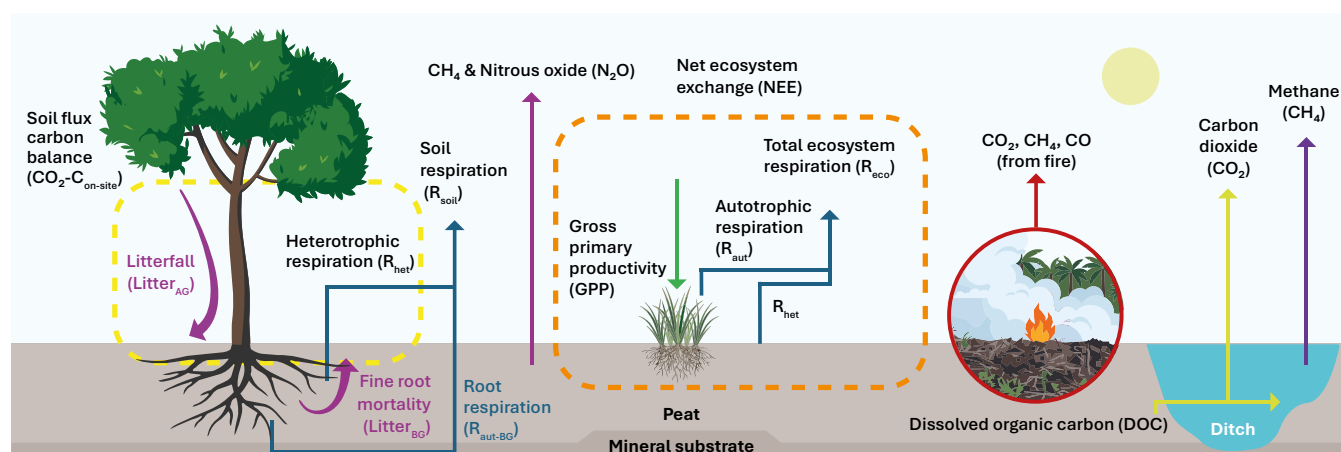
- $CO_2 - C_{on-site}$ is the soil CO₂-C balance.
- R_{het} is heterotrophic respiration.⁴
- $Litter_{AG}$ is the carbon input from the above-ground plant litterfall.
- $Litter_{BG}$ is the carbon input from below-ground litter due to fine root mortality.

This balance is represented by the fluxes/inputs contained within the yellow box on Figure 1. Note that in line with the 2006 IPCC Guidelines and the Wetlands Supplement, inputs from the dead wood carbon pool are excluded from the soil carbon balance due to very high uncertainties, and aquatic carbon losses are treated separately (see Equation 1).

Chamber measurements of ecosystem–atmosphere GHG fluxes involve the temporary enclosure of a volume of air adjacent to the land surface within the chamber headspace and the measurement of the change of concentration of GHGs within the headspace over the duration of the enclosure period. Chamber measurements have the advantage of being relatively low cost. They also permit spatially targeted measurements and a reasonable degree of spatial replication, which can be advantageous where differences between the types of landforms and habitats within an ecosystem are of interest, or for the comparison of experimental conditions. The use of opaque chambers to estimate the soil flux carbon balance has particular utility in ecosystems with tall vegetation (such as forests and plantations) where the capture of gaseous vegetation fluxes requires expensive equipment (such as flux towers).



⁴ Heterotrophic respiration: CO₂ release from microbial decomposition of soil organic matter and above-ground and below-ground litter inputs.

Figure 1 Summary of fluxes from organic soils

Notes: The balance of fluxes within the orange box represents the net ecosystem exchange (NEE) of CO₂. In ecosystems where the biomass carbon stock has reached a steady state, NEE represents the land carbon dioxide balance under the ecosystem flux carbon balance method. In ecosystems where the biomass carbon stock has not reached a steady state, changes in the biomass carbon stock must also be accounted for.

Source: Adapted from IPCC. 2014. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Geneva, Switzerland. <https://www.ipcc-nggip.iges.or.jp/public/wetlands/index.html>

As this is a soil balance approach, chamber flux measurements must exclude gaseous vegetation fluxes, including photosynthesis and autotrophic respiration (R_{aut}).⁵ To exclude photosynthesis and above-ground autotrophic respiration, measurements must be made with no above-ground vegetation in the chamber footprint. Below-ground vegetation must also be excluded from the chamber footprint (for example, by trenching) to exclude below-ground autotrophic respiration (R_{aut-BG}). If these conditions are met, then the measured flux can be treated as an estimate of the rate of CO₂-C loss from R_{het} . If above-ground vegetation is absent, but roots cannot be excluded from the chamber footprint, then the resulting measurement will estimate soil respiration (R_{soil})⁶ and not R_{het} (see Equation 2). Site-specific values for R_{het} are not always reported. Where studies report only R_{soil} , this may be converted to an estimate of R_{het} by using average values for the heterotrophic proportion of R_{het}/R_{soil} obtained from the literature.

Equation 3

$$R_{soil} = R_{het} + R_{aut-BG}$$

Based on Equation 2, the rate of CO₂-C loss from R_{het} must be balanced against the rate of carbon inputs to the soil from vegetation sources. Measurements of carbon inputs from the above-ground plant litterfall ($Litter_{AG}$) are usually conducted using litterfall traps. Where these are of known dimensions, where litter is removed regularly (to avoid decomposition losses), and where sampling is appropriately stratified and frequent, this allows upscaled estimates of annual soil carbon inputs from litterfall. Measurements of carbon inputs from below-ground litter due to fine root mortality ($Litter_{BG}$) are derived using fine root biomass (usually defined as roots of diameter smaller than 2 mm) and the fine root turnover (defined as the number of times that fine root biomass is replaced each year), allowing an estimation of the carbon input to the soil from fine root mortality. Several methods

⁵ Autotrophic respiration: CO₂ release from plants due to cellular respiration from both above-ground and below-ground vegetation.

⁶ Soil respiration: CO₂ release from plant roots due to autotrophic respiration and from microbial decomposition of soil organic matter, and above-ground and below-ground litter inputs (heterotrophic respiration).

exist to calculate fine root biomass and fine root turnover and production, including sequential soil coring, ingrowth cores, minirhizotrons, and radiocarbon measurements (Majdi *et al.*, 2005). Similarly to R_{het} , site-specific values for $Litter_{AG}$ and $Litter_{BG}$ are not always reported, and these data are also generally less widely reported in isolation.

Closing soil flux carbon balances is often (but not always) dependent on non-site-specific data, which introduces additional uncertainty into the resulting estimates for the soil CO_2 -C balance ($CO_2-C_{on-site}$). Similar challenges are described in the *Wetlands Supplement*, as many studies reported R_{soil} but not R_{het} owing to the relatively greater difficulty of measuring the latter, and relatively few studies reported values for carbon inputs (especially fine root mortality, again due to the difficulty of measurement). If site-specific values were available for a given site, these were applied in the calculation of the CO_2 -C balance ($CO_2-C_{on-site}$). However, wherever site-specific values were not available, category average values were calculated for the R_{het}/R_{soil} , $Litter_{AG}$ and fine root mortality $Litter_{BG}$, which were then applied in calculations of the CO_2 -C balance ($CO_2-C_{on-site}$). Where possible, these averages were stratified by management, drainage and land use/cover in line with the classification of other outcome data (see [Section 2.1.5](#) and [Appendix 2](#)). Particularly in forest ecosystems, litter inputs appear to be relatively consistent ([Appendix 2](#)).

There is less certainty around the application of category average values for the heterotrophic proportion of soil respiration (R_{het}/R_{soil}), as these may be more sensitive to environmental conditions (such as water table depth). However, for the current analysis, the increase in data availability using this approach was considered a tolerable trade-off against the potential reduction in precision, as within-category variation was not excessive ([Appendix 2](#)). Where site-specific data were not available, category average parameter values were applied for all land-use categories in warm climate Asia. However, category average values were only applied in the absence of site-specific data for Forest Land in other regions because the required additional parameter values are very rarely reported in publications for other land-use categories. It is, therefore, inadequately evidenced that these values would be sufficiently internally consistent within land-use categories. The data obtained for estimating these non-site-specific parameter values are presented in [Appendix 2](#).

Ecosystem flux carbon balance

This approach uses either transparent chamber or flux tower (predominately eddy covariance) measurements to estimate the net ecosystem exchange (NEE) of CO_2 ([Equation 4](#)). NEE is the balance of total CO_2 uptake via photosynthesis (gross primary productivity [GPP]) and the CO_2 losses resulting from total ecosystem respiration⁷ (R_{eco}), which is the sum of R_{het} and R_{aut} ([Equation 5](#)). As long as any changes in biomass carbon stocks can be accounted for (or can be assumed to be negligible), then the residual net flux represents the balance of carbon inputs to the soil from vegetation and CO_2 emissions from the soil due to decomposition, and is therefore effectively equivalent to the net CO_2 emissions estimate obtained by the soil flux carbon balance method described above. However, the ecosystem flux carbon balance approach differs from the soil flux carbon balance approach in that gaseous vegetation fluxes are measured and accounted for in the former as opposed to being excluded in the latter.

Equation 4

$$NEE = R_{eco} - GPP$$

Equation 5

$$R_{eco} = R_{het} + R_{aut}$$

Due to the need to capture vegetation fluxes, the transparent chamber approach is only applicable for ecosystems with short vegetation that can be enclosed within the chamber headspace. In this case, a transparent chamber measurement will estimate NEE, whereas an associated opaque chamber measurement will estimate R_{eco} , with GPP calculated as the difference. Only used data from transparent chamber studies reporting NEE were used and not data from studies reporting R_{eco} alone. Conversion of R_{eco} to NEE using category average values of GPP risks introducing substantial errors due to the tight linkage between R_{eco} and GPP within both sites and years. Modelling of R_{eco} and GPP using environmental variables (such as temperature and photosynthetically radiation [PAR]) can be used to gap-fill time periods between chamber measurements to estimate annual NEE. Where automated chambers are deployed, the extent of gap-filling required to produce annual estimates is generally relatively limited. However, where manual chambers are used, substantial gap-filling is often required to produce annual estimates, as measurements can be relatively infrequent. Chamber measurements must also be upscaled based on appropriate sampling and habitat stratification to produce representative estimates for spatially variable sites. Despite these challenges, chamber measurements (both opaque and transparent) account for many of the flux measurements used to derive the default EFs in the *Wetlands Supplement* because of their low cost, and relative simplicity.

Flux towers are located above the vegetation canopy and provide high-frequency data on ecosystem-atmosphere gas exchange. Most are based on the eddy covariance technique, where high-frequency measurements of gas concentrations and three-dimensional wind speed are used to determine vertical net GHG fluxes. The high frequency and large footprint of flux tower measurements allow this method to capture a far greater proportion of temporal and spatial variation relative to chamber measurements. However, their cost and the logistical challenges of deploying them over forest canopies limit the number of established sites, particularly in the tropics.

For any unmanaged ecosystems where biomass carbon stocks could be assumed to be in a steady state (based on assessment of site data time series and land-use/cover history), NEE is equal to the net ecosystem CO_2 balance or net ecosystem production⁸ (NEP) and was therefore treated as the CO_2 -C balance (CO_2 -C_{on-site}) value. In managed ecosystems, anthropogenic lateral biomass carbon fluxes, including biomass carbon inputs ($C_{biomass-in}$), such as organic fertilizer, and biomass carbon removals ($C_{biomass-out}$), such as harvested biomass, must also be included in NEP calculations (Equation 6). For any managed ecosystem that could be assumed to be in a long-term quasi-steady state in terms of its biomass carbon stocks (such as a regularly harvested cropland, grassland or plantation), and where biomass carbon inputs and removals could be accounted for, the estimate of NEP was treated as the CO_2 -C balance (CO_2 -C_{on-site}) value but NEE was not. It should also be noted that the fate of biomass carbon removals

⁸ Net ecosystem production: The CO_2 balance of the ecosystem after accounting for any carbon inputs (such as manure) and exports (such as biomass harvest). When estimating CO_2 emissions/removals due to land use, it is assumed that all harvested biomass is eventually respired. Therefore, these potential emissions are treated as direct ("onsite") emissions when estimating the CO_2 -C balance (CO_2 -C_{on-site}).

will influence the full life cycle net CO₂ balance of a production system. However, as this project’s purpose was to estimate the organic soil net CO₂ emissions/removals associated with land use, such considerations are external to this calculation. Substantial inputs/removals of inorganic carbon are rare but must also be accounted for where they do occur. In line with the *Wetlands Supplement*, peatlands are assumed to be net sources of aquatic carbon on average, with associated indirect (“offsite”) CO₂ emissions treated separately to direct (“onsite”) terrestrial CO₂ emissions/removals. For studies reporting NEE, reported lateral biomass carbon fluxes were included where relevant and available (for example, for any managed plantations) and sites were also included where these fluxes could be assumed to be negligible or in a steady state (such as unmanaged forests).

Equation 6

$$NEP = NEE - C_{biomass-in} + C_{biomass-out}$$

For systems where biomass carbon stocks are not in a steady state, changes in biomass carbon stocks must be accounted for if NEP is used to derive a CO₂-C balance (CO₂-C_{on-site}) value. For example, following a land-clearing fire, rates of CO₂ uptake may be high for many years during the vegetation regrowth period, and measured NEE may be small or even negative (implying a net CO₂ sink), even though terrestrial CO₂ emissions from organic soil continue unabated. Conversely, after conversion of an unmanaged forest to a managed plantation system, the decomposition of residual above-ground biomass (such as fallen trees and large litter) and below-ground biomass (such as dead roots of felled trees) may temporarily and substantially increase NEE as determined by flux tower measurements. Although these net CO₂ fluxes are real and may be large, they are transient “land-use change” emissions rather than the steady emissions resulting from continuous mineralization of drained organic soil, and as indicated in the 2006 *IPCC Guidelines* and the *Wetlands Supplement* should therefore be considered separately and not used to calculate terrestrial CO₂ land use EFs for organic soil. Studies reporting NEE and/or NEP for sites experiencing land-use change must therefore also account for associated changes in biomass carbon stocks. Studies reporting NEE for systems that were clearly not in steady state (such as a forest regrowing after a fire) and did not provide data on biomass carbon stock changes were omitted from the analysis.

Soil carbon stock change – subsidence rate

When combined with average values of soil carbon density, peatland surface subsidence measurements allow estimation of soil carbon stock change and thus provide an indirect means of estimating organic soil CO₂ emissions. However, this approach is only valid if physical subsidence processes (such as consolidation, shrinkage, erosion) are accounted for, as these processes do not lead to carbon losses (with the exception of erosion, if this leads to POC export). Subsidence measurements can be low-cost, relatively simple to make in the field (such as using subsidence poles), require low measurement frequency (as it is an integrated/cumulative measurement), and can also be derived from remote sensing elevation measurements, for example by using light detection and ranging (LiDAR). Subsidence measurements are therefore widely used in peatland research and monitoring (particularly in Southeast Asia), as the approach is suitable for organizations or researchers with limited resources or access to technology. Subsidence data are available for more locations than direct flux measurements and often cover longer historical measurement periods.

However, complicating factors are:

- numerous assumptions and average parameter values (such as carbon density data) are required to infer rates of total carbon loss (soil carbon stock change) from measurements of long-term surface elevation change; and
- the inferred total carbon loss must be partitioned into component gaseous fluxes (CO₂ and CH₄) and aquatic fluxes (DOC and POC) to align with the IPCC reporting framework.

There are two main approaches for inferring total carbon loss from changes in peat surface elevation. The first is the method described by Den Haan *et al.* (2012) and Couwenberg and Hooijer (2013) who use Equation 7.

Equation 7

$$C_{loss-total} = S_{total} \times DBD_{lower} \times C_{dw-lower}$$

Equation components include:

- $C_{loss-total}$ is the total carbon loss from the peat (kg m⁻² yr⁻¹).
- S_{total} is the annual peat surface subsidence rate (m y⁻¹).
- DBD_{lower} is the dry bulk density of the lower saturated peat layer (kg m⁻³).
- $C_{dw-lower}$ is the carbon content of the lower saturated peat layer (kg kg⁻¹).

This method also is based on the following assumptions:

1. Consolidation of the lower saturated peat layer (below the water table) is a relatively short-lived process, occurring immediately after drainage.
2. Following this initial consolidation period, the contribution of consolidation to surface subsidence is negligible.
3. Subsequent surface subsidence results entirely from compaction and mineralization of organic matter in the upper drained peat layer, and peat loss due to wind and surface erosion is assumed to be negligible.
4. Management responds to surface subsidence by regularly and progressively deepening drainage to maintain a constant water table depth below the peat surface.
5. Consequently, the thickness of the upper drained layer remains approximately constant. Surface subsidence is offset by the inclusion of newly drained peat into the upper drained layer, as the water table moves deeper, exposing peat that was previously in the lower saturated layer.
6. If the weighted average carbon density and thus the carbon stock of the upper drained layer remains constant, then this represents a state of dynamic equilibrium, where (assuming compaction is at a steady state) the mass of carbon lost due to decomposition in the upper drained layer is equal to the mass of carbon input to the upper drained layer as peat from the lower saturated layer is exposed through drainage.

The second method, proposed by Anshari *et al.* (2021), also assumes that consolidation of the saturated lower peat has been completed, and that consolidation no longer contributes to subsidence. However, this method (Equation 8), which estimates the carbon loss based on the carbon density of the upper peat, incorporates a multiplier to account for the fraction of subsidence that is due to oxidation rather than compaction and shrinkage (value from Wösten *et al.*, 1997).

Equation 8

$$C_{loss-total} = S_{total} \times 10\,000 \times DBD_{upper} \times C_{dw-upper} \times Frac_{oxidation}$$

Equation components include:

- $C_{loss-total}$ is the carbon loss from the upper drained peat layer ($t\ C\ ha^{-1}\ yr^{-1}$).
- S_{total} is the annual peat surface subsidence rate ($m\ yr^{-1}$).
- DBD_{upper} is the dry bulk density of the upper drained peat layer ($t\ m^{-3}$).
- $C_{dw-upper}$ is the carbon content of the upper drained peat layer ($kg\ kg^{-1}$).
- $Frac_{oxidation}$ is the proportion of subsidence attributed to oxidation (as opposed to compaction/shrinkage).

If the soil carbon stock change estimated using subsidence rate is to be used as an estimator of CO_2 emissions due to peat mineralization ($CO_2-C_{on-site}$), then carbon losses due to CH_4 emissions and aquatic fluxes must also be accounted for (Equation 9).

Equation 9

$$CO_2 - C_{on-site} = C_{loss-total} - CO_2 - C_{DOC} - CH_4 - C_{organic}$$

Equation components include:

- $CO_2-C_{on-site}$ and CO_2-C_{DOC} are terrestrial and aquatic CO_2 emissions ($t\ CO_2-C\ ha^{-1}\ yr^{-1}$) respectively (see Equation 1).
- $CH_4-C_{organic}$ is the total CH_4 emissions from terrestrial and aquatic sources expressed in terms of carbon loss ($t\ CH_4-C\ ha^{-1}\ yr^{-1}$) (see Equation 10).

The main challenges and uncertainties for the first approach centre on the following issues:

1. whether following initial consolidation, all remaining subsidence can be solely attributed to compaction and oxidation within the upper drained peat layer (Den Haan *et al.*, 2012);
2. whether land managers can/do regularly adjust drainage to compensate for surface subsidence and maintain a relatively stable water table depth across diverse land-use/cover categories, beyond industrial plantations alone (Couwenberg and Hooijer, 2013);
3. whether compaction in the upper drained layer eventually reaches a steady state, such that its carbon stock remains constant over time;
4. whether sufficient peat dry bulk density and carbon content measurements can be obtained to adequately capture land-use/cover variability and allow robust calculation of carbon losses for studies reporting only surface subsidence rates;
5. whether adequate data are available to accurately adjust total carbon losses for aquatic carbon fluxes and CH_4 emissions when estimating net CO_2 emissions; and
6. this method is only valid where a saturated lower peat layer persists below the water table. It can no longer be applied when the entire peat layer is drained and above the water table.

The second approach has similar uncertainties and limitations to the first, as both methods assume no ongoing consolidation, a constant contribution of compaction, and no decomposition of saturated peat. Additionally, both methods consider that wind and surface erosion (Li *et al.*, 2018) to be either negligible or accounted for in aquatic fluxes and rely on the availability of sufficient input data for robust estimation of average parameter values. Unlike the method of Couwenberg and Hooijer (2013), the second method can be applied to drained peatlands where the entire peat layer is above the water table. However, this method is still highly dependent on whether adequately robust values for the proportion of subsidence attributed to oxidation ($Frac_{oxidation}$) can be obtained, and whether a constant value is appropriate, which remains unclear. In Anshari *et al.* (2021), the uppermost drained organic soil layer was treated as 50 cm thick, but this method would be applicable to other drainage depths if appropriate input parameters were used.

Subsidence-derived estimates of soil carbon stock change were included (for tropical peatlands only) in the *Wetlands Supplement*, but full carbon mass balance approaches were not. This was due to guidance in the Wetlands chapter of the 2006 IPCC Guidelines against their use unless data were carefully calibrated. A full review of empirical carbon stock change methods for organic soils was beyond the scope of this study. Therefore, these studies were not included in the methods presented here as a precautionary measure. However, given that surface subsidence measurements and non-site-specific average values for carbon density have been used to derive IPCC Tier 1 EFs, there is no obvious reason why accurately measured changes in carbon stock based on site-specific carbon density values should not also be used. The cost and practical challenges of obtaining such data are necessarily higher than for subsidence measurements alone, and therefore both methods will likely fulfil different purposes and may be more or less suitable for different regions and organic soil types. However, many of the challenges and uncertainties of the subsidence approach could be resolved if site-specific carbon stock data of sufficient quality could be obtained. Also, the collection of such data could improve the input parameters and calibration for estimates using subsidence measurements alone.

In the method of Couwenberg and Hooijer (2013):

- The dry bulk density of the lower saturated peat layer (DBD_{lower}) equals 78 kg m^{-3} .
- The carbon content of the lower saturated peat layer ($C_{dw-lower}$) equals 0.55 kg kg^{-1} .

In the method of Anshari *et al.* (2021):

- The dry bulk density of the upper drained peat layer (DBD_{upper}) equals 140 kg m^{-3} .
- The carbon content of the upper drained peat layer ($C_{dw-upper}$) equals $0.50 \text{ (kg kg}^{-1})$.
- The proportion of the subsidence attributed to oxidation ($Frac_{oxidation}$) equals 0.60.

When using the parameter values presented in the associated publications for Southeast Asia, these two methods produce very similar estimates of carbon loss based on subsidence rates. For positive, non-zero rates of subsidence, the estimates produced by the method of Couwenberg and Hooijer (2013) are 1.02 times the estimates produced by the method of Anshari *et al.* (2021). Therefore, for simplicity, when calculating total carbon losses based on subsidence rates for sites in Southeast Asia, only the method of Couwenberg and Hooijer (2013) using Equation 7 and Equation 9 was applied with the following parameter values:

- dry bulk density of the lower saturated peat layer (DBD_{lower}) equal to 75 kg m^{-3} ; and
- $C_{dw-lower}$ equal to 0.52 kg kg^{-1} for Equation 7.

For the small number of subsidence data points obtained for cropland in Florida, United States, both the methods of Couwenberg and Hooijer (2013) for Equation 7, and Anshari *et al.* (2021) for Equation 8 were applied.

For the method of Couwenberg and Hooijer (2013), the parameter values used were:

- the dry bulk density of the lower saturated peat layer (DBD_{lower}) equals 133.3 kg m^{-3} ; and
- the carbon content of the lower saturated peat layer ($C_{dw-lower}$) equals 0.55 kg kg^{-1} .

For the method of Anshari *et al.* (2021), the parameter values used were:

- the dry bulk density of the upper drained peat layer (DBD_{upper}) equals 318.8 kg m^{-3} ;
- the carbon content of the upper drained peat layer ($C_{dw-upper}$) equals 0.405 kg kg^{-1} ; and
- the proportion of the subsidence attributed to oxidation ($Frac_{oxidation}$) equals 0.60.

Values for lower peat used in the method of Couwenberg and Hooijer (2013) were the average of values for peat in Florida at depths greater than 50 cm obtained from Aich *et al.* (2013). Values for upper peat used in the method of Anshari *et al.* (2021) were derived as the average of measured values for peat in Florida at depths less than 50 cm based on data from Aich *et al.* (2013) and Hu *et al.* (2017).

The value for $Frac_{oxidation}$ used by Anshari *et al.* (2021) was retained as no superior alternative was identified for Florida peatlands.

Equation 9 was then applied using:

- the *Wetlands Supplement* Tier 1 default value of $0.82 \text{ t C ha}^{-1} \text{ yr}^{-1}$;
- the *Wetlands Supplement* Tier 1 default ditch CH_4 EF value of $2\,259 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$;
- the *Wetlands Supplement* default fraction of the area that is occupied by drainage ditches (F_{ditch}) of 0.02 for tropical drained organic soils; and
- the appropriate terrestrial CH_4 EF (Table A3.7) to estimate $\text{CO}_2\text{-C}_{on-site}$ from the total soil carbon stock change.

This same approach was also used to estimate CO_2 emissions from the total carbon loss values obtained for subsidence studies in tropical Asia. The mean of the two resulting values was taken as the $\text{CO}_2\text{-C}_{on-site}$ estimate for each site in Florida, as neither method was specifically developed for use in this region. Ultimately, the two methods demonstrated high consistency, with the difference between the values produced by the two methods being approximately 6 percent of the magnitude of their mean.

Soil carbon stock change – accumulation rate

For regions or land-use categories where contemporary flux datasets contain very few data, the long-term observed rate of carbon accumulation (LORCA), may provide an additional source of information about soil carbon stock change. Estimation of LORCA is undertaken by peat coring and dividing the carbon stock of an entire peat profile by the basal age of the peat. The resulting estimate of LORCA is equivalent to the historical mean carbon balance of a peatland across its entire history. Other measures of carbon accumulation include the apparent carbon accumulation rate (aCAR) of discrete layers within the depth profile and the recent rate of carbon accumulation (RERCA). However, neither of these measures provide a reliable indicator of either the past or present-day net carbon balance of a peatland (Young *et al.*, 2019, 2021). For this analysis, peat core data were only included from studies where the estimation method was reported as covering the entire peat profile depth.

Present-day vegetation, climate and hydrological conditions may differ substantially from past conditions. Therefore, LORCA is not an estimate of the present-day carbon balance of a peatland (Young *et al.*, 2019). However, where no flux measurements are available, the estimates of historical carbon stock change provided by LORCA may still have value as a guide to the approximate rate of net CO₂ sequestration that might be achieved by different ecosystems. On this basis, peat core data were only included for regions with relatively few direct flux measurements, where the potential benefits may outweigh the limitations. Peat core data were not included for warm climate (Southeast) Asia. Results are presented both with and without peat core data, to allow end users to make their own assessment of suitability.

Because substantial drainage and associated mineralization can fundamentally alter the peat depth profile, LORCA can only accurately represent the mean historical rate of carbon accumulation in the absence of anthropogenic drainage. Peat core studies from locations with clear evidence of drainage were therefore excluded from this analysis. Peat core data were also only used to estimate CO₂-C_{on-site} values for unmanaged land. By definition this means these data were used only for undrained organic soils.

Because peat core studies measure total soil carbon stock change – the long-term balance of net CO₂, CH₄ and aquatic carbon fluxes – they must also be adjusted to obtain estimates of net CO₂ sequestration using Equation 9 (by substituting C_{loss-total} with the estimate of LORCA). For any category where data from peat core studies were included in the CO₂ data sample, a category specific terrestrial CH₄ EF was calculated first, provided that sufficient data were available. If a category specific terrestrial CH₄ EF could be determined, then this value was used in Equation 9. Otherwise, the appropriate Tier 1 default CH₄ EF value from the *Wetlands Supplement* was applied along with the appropriate Tier 1 DOC EF (IPCC, 2014). Since the included sites consisted only of undrained organic soils, the Tier 1 EFs for rewetted organic soils were adopted as the most suitable available analogues when applying Equation 9.

2.1.2 Methane emissions

Drainage aerates upper organic soil layers and increases CH₄ consumption rates (methanotrophy). This leads to relatively low terrestrial CH₄ emissions from drained organic soil under more deeply drained land uses. However, substantial terrestrial CH₄ emissions still occur under less deeply drained land uses, and from natural (undrained) and rewetted sites. Emissions of CH₄ from drainage ditches can also be substantial, so CH₄ emissions must be accounted for to support accurate GHG emissions reporting for organic soil. In the *Wetlands Supplement* (IPCC, 2014), CH₄ emissions (kg CH₄ ha⁻¹ yr⁻¹) from drained inland organic soils are calculated using Equation 10.

Equation 10

$$CH_4\text{-organic} = \sum_{c,n,p} (A_{c,n,p} \times ((1 - F_{ditch}) \times CH_4\text{-land}_{c,n} + F_{ditch} \times CH_4\text{-ditch}_{c,p}))$$

- $CH_4\text{-organic}$ is the annual CH₄ loss from organic soil.
- $A_{c,n,p}$ is the land area (ha) of organic soil in a land-use category (in climate zone c , nutrient status n and soil type p).
- $CH_4\text{-land}_{c,n}$ is the EF for direct terrestrial CH₄ emissions from organic soil (in climate zone c , and nutrient status n).
- $CH_4\text{-ditch}_{c,p}$ is the EF for CH₄ emissions from drainage ditches (in climate zone c and soil type p).
- F_{ditch} is the fraction of $A_{c,n,p}$ which is occupied by drainage ditches.

In this study, only data relevant for estimating the EF for direct terrestrial CH₄ emissions from organic soil (*CH₄-land*) were collated. Terrestrial CH₄ flux measurements can be made using both chamber and flux tower methods, but the latter method remains rare.

2.1.3 Nitrous oxide emissions

N₂O emissions are produced by soil microbes, predominantly through the processes of nitrification and denitrification. The main environmental/soil factors controlling these processes are soil moisture content, temperature, and available N. Saturated organic soil produces very small amounts of N₂O emissions because organic matter decomposition rates are constrained by anaerobic conditions, limiting N mineralization. However, in drained organic soil, under aerobic conditions, increased organic matter mineralization rates alleviate these constraints, and consequently, drained organic soil has the potential to produce substantial N₂O emissions. This is especially the case in tropical regions, where higher temperatures are associated with increased chemical reaction rates, leading tropical organic soil to be considered an N₂O emission hotspot (Pärn *et al.*, 2018). Application of inorganic fertilizers can also produce very high N₂O emissions from cultivated organic soils.

Only direct terrestrial N₂O emissions resulting from organic matter mineralization in organic soil were addressed by this project. In principle, this EF should exclude N₂O emissions associated with agricultural inputs of N in mineral or organic fertilizers, which are reported separately. However, when measuring N₂O emissions from agricultural systems, complete exclusion of fertilizer N additions from flux measurement locations is extremely difficult and unlikely to have occurred in many studies. Therefore, it is likely that N₂O EFs for agricultural land-use categories may incorporate some contribution from fertilizer N inputs, as was the case for the *Wetlands Supplement*. N₂O emissions are predominately measured using chambers. Flux tower measurements are very rare.

Per the *Wetlands Supplement* (IPCC, 2014), direct terrestrial N₂O emissions from drained inland organic soils are calculated using Equation 11.

Equation 11

$$N_2O - N_{OS} = \left[\begin{aligned} &(F_{OS,CG,Bor} \times EF_{2CG,Bor}) + (F_{OS,CG,Temp} \times EF_{2CG,Temp}) + \\ &(F_{OS,CG,Trop} \times EF_{2CG,Trop}) + (F_{OS,F,Bor,NR} \times EF_{2F,Bor,NR}) + \\ &(F_{OS,F,Temp,NR} \times EF_{2F,Temp,NR}) + (F_{OS,F,Bor,NP} \times EF_{2F,Bor,NP}) + \\ &(F_{OS,F,Temp,NP} \times EF_{2F,Temp,NP}) + (F_{OS,F,Trop} \times EF_{2F,Trop}) \end{aligned} \right]$$

Equation components include:

- $N_2O - N_{OS}$ is the annual direct N₂O-N emission from managed/drained organic soils in kg N₂O-N yr⁻¹.
- F_{OS} is the annual area of managed/drained organic soils in ha.
- EF_2 is the EF for N₂O emissions from managed/drained organic soils in kg N₂O-N ha⁻¹ yr⁻¹.

- The following abbreviations are used for the subscript:
 - CG – Cropland and Grassland
 - F – Forest Land
 - Bor – Boreal
 - Temp – Temperate
 - Trop – Tropical
 - NR – Nutrient-rich
 - NP – Nutrient-poor

Equation 11 simply defines the approach for estimating national emissions of N₂O from organic soil based on the combination of EFs and areal activity data. This analysis focused exclusively on estimating values of the EF for N₂O emissions from organic soils (EF₂) for different land-use/cover categories and climate zones.

2.1.4 Fire emissions

For the calculation of CO₂ and non-CO₂ emissions resulting from peat fires, the *Wetlands Supplement* approach is described by Equation 12.

Equation 12

$$L_{fire} = A \times M_B \times C_f \times G_{ef} \times 10^{-3}$$

Equation components include:

- L_{fire} is the amount of CO₂ or non-CO₂ emissions from fire (tonnes).
- A is the total area burned (ha).
- M_B is the mass of fuel available (tonnes ha⁻¹) for combustion (mass of dry peat fuel) (the *Wetlands Supplement* provided default values).
- C_f is the combustion factor, dimensionless (*Wetlands Supplement* default value of 1.0).
- G_{ef} is the EF for each gas, g kg⁻¹ dry matter burnt (the *Wetlands Supplement* provided default values).

Application of the 10⁻³ factor ensures proper unit conversion. The total GHG emissions are estimated by summing the amount of CO₂ or non-CO₂ emissions from fire (L_{fire}) of the individual GHGs after their conversion into CO₂ equivalents.

Most studies used to derive *in situ* GHG EFs for peatland fires rely on data from direct field-based measurements of the mass concentration of different gas species during a specific peat fire episode. Researchers (Huijnen *et al.*, 2016; Stockwell *et al.*, 2016; Smith *et al.*, 2018; Wooster *et al.*, 2018; Yokelson *et al.*, 2022) using a gas analyser have measured trace gas emissions in peat fire smoke plumes *in situ* to provide realistic measurements representative of field conditions, for example for different land covers and land uses and burning conditions (Smith *et al.*, 2018; Wooster *et al.*, 2018). In some studies, field measurements have been accompanied by collection of whole air grab samples for subsequent laboratory gas analysis (Stockwell *et al.*, 2016; Yokelson *et al.*, 2022).

In addition to field-based measurements, there have been a few laboratory-based studies of gaseous emissions where small samples of peat are burned and emissions measured under controlled conditions (Christian *et al.*, 2003; Stockwell *et al.*, 2014, 2015; Hu *et al.*, 2019). The mass of fuel consumed (M_b) is derived from measurements of depth of burn and soil dry bulk density. Depth of burn has only been measured in a limited number of studies, either directly in the field (Page *et al.*, 2002; Saharjo and Munoz, 2005) using Earth observation techniques employing LiDAR (Konecny, 2016) or unmanned aerial vehicle (UAV) photography (Simpson *et al.*, 2016). Bulk density measurements (dry weight, g cm^{-3}) are either derived from field data or are based on literature values.

2.1.5 Categorization approach

The 2006 IPCC Guidelines, the Wetlands Supplement, and the 2019 Refinement adopted a categorical approach to EF development, whereby sites are classified according to land-use/cover criteria, and category-appropriate average EF values are applied for inventory reporting purposes. A five- to six-step categorical site classification approach with only minor deviations from the IPCC method was used during Peat-Emit to maximize consistency between EF datasets and the utility of the EFs produced by this project. The classification process for steps three to five is summarized in Figure 2. The extended classification process for steps four to six as applied for warm climate sites in Asia is summarized in Figure 3.

The classification process used during the Peat-Emit project included the following steps:

1. Sites were classified by climate. Site coordinates were used along with a publicly available Google Earth layer (Kottek *et al.*, 2006; Rubel *et al.*, 2017)⁹ to identify the Köppen-Geiger climate classification for each site. Sites were then classified as either warm climate or cool climate. Most warm climate sites in the dataset fall within the tropical climate zone (Köppen-Geiger: A), characterized by monthly mean temperatures above 18 °C throughout the year. However, to avoid excluding useful data points, slightly wider definition of warm climate was used to include data from the Okavango Delta in Africa (Köppen-Geiger: Bsh) and subtropical Brazil (Köppen-Geiger: Cwa/Cfa), all of which have mean annual temperatures higher than 18 °C. All remaining sites experiencing temperate, boreal and polar climates (Köppen-Geiger: C/D/E) were aggregated and classified as cool climate sites. The Wetlands Supplement relied heavily on data from Europe and North America, which are data-rich cool climate regions, to support the subdivision of many EFs into temperate and boreal climate regions. However, for the relatively less data-rich cool climate regions within the scope of this study, this level of disaggregation was generally impractical. This aggregated approach to the cool climate zone was also adopted in part to accommodate high-altitude sites in tropical latitudes within the cool climate category.
2. Sites were classified by region. Asia, Latin America and the Caribbean, and Africa were defined as key regions of interest. Asia was disaggregated further into warm climate (Southeast Asia) and cool climate regions during the literature search and analysis as Southeast Asia is a climatically distinct and data-rich area for which there is a great deal of policy interest around peatland emissions.
3. Per the 2006 IPCC Guidelines, land was assigned to a management category. Land was treated as either “unmanaged” or “managed” land. Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions. The 2006 IPCC Guidelines use a managed land proxy to account for anthropogenic GHG emissions resulting from land use. Consequently, emissions from unmanaged land do not need to be reported for national inventory purposes. However, individual countries have discretion on whether to classify land as managed land or unmanaged land. For example, they may

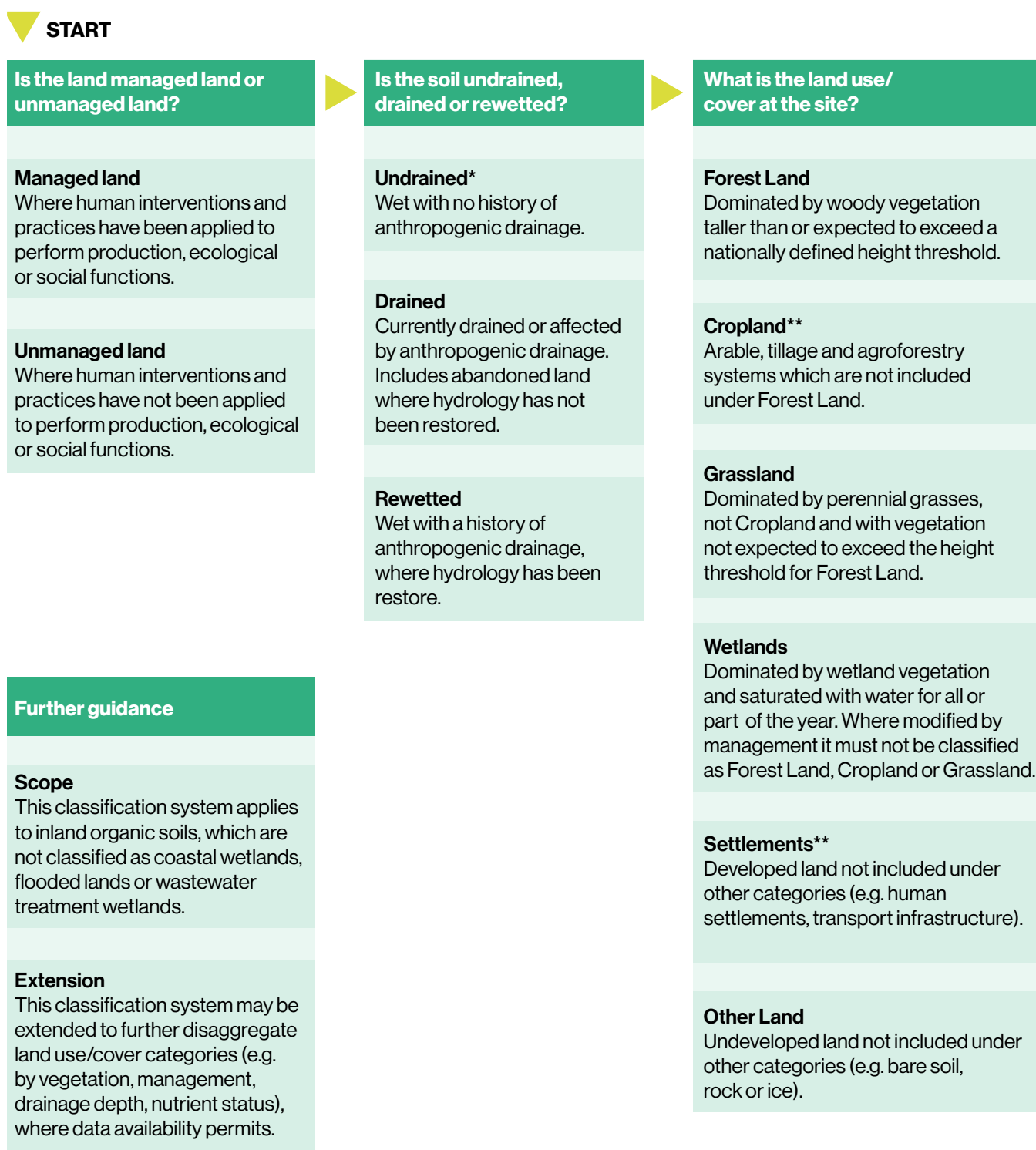
⁹ Available at: <https://koeppen-geiger.vu-wien.ac.at/present.htm>

consider land to be managed even when management is very low intensity, such that ecosystem function is largely unaffected, or where apparently unmanaged land is set within larger managed landscapes and thus subject to indirect anthropogenic influences. Unmanaged land EFs also have potential utility as emissions baselines for carbon finance schemes and peatland rewetting projects. Emission factors for both managed land and unmanaged land were calculated where data were available.

4. Following the *Wetlands Supplement*, land was assigned to an organic soil drainage category. All organic soils on Unmanaged Land were treated as undrained organic soils, where these are wet organic soils that have not been previously drained. In the *Wetlands Supplement*, all organic soils on managed land were assumed to be either drained organic soils (subject to active drainage) or rewetted organic soils (subject to active hydrological restoration). This analysis deviated from the IPCC approach by allowing for undrained organic soils on managed land. This refinement resulted from the description of such sites in published studies, guidance by TSC members, and the identification of such sites within the Peat-Emit dataset (such as grazed but undrained Andean peatlands and harvested but undrained tropical palm forests). Several countries also already report emissions from managed land on undrained organic soils in their national reporting. For example, the United Kingdom includes undrained upland bogs that have been modified by grazing or burn management. Drainage category assignment relied on assessment of site hydrological data and descriptions and on evidence of management interventions applied (such as narrative descriptions or visible interventions such as drainage ditches). Where data were available, the allocation to drained organic soil or rewetted organic soil categories was based on evidence of relevant human activities and corroborating hydrological data. Allocation to the undrained organic soil category was based on either evidence of minimal historical anthropogenic disturbance or the absence of evidence of drainage activities. In the latter case higher weight was assigned to the presence of corroborating hydrological data where available.
5. The method outlined in the *2006 IPCC Guidelines* was used for assigning land to a land-use (or land-cover) category. This method uses a hierarchical approach with land classified as either Forest Land, Cropland, Grassland, Wetlands, Settlements or Other Land, depending on ecological, hydrological and management criteria (Figure 2). Emission factors were calculated at this level of disaggregation for the less data-rich regions: Latin America and the Caribbean, Africa, and cool climate Asia.
6. Finally, due to the relatively large dataset obtained for warm climate Asia, it was possible to further subdivide the overarching IPCC land-use categories to produce a higher-resolution set of EFs for this region. Nonetheless, like the situation encountered by the authors of the *Wetlands Supplement*, the available data were not evenly distributed across land-use categories. Therefore, far greater disaggregation was possible for Forest Land and Cropland (including Plantations) than for other land-use categories in this region.

2.1.6 Emission factor calculations

Where possible the EF estimation approaches described in the *2006 IPCC Guidelines*, the *2019 Refinement* and the *Wetlands Supplement* were followed. Input data were obtained through a literature review process described in Section 2.2. The approach described in Section 2.1.1 through Section 2.1.4 was used to estimate organic soil GHG emissions for each site that reported flux or stock change data. Categorical EFs were calculated as the equal-weight arithmetic mean of the relevant sample. Where relevant, EFs were calculated for categories separately while both including and excluding peat core data. Due to data constraints, error extrapolation methods would not be possible in all cases. Therefore, in the interest of methodological consistency, simple, symmetrical 95 percent confidence intervals (CIs) were derived from the variance of the relevant sample. Due to the small sample size of many categories, 95 percent CIs were calculated using the “CONFIDENCE.T()” function in Microsoft Excel. CIs were not reported for any category where the relevant sample contained less than three data points.

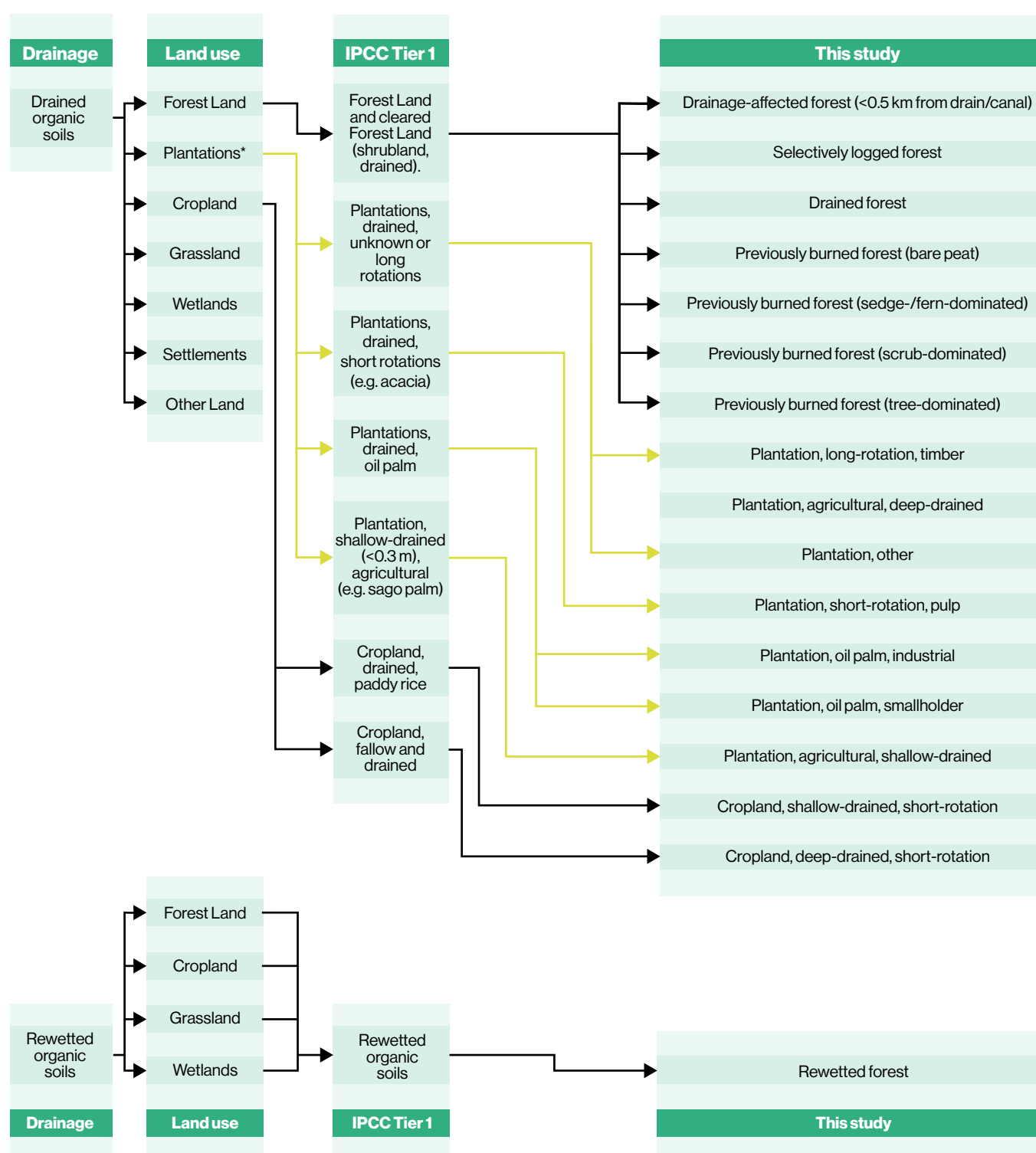
Figure 2 Overview of the broad land classification system used for this analysis


Notes: This figure is based on the classification system of the 2006 IPCC Guidelines and the 2019 Refinement.

* Unmanaged land must be undrained.

** Cropland and settlements must be managed land.

Source: Authors' own elaboration

Figure 3 Extension of the classification system for Southeast Asia

Notes: This figure shows disaggregation beyond both the basic land-use categories and the Tier 1 categories as outlined in the *Wetlands Supplement*. Further disaggregation of IPCC Tier 1 categories (such as more rewetted land uses) would be possible with data on additional ecosystems.

* Plantations may be included under Forest Land or Cropland as decided by national inventory compilers.

Source: Authors' own elaboration

2.2 Data collection

2.2.1 Terrestrial greenhouse gas emissions

Separate structured literature searches were completed to identify publications presenting data relevant to terrestrial GHG fluxes from organic soils for developing economies in:

- warm climate Southeast Asia,
- cool climate Asia,
- Latin America and the Caribbean, and
- Africa.

Developing economies were defined following the classification used in the *World Economic Situation and Prospects 2023* report (United Nations, 2023). The main GHG outcomes of interest were terrestrial emissions of CO₂, CH₄ and N₂O. The objectives of the search were to:

- support the development of proposed new/updated organic soil GHG EFs for developing economies in these regions; and
- identify knowledge gaps and data limitations that create emissions reporting challenges for developing economies in these regions.

For warm climate Asia, Scopus searches were conducted separately for each gas to manage the large number of publications retrieved for this region (Appendix 1: Table A1.1). Search results represent all available publications from the Elsevier Scopus database up to 1 August 2024. The outcome search terms were varied as detailed in Table A1.1, conducting individual searches to identify papers that reported CO₂ fluxes, CH₄ fluxes, and N₂O fluxes. Separate targeted searches were also conducted to identify publications reporting CO₂ fluxes obtained using flux tower methods and publications reporting subsidence rates. The flux tower search focused on identifying eddy covariance measurements. However, one study (Suzuki *et al.* 1999) that employed a similar relaxed eddy accumulation method, which bypasses the need for rapid response sensors and measurements of CO₂ concentrations, was also included even though this method is generally expected to have a lower accuracy.

Separate “title, abstract and keyword” searches of the Elsevier Scopus database were performed using tailored search strings on 21 May 2024 for Latin America and the Caribbean (Appendix 1: Table A1.2); 20 June 2024 for Africa (Table A1.3); and 13 August 2024 for cool climate Asia (Table A1.4). For each of these regions, a single search string was used, which included all outcomes of interest due to the lower number of publications retrieved for these regions. These search strings were organized using Boolean operators, ensuring that publications were included only if they mentioned a relevant outcome, a relevant population, and a relevant region. A broad set of search terms was used to define the study population, including non-specific habitat terms (such as wetland) to capture the widest possible range of sources because relevant publications do not always explicitly refer to “peat” or “organic soil”. For the cool climate Asia search, exclusion terms were used when defining the relevant region to filter out results related to warm climate Asia, which would have been identified in the separate search for that region. Indirect estimators of the main outcomes of interest were also targeted (such as subsidence and carbon accumulation rate), along with component measures that can be combined to derive values for the main outcomes of interest (such as litterfall, fine root mortality and R_{het}). Search terms for outcomes related to peat fires (fire, combustion, burn) were also included in the Latin America and the Caribbean, Africa, and cool climate Asia region-specific searches to identify additional sources to support the parallel work to update tropical peatland fire EFs. Additional literature was identified by “snowballing” from search results, additional targeted searches using Google Scholar, and through the support of the

TSC. Following the TSC meeting in July 2024, additional search terms were included, and the Scopus searches were updated (23 July 2024) for Latin America and the Caribbean (Table A1.2), and Africa (Table A1.3). In addition, following the recommendation of the TSC, a regionally focused Scopus search was conducted (5 August 2024) for tropical Florida, United States, specifically targeting the Everglades (Table A1.5). The objective was to identify potential analogues for warm climate sites in Latin America and the Caribbean where data availability is limited.

Given the large number of publications retrieved, particularly those reporting CO₂ emissions, a two-stage screening process was used. First, the results of the literature search were sequentially screened for relevance by title, abstract and full text. At each level, publications were excluded if there was evidence that they did not include relevant data. Where relevance was unclear, publications were retained for the next level of screening to minimize false negatives. Second, given the project's objective was the development of proposed new/updated Tier 1 EFs, the remaining publications were further screened to assess the suitability of the presented data for this purpose.

The following data were extracted where available for publications from all regions:

- lead author, publication and year;
- country and geographical region;
- study site name;
- latitude and longitude;
- land-use/cover description and history;
- habitat/vegetation description;
- depth of organic soil layer
- soil description/classification;
- hydrological description;
- water table depth;
- measurement method and frequency;
- start/end dates of study period;
- flux calculation methodology;
- NEE, R_{eco} , GPP, biomass carbon inputs ($C_{biomass-in}$), biomass carbon removals ($C_{biomass-out}$), net ecosystem production (NEP), soil respiration (R_{soil}), heterotrophic respiration (R_{het});
- litterfall inputs ($Litter_{AG}$);
- fine root mortality inputs ($Litter_{BG}$);
- long-term carbon accumulation rate (LORCA);
- CH₄ flux; and
- N₂O flux.

For warm climate Asia, additional data was collected on the distance to drainage/canal systems. Appendix 5 (Table A5.1) contains a detailed list of all data that would be collected under ideal circumstances.

2.2.2 Tropical peatland fires and fire emissions

Building on a previous literature review undertaken by FAO (2021), a systematic literature search was completed to identify publications presenting data relevant to emissions from peatland fires. The main outcomes of interest for this review were:

- fire-derived GHG emissions; and
- the mass of peat combusted (fuel consumption).

In addition, the appropriateness of the recommended C_f of 1.0 was evaluated. To illustrate the prevalence of contemporary (as opposed to paleo) peatland fires within the regions of interest, an indicative literature database of publications reporting peatland fires in countries with developing economies was compiled.

Like the search methods described above for terrestrial GHG emissions, a search of the Scopus database was completed to locate publications on peatland fires and fire emissions. The search string used (Table A1.6) did not employ specific regional or country terms to avoid excluding any studies that were of wider relevance to the topic. An initial search was undertaken on 9 May 2024 and repeated on 3 October 2024. The results of this literature search were screened for relevance based on title, abstract and full text. Studies were specifically selected that provided information on fire driven GHG emissions and mass of peat combusted. Papers were also retained where they provided information on the location of peatland fires outside of Southeast Asia (given that the bulk of studies are for that region), even if they did not contain data that was directly relevant to the development of peatland fire EFs.

For the fire-related literature, data were extracted on:

- study site location;
- land-use category;
- vegetation cover;
- year(s) in which the study was conducted;
- methodology;
- types and numbers of measurements;
- values for GHG EFs (G_{ef} for CO_2 , CO and CH_4);
- mass of fuel available for combustion (M_B);
- peat bulk density; and
- depth of burn.

Peat carbon content and fuel moisture content (FMC) were also noted where this information was available, and values for modified combustion efficiency (MCE) that provide confirmation that emissions are from smouldering combustion (combustion of peat with MCE values typically less than 0.9, as opposed to MCE values typically equal or greater than 0.9 for flaming combustion of above-ground fuels). In addition, it was considered whether use of the default value of 1.0 for the C_f remained appropriate.

2.2.3 Assessment of study suitability

Publications identified through the database searches were critically appraised to evaluate their suitability for inclusion in the EF database. Publications and data points were subjected to a thorough screening process intended to optimize the balance between inclusivity and quality control required to obtain the most useful possible dataset (given the literature search targeted several less data-rich regions). Most of the data points were identified from the published literature and have been subject to peer review. A small number of unpublished data points were also obtained through personal communications, and in this case, a copy of a manuscript under preparation was provided to enable a comparable screening process to that used for published literature to be undertaken. Where more than one publication reported data from the same exact location and extended time series from the same sampling points (such as collars and subsidence poles), the most recent study was used if it presented the full time series or estimates from multiple studies were aggregated to cover the full time series. Studies from the same peatland at different locations were considered distinct sites.

During the literature screening process, a set of criteria were developed to use as guidelines when assessing the suitability of studies for use in EF derivation. These criteria reflected strengths and weaknesses in study methodologies and reporting and are listed in [Appendix 6](#). These criteria should provide a useful guide for end users looking to understand the underlying decision-making processes used to derive EFs during this project. However, it should be recognized there was a degree of subjectivity in data screening. This is partly captured by the differences between *minimum* criteria and *recommended* criteria listed in [Appendix 6](#). Recommended criteria represent more stringent requirements for inclusion of data points from data-rich regions. These therefore provide a guide to the standards required for inclusion of data points in the warm climate Asia sample. Minimum criteria represent less stringent requirements imposed for inclusion of data points from less data-rich regions to balance an increase in data availability against a possible reduction in data quality. Minimum criteria are therefore more representative of standards required for inclusion of data points in the samples for Latin America and the Caribbean, Africa, and cool climate Asia. Studies were assessed holistically, and criteria were not treated as pass/fail. This was necessary (particularly in less data-rich regions) because studies might have strengths in some areas that counterbalance weaknesses in others (especially around measurement frequency, duration and timing). This holistic assessment avoids unnecessary exclusion of otherwise acceptable studies based on arbitrary thresholds. When studies did not meet some criteria, greater tolerance was shown for methods that could potentially lead to reduced precision, but studies were excluded if designs were considered likely to have created systematic (directional) biases. Also, studies were not included if any form of conversion was required for which there was not an IPCC precedent (see [Section 2.1](#)).

To appropriately aggregate seasonal values into annual emissions estimates, data points from studies covering only isolated seasonal periods were not included in the database due to the challenges associated with identifying comparable sites and time series. It is possible that the inclusion of seasonal studies could slightly increase the number of data points available for EF development. This is particularly the case for cool climate Asia, reflecting a slight trend towards publication of data covering shorter seasonal periods for that region. However, the number of additional data points obtained would likely be small. This benefit would therefore probably be outweighed by the risks of double counting emissions where time series overlap and could introduce unrealistic estimates if different seasonal periods from years with very different climatic conditions were combined.



The impact of grazing on a peatland in South America

© Christopher Evans

3. Results and discussion

This section presents project results, including:

- an evaluation of the availability of organic soil emissions data for developing economies; and
- the proposed new/updated terrestrial GHG and fire EFs produced during this project.

This is followed by a discussion of the implications of the Peat-Emit project's key findings for emissions reporting and research, before making a set of recommendations for key actors.

3.1 Emissions data availability

3.1.1 Terrestrial greenhouse gas emissions data

A total of 560 new data points relevant to terrestrial organic soil GHG emissions/removals were identified, which were not believed to have been included in the *Wetlands Supplement* (Figure 4). Data points from warm climate Southeast Asia (373) accounted for 66 percent of these new data points, and 79 percent of new data points if peat core studies were excluded.

The Peat-Emit EF database included 442 data points for the warm climate zone (Table 1). Of these, 249 (56 percent) reported CO₂ fluxes or indirect estimators of these (of which 23 were from peat core studies); 115 (26 percent) reported CH₄ fluxes; and 78 (18 percent) reported N₂O fluxes. Overall, there were more data for CO₂ than for the other GHGs for all warm climate regions. However, if peat core studies are excluded, there were very few warm climate CO₂ data points outside Southeast Asia (16 in total). Flux data for N₂O were far scarcer for Latin America and the Caribbean than Asia and unavailable for Africa (Table 1). Data points from Asia accounted for 84 percent of the warm climate zone emissions dataset; Latin America and the Caribbean accounted for 14 percent; and Africa accounted for 2 percent.

The Peat-Emit EF database also included 118 data points within the geographic scope of the project for the cool climate zone (Table 1). No cool climate data were obtained for Africa. Of the cool climate zone data points: 75 (63 percent) reported CO₂ fluxes or indirect estimators of these (of which 62 were from peat core studies); 34 (29 percent) reported CH₄ fluxes; and only 9 (8 percent) reported N₂O fluxes. A similar pattern was observed for both cool climate regions. Overall, the dominance of CO₂ data was more pronounced for Latin America and the Caribbean than for Asia (Table 1). However, this reflects a larger number of peat core studies within the sample for

Latin America and the Caribbean (51; 91 percent of CO₂ data points) than for Asia (11; 58 percent of CO₂ data points). As for the warm climate zone, if peat core studies are excluded, relatively few estimates of CO₂ emissions/removals remain (13). There were around 1.5 times as many cool climate data points for Latin America and the Caribbean (76) as there were for Asia (42).

There were, therefore, relatively similar numbers of cool climate (76) and warm climate (62) data points for Latin America and the Caribbean, suggesting that research efforts have been quite evenly distributed at a larger spatial scale in this region (Figure 4). However, it should be noted they can be more spatially concentrated at smaller scales, for example due to uneven spatial distribution of organic soil, sites of special interest, ease of access, or longstanding/ongoing research presence in certain areas. There were substantially more (approximately 9 times) warm climate than cool climate data points for Asia (Table 1; Figure 4). In part, this reflects the strong recent research focus on tropical Southeast Asian peatlands due to their intensive use and drainage and associated high GHG emissions.

Overall, the new data identified by the Peat-Emit project represents an approximately 45 percent increase in available data points of sufficient quality to support the development of organic soil direct terrestrial GHG EFs relative to the *Wetlands Supplement* dataset. Given that the literature search was regionally limited to focus on developing economies (Figure 4) and excluded some of the most data-rich regions (Europe and North America), this represents a major increase in available data. The total number of published studies from which EFs could now be derived globally is likely to be significantly higher than the number that were available in 2013.

Nonetheless, it is important to note that the utility of new data is somewhat dependent on obtaining enough data points within defined categories to produce robust category means. Data availability is not evenly distributed between regions or GHGs (Table 1). By far the largest concentration of new data points (66 percent) are from warm climate Southeast Asia (Figure 4; Table 1). There are now approximately 2.5 times as many data points available for warm climate Asia as there were at the time of the *Wetlands Supplement*. This could allow Tier 1 EFs for this region to be substantially updated. In contrast, the remaining 34 percent of data points are distributed across a very wide range of regions and climate zones. Therefore, although these also represent new data, they provide extremely limited scope for developing and proposing new/updated Tier 1 EFs.



A view of a peatland in Tierra del Fuego

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Table 1 Number of new organic soil emissions/removals data points identified by the Peat-Emit project compared to the *Wetlands Supplement*

Study	Climate		CO ₂	CH ₄	N ₂ O	All GHGs
<i>Wetlands Supplement</i> *	Tropical		65	46	34	145
	Boreal and temperate		441	430	254	1125
	Total		506	476	288	1270
This study	Warm	Asia	210	88	75	373
		Latin America and the Caribbean	13 (34)	25	3	41 (62)
		Africa	3 (5)	2	0	5 (7)
		Total (Warm)	226 (249)	115	78	419 (442)
	Cool**	Asia	8 (19)	19	4	31 (42)
		Latin America and the Caribbean	5 (56)	15	5	25 (76)
		Total (Cool)	13 (75)	34	9	56 (118)
	Total		239 (324)	149	87	475 (560)

Notes:

* *Wetlands Supplement* figures calculated as the sum of the sample sizes for each GHG for each climate zone for drained/rewetted organic soils. This does not therefore, include some data points used to derive EFs reported in the *2006 IPCC Guidelines* but is nonetheless indicative of additional data included during the work to produce the *Wetlands Supplement*.

** The literature searches conducted for this project were restricted to relatively less data-rich regions within the cool climate zone.

Therefore, a direct comparison with the number of data points in the *Wetlands Supplement* is of limited value. However, these values are included to highlight that a non-negligible number of additional data points from less data-rich regions have been identified, particularly for CO₂ emissions.

Values are presented excluding peat core studies, with totals including peat core studies presented in brackets where applicable.

Source: Authors' own elaboration

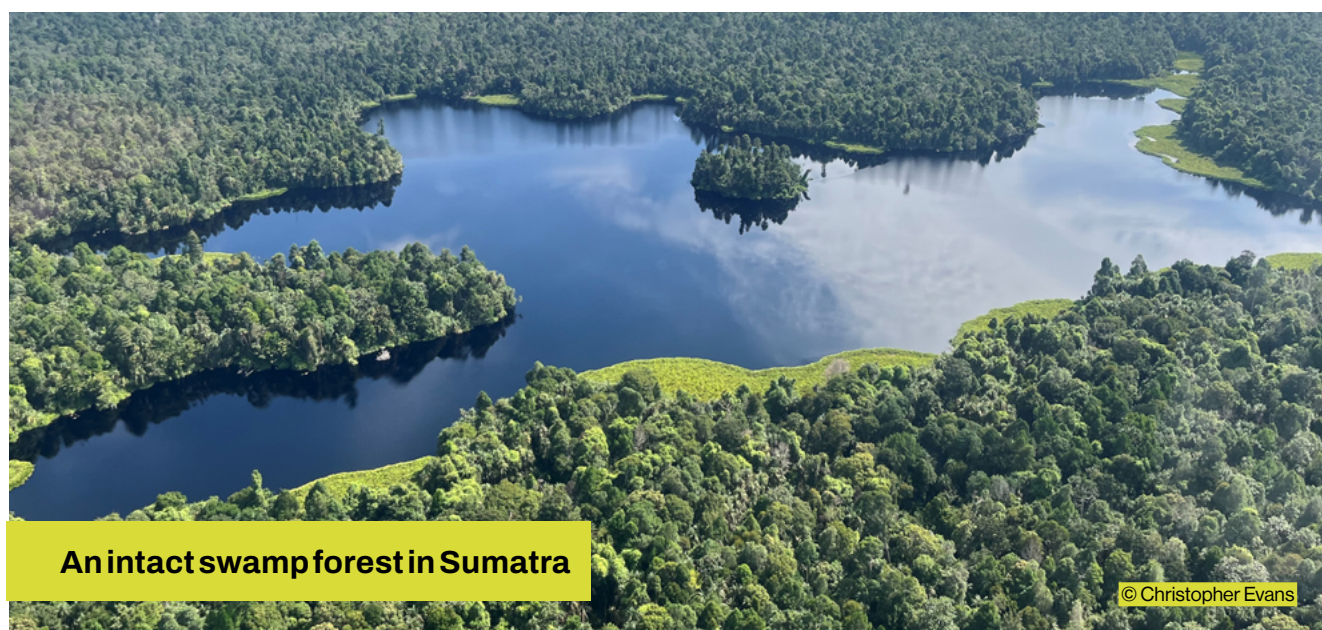
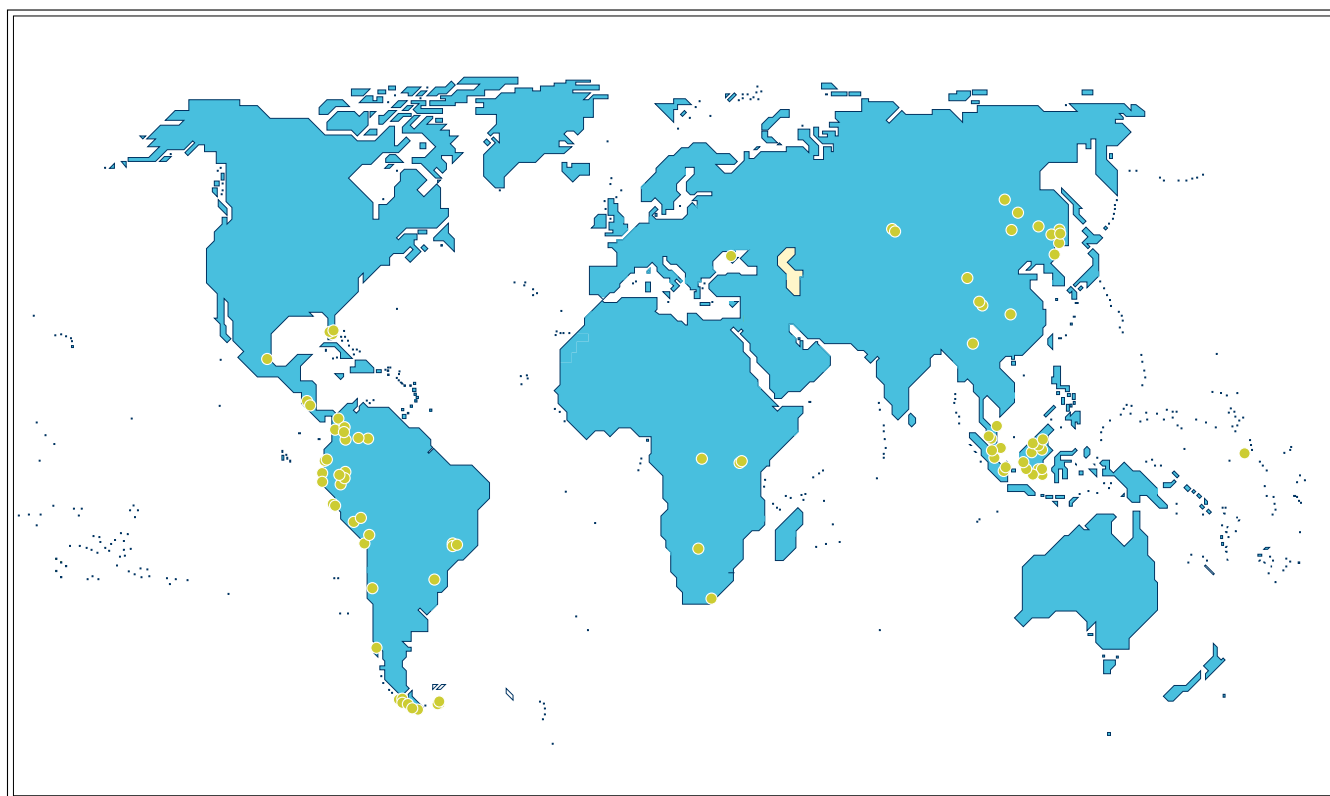


Figure 4 Geographic distribution of the organic soil terrestrial emissions/removals data points included in the Peat-Emit project EF database



Notes: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

The points on this map are indicative of the areas for which data were identified. However, map points do not indicate individual data points. Therefore this map should be interpreted as a guide to the geographic areas included in the Peat-Emit EF database. It does not display the total number of data points included or indicate the relative geographic density of data points for different regions.

Source: Authors' own elaboration

3.1.2 Fire emissions data

Compared to terrestrial GHG EFs, data availability for updating methodologies for tropical peatland fire emissions reporting remains relatively limited both in terms of the number of studies and their geographical scope (Table 2). However, of the 14 studies relevant to fire GHG EFs (Table 2), 13 have been published since the *Wetlands Supplement*. This represents a proportionally important increase in data availability and allows us to have increased confidence in the updated fire GHG EFs. It should also be noted, however, that all but one of these studies are from Southeast Asia. Similarly, the number of studies reporting on peat fuel consumption has risen from five to nine since the *Wetlands Supplement*, but all are from Southeast Asia (Table 2). Therefore, even though data availability is improving, it is still limited, and the regional concentration of data is even more pronounced than for terrestrial GHG emissions.

Table 2 Data sources related to peatland fires identified by the Peat-Emit project compared to the *Wetlands Supplement*

Time period	Articles using relevant terms	Relevant articles	Articles relevant to GHG EFs	Articles relevant to mass of fuel consumed	Articles relevant to fire location outside Southeast Asia
All dates	766	64*	14 (13 from Southeast Asia; 1 from Florida, United States)	9 (all from Indonesia)	15 (United States, Latin America and the Caribbean, and Africa)
2013 onwards	605 (79%)	54* (84%)	13 (93%) (12 from Southeast Asia; 1 from Florida, United States)	4 (44%)	11 (73%)

Notes: Values are counts apart from % values in brackets, which indicate the percentage of the total for each category which was published since 2013.

* Included articles such as reviews, meta-analyses, methodological and descriptive accounts, many of which did not contain primary data for determining default values for GHG emissions factors or mass of fuel.

Source: Authors' own elaboration

Like the situation for terrestrial GHG EFs, the geographical concentration of data points affects the utility of these new resources for updating peatland fire EFs. The limited literature on tropical peatland fire emissions and mass of fuel combusted is entirely for studies undertaken in Southeast Asia and tropical United States. Outside of these regions, records were found of peatland fires in South Africa (Elshehawi *et al.*, 2019; Grundling *et al.*, 2021; Le Roux *et al.*, 2021), Botswana (Ellery *et al.*, 1989; Gumbrecht *et al.*, 2002), the Kenyan highlands (D. Taylor, personal communication, 2025) and the Angolan Highlands (Lourenco *et al.*, 2023); and in Central and Latin America (Costa Rica: Perez-Castillo *et al.*, forthcoming; Brazil: Borges *et al.*, 2016; Guyana: A. Garbutt, personal communication, 2025). This suggests that peatland fires are widespread throughout many of the areas covered by this report and at least partly associated with management activities. However, none of the studies from these areas provided data that met the criteria for inclusion, so at this stage the evidence base for estimating fire emissions cannot be expanded beyond the comparatively data-rich Southeast Asian region.

3.2 New and updated emission factors

3.2.1 Terrestrial greenhouse gas emission factors

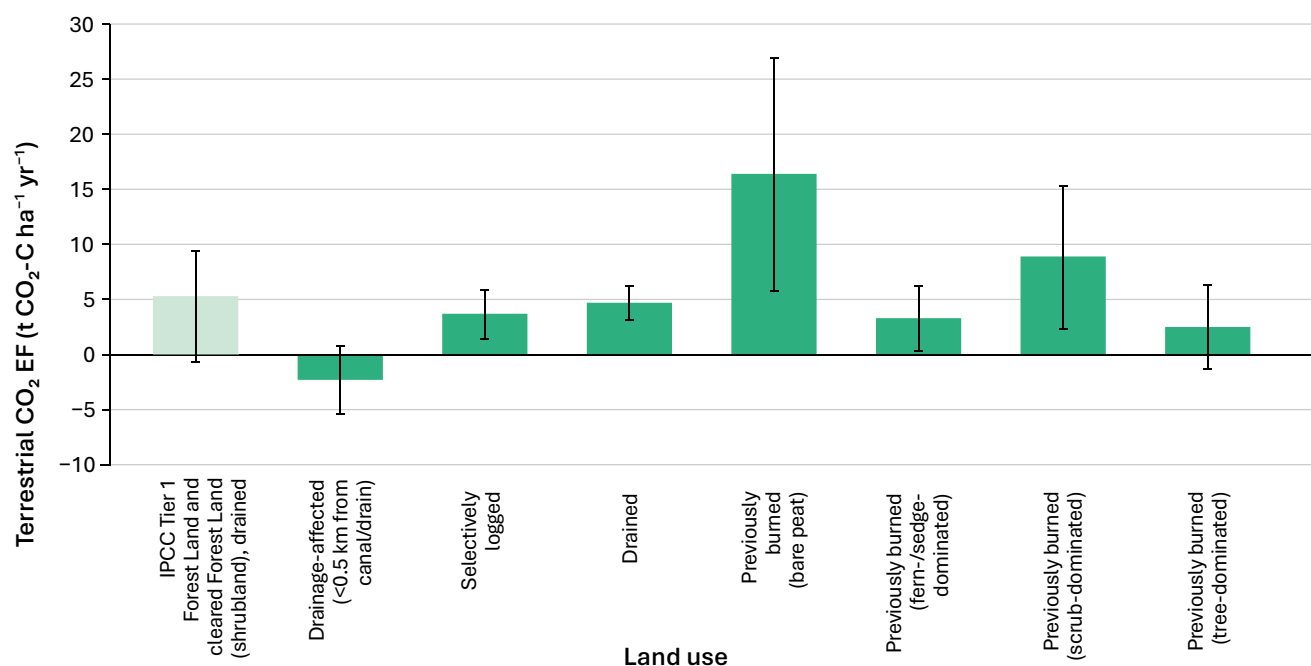
Where data were available, EFs were calculated for each GHG (CO₂, CH₄ and N₂O) for each climate zone (warm climate and cool climate) within each region (Asia, Latin America and the Caribbean, and Africa). Overall cool climate zone EFs were not estimated because a very large proportion of relevant data is from Europe and non-tropical North America, and these regions fell outside the scope of this project's literature searches, which focused on developing economies. Therefore, only regional cool climate EFs were calculated for Latin America and the Caribbean (Table A3.6.A, Table A3.6.B, Table A3.12, Table A3.17) and Asia (Table A3.5.A, Table A3.5.B, Table A3.11, Table A3.16). It should be highlighted that Japan (a developed economy) and most nations formerly within the former Soviet Union (economies in transition), were outside the scope of the search for cool climate Asia. Consequently, given that a large proportion of identified data were from China, any use of the regional cool climate Asia EFs produced by the Peat-Emit project would be most appropriate in the context of East Asia and with account taken of their limited scope.

The scope of the literature search provided far greater geographical coverage for the warm climate zone. Overall warm climate zone EFs were estimated (Table A3.1.A, Table A3.1.B, Table A3.7, Table A3.13), but these may not account for all warm climate zone data globally due to the Peat-Emit project’s focus on developing economies. Like the tropical EFs in the *Wetlands Supplement*, the warm climate zone EFs produced by this project were highly dependent on data from Southeast Asia. Tropical regions of Australia and Hawaii, United States fell outside of the search scope, and so any organic soil emissions data from these locations would not be included. A handful of subtropical sites from Brazil and hot semi-arid sites from Botswana were included in the dataset for the warm climate zone as they were not suitable for inclusion within the cool climate zone, and were viewed as potentially useful data for less data-rich regions. However, the search scope did not include large areas of subtropical climates elsewhere (for example, in North America). Therefore, the search was not fully exhaustive for the warm climate zone. Nevertheless, it should be largely consistent with the default tropical Tier 1 EFs from the *Wetlands Supplement* which were reliant on data from Southeast Asia. Regional warm climate EFs were also calculated separately for Asia (Table A3.2, Table A3.8, Table A3.14), Latin America and the Caribbean (Table A3.3.A, Table A3.3.B, Table A3.9, Table A3.15), and Africa (Table A3.4.A, Table A3.4.B, Table A3.10). The search scope covered the entirety of these three regions, so the resulting regional EFs should represent the most appropriate data sample available for each (subjectivity in inclusion criteria aside). Due to the large number of EF tables produced (21), these are presented in Appendix 3.

For warm climate Asia, the Peat-Emit EF database builds on the data collated for the *Wetlands Supplement*, and there are consequently similarities between some of the EFs proposed by this project and the tropical Tier 1 default EFs. However, the substantial increase in data availability for this region allowed both refinement of EFs for existing categories and disaggregation of Tier 1 categories into notably different land-use subcategories. This was particularly the case for managed Forest Land and Plantations on drained organic soil, where EFs for some new subcategories differed substantially from Tier 1 values.

Disaggregation of the Forest Land (including cleared forest) category into more specific subcategories, revealed substantial differences in terrestrial CO₂ emissions/removals between these (Figure 5). The IPCC Tier 1 default EF for tropical Forest Land agrees well with this project’s new/updated EFs for “drained” and “selectively logged” forest. However, the IPCC value would not be applicable to “drainage-affected forest (within less than 0.5 km from a canal/drain)”. These sites may be identified as drained organic soil, but the change in water table depth is in many cases minimal, and these sites may still be net terrestrial CO₂ sinks. There was also a substantial amount of variation among “previously burned” forest subcategories. This high variation was also present within these subcategories, reflecting lower data availability, so conclusions should be drawn cautiously. However, these data do suggest that the IPCC Tier 1 default EF for Forest Land may under-estimate terrestrial CO₂ emissions from cleared Forest Land during some successional stages. Similarly, the data obtained by the project suggest that the single composite IPCC Tier 1 default EF for tropical “long-rotation” and “unknown” Plantations on drained organic soil may no longer be the most accurate estimate available. Disaggregation of this category into appropriate subcategories (Figure 6) suggests that emissions from both “long-rotation, timber” Plantations and unknown (“other”) Plantations may be lower than the IPCC value in warm climate Asia.

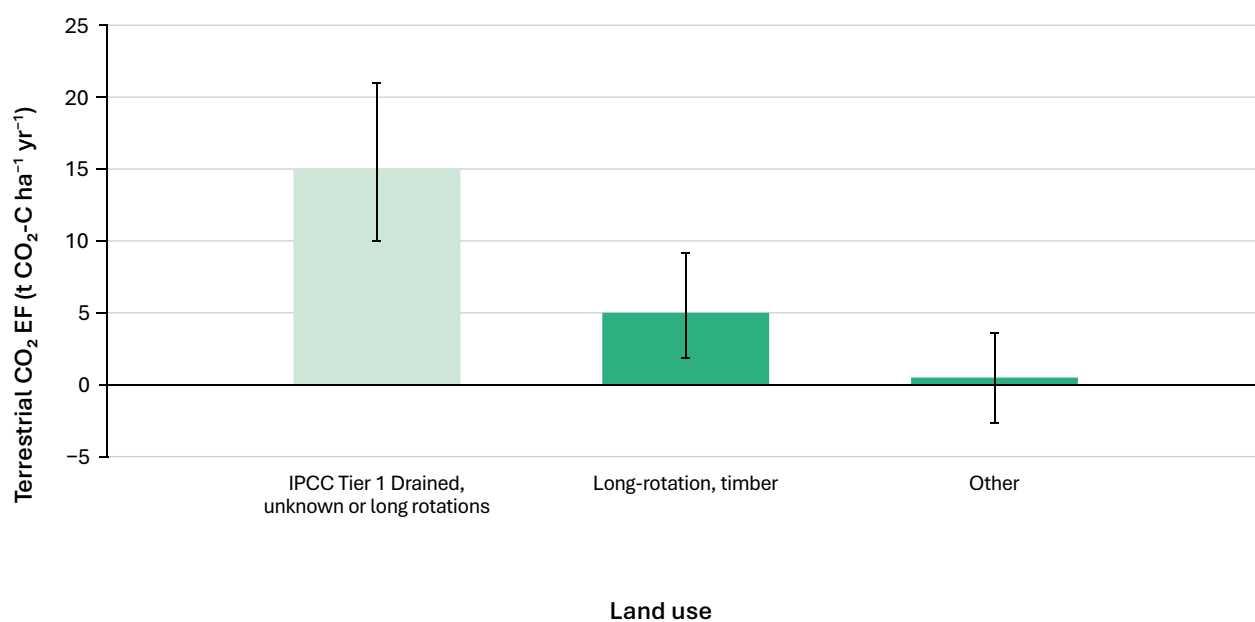
Figure 5 Disaggregation of terrestrial carbon dioxide emission factors for Forest Land on drained organic soil in warm climate Asia



Notes: The figure shows the IPCC Tier 1 default EF from the *Wetlands Supplement* (lighter green) and subcategory EFs produced by this study (darker green). Error bars represent 95% confidence intervals (CIs).

Source: Authors' own elaboration

Figure 6 Disaggregation of terrestrial carbon dioxide emission factors for long-rotation plantations on drained organic soil in warm climate Asia



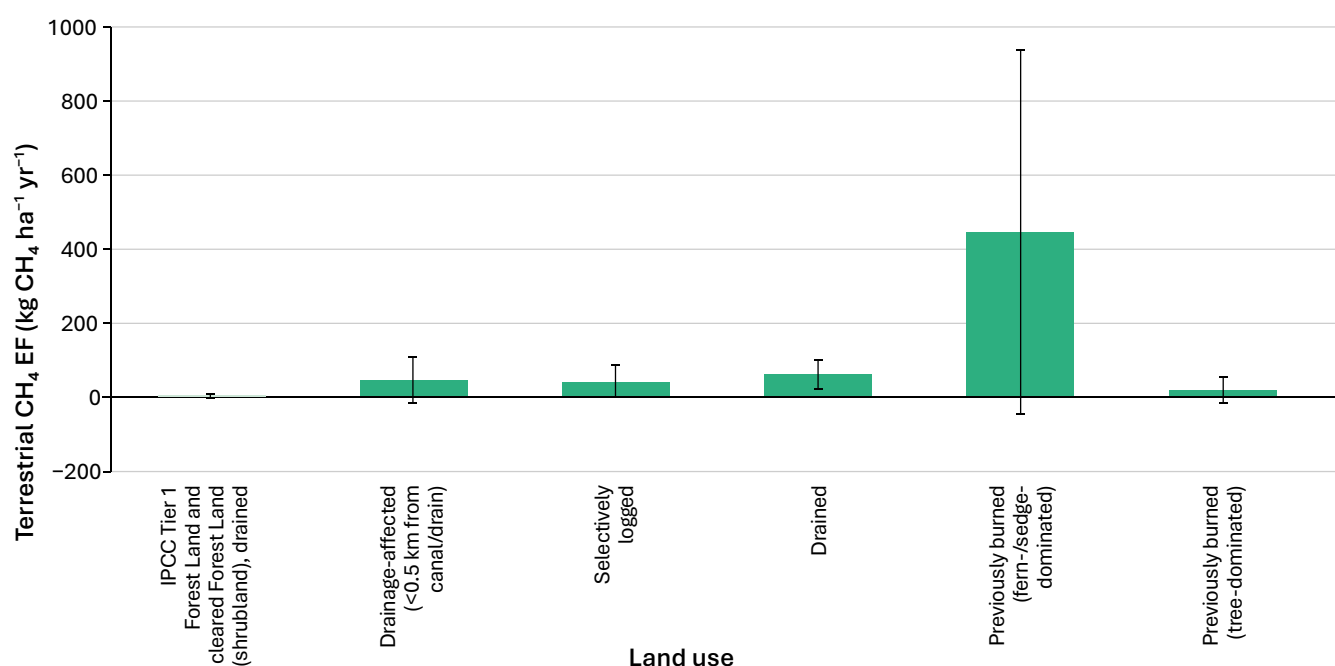
Notes: The figure shows the IPCC Tier 1 default EF from the *Wetlands Supplement* (lighter green) and subcategory EFs produced by this study (darker green). Error bars represent 95% confidence intervals (CIs).

Source: Authors' own elaboration

Disaggregation of the Forest Land (including cleared forest) category into more specific subcategories, also revealed potentially substantial differences in terrestrial CH₄ emissions between these subcategories (Figure 7). Variability in estimates of CH₄ emissions is notably higher than for CO₂ emissions, and thus there is a large amount of overlap between the 95 percent CIs for the various subcategory estimates. However, two conclusions do appear to be supported by the data. The first is that the IPCC Tier 1 default EF for tropical Forest Land is likely to be an underestimate of CH₄ emissions in many cases, as the EFs estimated by this project were higher for all subcategories. This is true even for the “drained” Forest Land subcategory, suggesting that the IPCC Tier 1 default EF may not have captured sufficient variability to be representative of the full range of conditions possible for this land-use category. Secondly, very high variability in CH₄ emissions was observed even within some subcategories, suggesting that land-use categorization alone may not fully reflect the underlying environmental dynamics driving CH₄ emissions.

This project’s proposed new EFs also suggest that the IPCC Tier 1 default EF for CH₄ emissions from oil palm Plantations, which was based on a single study, may be an underestimate. Disaggregation of the oil palm Plantations category into “industrial” and “smallholder” subcategories further suggests that the magnitude of this underestimation could be substantial for industrial oil palm Plantations in particular (Figure 8). However, data for “industrial” oil palm Plantations were highly variable. Therefore, even though there are now substantially more data (n = 10 for this subcategory), there remains a relatively high degree of uncertainty in the value of the proposed new EF for this subcategory. It is therefore not currently possible to make a precise assessment of the degree to which the IPCC Tier default EF may underestimate CH₄ emissions from oil palm Plantations.

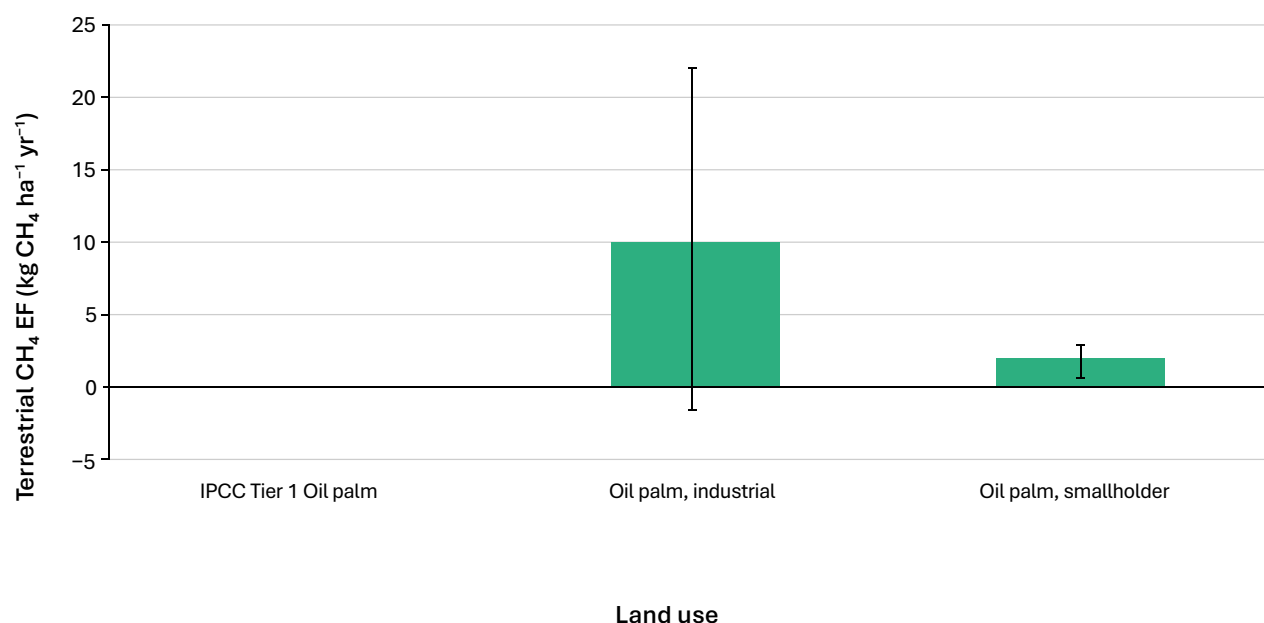
Figure 7 Disaggregation of terrestrial methane emission factors for Forest Land on drained organic soil in warm climate Asia



Notes: The figure shows the IPCC Tier 1 default EF from the *Wetlands Supplement* (lighter green) and subcategory EFs produced by this study (darker green). Error bars represent 95% confidence intervals (CIs).

Source: Authors' own elaboration

Figure 8 Disaggregation of terrestrial methane emission factors for oil palm Plantations on drained organic soil in warm climate Asia



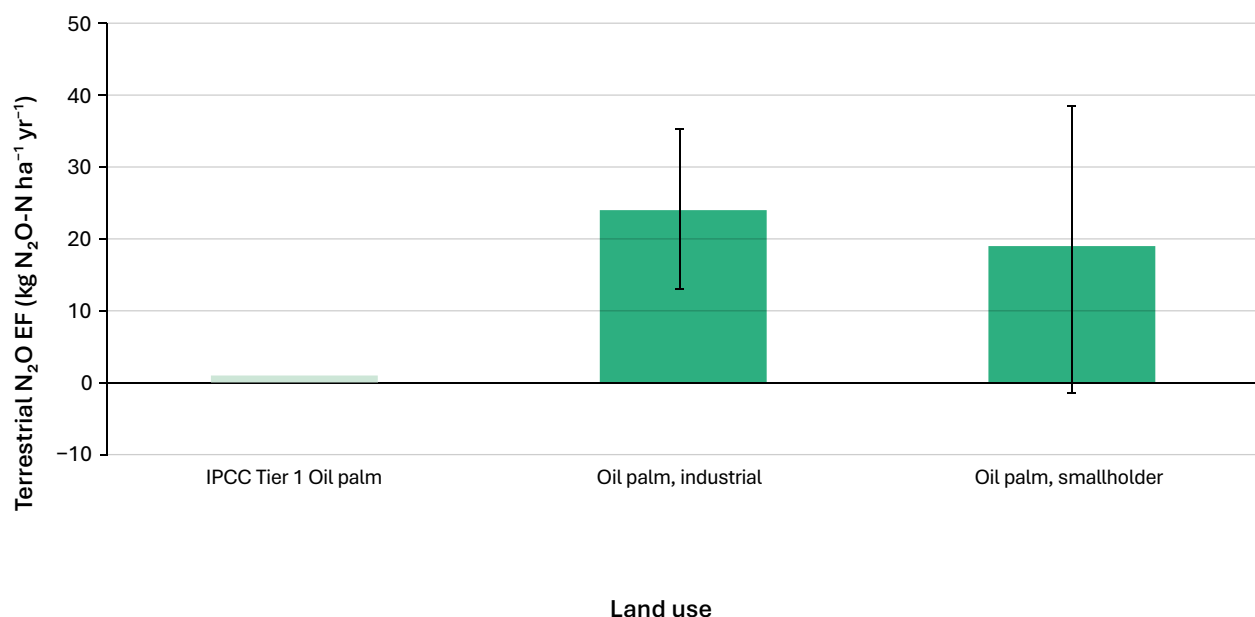
Notes: The figure shows the IPCC Tier 1 default EF from the *Wetlands Supplement* (lighter green) (note that in this case the Tier 1 default value is 0 based on $n = 1$) and subcategory EFs produced by this study (darker green). Error bars represent 95% confidence intervals (CIs).

Source: Authors' own elaboration

Disaggregation of the oil palm Plantations category into “industrial” and “smallholder” subcategories also suggests that the IPCC Tier 1 default EF for N₂O emissions for oil palm Plantations may quite substantially underestimate N₂O emissions from oil palm Plantations (Figure 9). This conclusion is better supported for “industrial” than “smallholder” oil palm Plantations, which likely reflects greater variation in fertilization practices on smallholder sites, and thus greater variability in N₂O emissions data, as the sample sizes were similar for the two subcategories (industrial vs smallholder: $n = 13$ vs $n = 15$, respectively).

The Peat-Emit project’s updated dataset also indicates that the IPCC Tier 1 default EF for tropical drained Cropland is likely to substantially underestimate average N₂O emissions for this land use (Figure 10). Even with a relatively large sample size ($n = 34$), variability for deep-drained, short-rotation Cropland was high. As with smallholder oil palm Plantations, it appears likely that variation in fertilizer use within the land-use subcategory results in variation in N₂O emissions. This indicates that there is very likely to be a degree of double counting of N₂O emissions for fertilized land uses, with fertilizer emissions captured both by organic soil EFs and fertilizer EFs. No new data for sago Plantations or rice paddy Cropland have been published since the *Wetlands Supplement*, so it is unclear whether this effect applies to other fertilized land uses at this time.

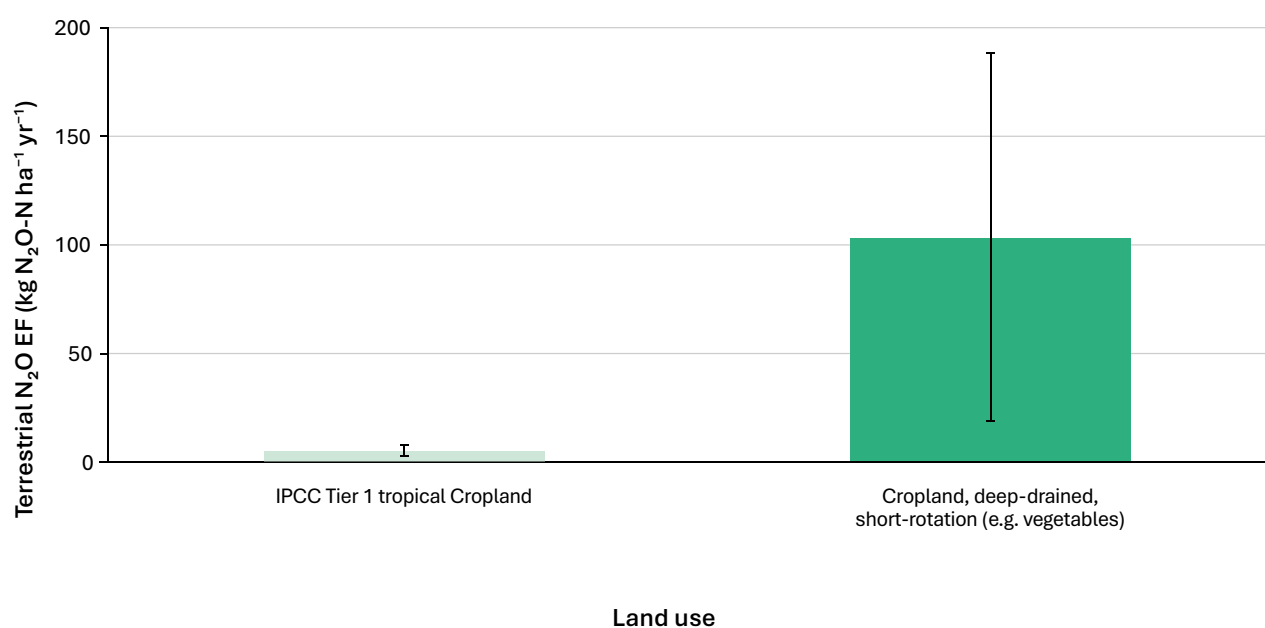
Figure 9 Disaggregation of terrestrial nitrous oxide emission factors for oil palm Plantations on drained organic soil in warm climate Asia



Notes: The figure shows the IPCC Tier 1 default EF from the *Wetlands Supplement* (lighter green) and subcategory EFs produced by this study (darker green). Error bars represent 95% confidence intervals (CIs).

Source: Authors' own elaboration

Figure 10 Terrestrial nitrous oxide emission factors for deep-drained Cropland (excludes rice cultivation) on drained organic soil in warm climate Asia



Notes: The figure shows the IPCC Tier 1 default EF from the *Wetlands Supplement* (lighter green) and subcategory EFs produced by this study (darker green). Error bars represent 95% confidence intervals (CIs).

Source: Authors' own elaboration

There is a notable division in the warm climate dataset. Warm climate zone EFs for undrained organic soils are entirely reliant on data from outside Asia. This is likely to be largely a consequence of the scale of regional land-use change, which makes it likely that even the least disturbed forests may be affected by drainage of adjacent land and/or selective logging. As such, none of these areas can be strictly categorized as unmanaged land on undrained organic soil. In contrast, the warm climate managed land (drained and rewetted organic soil) EFs are highly (and in most cases entirely) dependent on data from warm climate Southeast Asia. The only overlap between regional datasets for the warm climate zone was for CO₂ emissions from the “Cropland, deep-drained, short rotation (e.g. vegetables)” subcategory (Table A3.1.A, Table A3.1.B). Beyond the relatively large Southeast Asian sample, the additional data for this category were based on three subsidence estimates from Florida, United States (Table A3.3.A) and a single data point from East Africa (Table A3.4.A). The values for these four additional data points all sit below the 95 percent CIs of the warm climate Asia EF for this subcategory (Table A3.2). This suggests there may be some regional variations in Cropland CO₂ emissions due to drainage intensity and the length of time since drainage. However, given the small number of data points available outside of Asia, no strong conclusions can be drawn.

Generally, the warm climate terrestrial GHG EFs that could be estimated for Latin America and the Caribbean agree well with those for Africa. Undrained land-use categories generally show some degree of net CO₂ uptake, while net CO₂ emissions are observed from drained Cropland (Table A3.3.A, Table A3.3.B, Table A3.4.A, Table A3.4.B). Undrained categories are also associated with relatively high warm climate CH₄ EFs in these regions (although there is a high degree of variability associated with these values), and they are notably higher than the tropical rewetted organic soils CH₄ EF from the *Wetlands Supplement* (Table A3.9, Table A3.10). EFs for N₂O are low for undrained organic soil in Latin America and the Caribbean (Table A3.15), but there are no N₂O flux data available for Africa. Reflecting patterns in data availability, warm climate EFs were consistently more robust for CO₂ than for CH₄ and again for N₂O, for all regions. In fact, no robust CH₄ or N₂O EFs were produced for Africa. For warm climate Latin America and the Caribbean, it could be argued (subjectively) that only one genuinely robust CH₄ EF was produced for unmanaged and undrained Forest Land, and none for N₂O. If data from peat core studies are excluded it could also be argued that no truly robust CO₂ EFs were produced for these two regions either. A far greater number of (subjectively) robust EFs were produced for warm climate Asia than for other regions in the warm climate zone. Again, reflecting variation in sample size and measurement variability, CO₂ EFs were generally identified as being more robust than those for CH₄ and N₂O for this region. However, a number of robust EFs were also produced for CH₄ and N₂O. For warm climate Asia, the use of regionally specific EFs can be justified for most land-use subcategories, but end users should consider the robustness of individual EFs in their decision-making processes because some categories are supported by only relatively small sample sizes. The use of regionally specific EFs cannot currently be justified in most cases for managed land from warm climate regions outside of Asia, because of the scarcity of relevant data points. Therefore, either the IPCC Tier 1 default EFs or the overall warm climate zone EFs presented in this report (Table A3.1.A, Table A3.1.B, Table A3.7, Table A3.13) should be considered as alternatives.

For cool climate Latin America and the Caribbean, all data points were obtained from undrained organic soils (Table A3.6.A, Table A3.6.B, Table A3.12, Table A3.17). Most data for cool climate Asia also represented undrained organic soil (Table A3.5.A, Table A3.5.B, Table A3.11, Table A3.16). However, there was also a single measurement of CO₂ emissions from drained Grassland. The very large CO₂ uptake for cool climate Forest Land in Latin America and the Caribbean (Table A3.6.A) is only based on a single data point (Perez-Quezada *et al.*, 2024). Otherwise, terrestrial CO₂ balances for cool climate undrained organic soils tend to be close to zero for Latin America and the Caribbean and show a net uptake in many cases (Table A3.6.A, Table A3.6.B). Except for managed but undrained organic soil, CH₄ emissions were surprisingly low from undrained organic soil in cool climate Latin America and the Caribbean (Table A3.12) compared to cool climate Asia (Table A3.11). This may reflect the presence in the Peat-Emit EF database of shallow organic soils, the formation of which is strongly influenced by recalcitrant litter inputs (such as montane

cloud forests) or chemical inhibition of mineralization (such as volcanic influenced upland soils in the Andes) (Tonneijck *et al.*, 2010). Compared to peatlands formed predominantly due to water saturation, the presence of persistent anoxia favouring methanogenesis may be less common in these ecosystems. Also, cushion plant vegetation, common on South American peatlands, may be associated with high levels of CH₄ oxidation in the rhizosphere, which could also explain low CH₄ emissions from some sites classified as undrained Wetlands (Fritz *et al.*, 2011). Emissions of N₂O were generally low for sites in the database located within cool climate Latin America and the Caribbean (Table A3.17), and Asia (Table A3.16). This likely reflects the fact that these sites were generally not subject to intensive drainage or fertilization. Apart from CH₄ EFs for Latin America and the Caribbean, most values produced for cool climates in this analysis were broadly comparable to IPCC Tier 1 default EF values for similar land uses or their closest analogues (if undrained sites are compared to IPCC Tier 1 default EFs for rewetted organic soil, which relied on a large number of studies from undrained sites). By far the most robust EFs produced in both cool climate regions are those for undrained Wetlands. However, the apparent robustness of these EFs is highly dependent on the inclusion of many data points from peat core studies, which introduces a degree of uncertainty about the differences between past and current conditions. Overall, due to the substantial data limitations outside of Europe and North America, the IPCC Tier 1 default EFs remain the most robust option for most cool climate locations.

3.2.2 Fire emission factors

The parameters required for the quantification of the gaseous products of peatland fires are the area burnt, the mass of dry matter combusted (peat fuel), an appropriate GHG EF, and a C_f. The mass of fuel available for combustion is derived from measurements of depth of burn and peat bulk density. The *Wetlands Supplement* provides default values for GHG EFs (G_{ef}) and for dry matter combusted (M_b). It also assumes that the C_f is 1.0, which implies all fuel is combusted. Updated values for GHG EFs (G_{ef}) and for dry matter combusted (M_b) were derived based on the results of the literature review.

Fire greenhouse gas emission factors

A total of 14 suitable studies from tropical peatlands met the inclusion criteria. Of these, 13 studies provided data on CO₂ and CO emissions from tropical peat fires, and 14 studies provided data on CH₄ emissions (Table A4.1). Most studies took place in or used peat samples from Southeast Asia, mainly from Indonesia (Kalimantan and Sumatra). Only one study provided data from outside this region (Florida, United States; Watson *et al.*, 2019). This study is not from a developing economy, but it was included to illustrate the comparability of emissions values with the Southeast Asian studies.

In compiling Table A4.1, emissions data were only included if they had been obtained from smouldering peat fires with a MCE less than 0.9 (values ranging between 0.69–0.89). Data from fires consuming above-ground vegetation were excluded, even if measurements also included emissions from peat smouldering. For example, for the study by Wooster *et al.* (2018), only the data for “close-to-source peat only” fires were included, and for the study by Watson *et al.* (2019), data for combined flaming and smouldering combustion of peat from the Everglades was excluded. In addition, for the study by Hu *et al.* (2024), which measured emissions throughout the entire fire cycle from ignition to suppression, only emissions from the smouldering phase were included.

The proposed updated Tier 1 peat fire GHG EFs derived from this review (Table 3)¹⁰ compare with those published in the *Wetlands Supplement* guidance as follows:

- The proposed new EF for CO₂-C is 432 ± 25 g kg⁻¹ and agrees well with the *Wetlands Supplement* value of 464 g kg⁻¹.
- The proposed new EF for CO is 242 ± 32 g kg⁻¹ and agrees well with the *Wetlands Supplement* value of 210 g kg⁻¹.
- In contrast, the proposed new EF for CH₄ is 10.0 ± 2.3 g kg⁻¹, which is about half the value of 21 g kg⁻¹ reported in the *Wetlands Supplement*.

The *Wetlands Supplement* Tier 1 values were all derived from a single laboratory study (Christian *et al.*, 2003), whereas the proposed new EFs are derived from a total of 14 studies (eight field and six laboratory studies). The inclusion of both field and laboratory studies gives greater confidence in the suitability of the derived EFs for emissions reporting. Studies of emissions from a wider geographical range of locations (Central and Latin America and Africa) may, in future, permit derivation of region- or biome-specific EFs. The use of EFs derived from a single region requires assumptions about the consistency of peatland fire emissions across different regions. The data for fire-derived GHG EFs are relatively consistent between studies (Table A4.1), allowing greater confidence in the use of default EFs. Importantly, in this case, the suitability of the EFs presented in Table 3 could also be confirmed relatively easily by carrying out laboratory combustion studies of a suitable range of peat samples obtained from peatlands outside of Southeast Asia.

Table 3 Proposed updated Tier 1 peatland fire emission factors from this review compared to values in the *Wetlands Supplement*

Study	Emission factors (g kg ⁻¹ dry matter burned)					
	Carbon dioxide (CO ₂ -C)		Carbon monoxide (CO)		Methane (CH ₄)	
	EF (95% CIs)	n	EF (95% CIs)	n	EF (95% CIs)	n
This study	432 (407–457)	13	242 (210–274)	13	10 (8–12)	14
Wetlands Supplement	464		210		21	

Notes: EF values presented as means with 95% confidence intervals (CIs).

n = sample size.

Source: Authors' own elaboration

¹⁰ IPCC reports CO₂ emissions as CO₂-C, hence the average CO₂ emissions value reported in Table 3 has been adjusted accordingly.

Fuel consumption values

Data from a total of nine studies were retrieved for inclusion in [Table A4.2](#) (peat fuel consumption). All were from tropical peatlands in Southeast Asia (Kalimantan and Sumatra, Indonesia).

[Table A4.2](#) presents mass of (peat) fuel combusted. These studies encompass studies undertaken in forested peat landscapes, with a high above-ground fuel load, as well as studies in landscapes that have undergone deforestation and drainage and up to four or more consecutive fires and hence have a reduced above-ground fuel load. In the *Wetlands Supplement* guidelines, the peat fuel combustion values from five studies were stratified according to whether the fire was a wildfire on drained peat or a prescribed fire used as part of agricultural land management. Since the publication of the *Wetlands Supplement* guidance, the number of studies reporting mass of combusted fuel has hardly increased, with the current review yielding nine studies that met the inclusion criteria. Nevertheless, it may be possible to stratify based on fire recurrence (first fire, second fire and so on; [Table A4](#)). The stratification proposed here recognizes that:

- the land cover/vegetation of peatland being prepared for agriculture is essentially the same as that of a deforested peatland previously impacted by fire (ferns and low growing shrubs/small trees); and
- with successive fires the above-ground biomass stock is reduced, thereby reducing the vegetation fuel load, and combustion lowers the height of the peat surface bringing it closer to the water table, reducing depth of burn (Konecny *et al.*, 2016).

The reduced mass of peat fuel available for combustion with successive fires provides the basis for the stratification proposed in [Table 4](#). [Table 5](#) allows a comparison with the *Wetlands Supplement* default mass of fuel values.

It should be noted that values for mass of peat fuel available for combustion will vary not only according to vegetation cover and fire history, but also by water table depth, and hence peat water content, and drought occurrence (influenced in the Southeast Asian region by El Niño Southern Oscillation and Indian Ocean Dipole events). Burn depth may also be greater in the vicinity of tree trunks/tree bases and may change over the fire period. For example, Graham *et al.* (2022) report temporal variation, with an average burn depth of 0.012 m during August 2015 increasing to 0.075 m during September 2015. The spatial variability in burn depth is illustrated by the high standard deviation (depth of burn 0.23 ± 0.19 m) reported by Simpson *et al.* (2016).

The calculation of mass of fuel consumed is not only dependent on burn depth but also on peat dry bulk density. For some studies, a value for bulk density is derived from the literature, which may not sufficiently account for changes in this parameter following multiple fires, given that repeated burning can alter peat structure, compaction, and decomposition rates, which can potentially lead to underestimations or overestimations when applying generic bulk density values rather than site-specific measurements. For example, Konecny *et al.* (2016) report an average peat bulk density (0–40 cm depth) of 0.117 ± 0.018 g cm⁻³ for unburnt peat swamp forest. The average peat bulk density increases to 0.121 ± 0.018 g cm⁻³ for areas experiencing a first fire but diminishes to 0.115 ± 0.020 g cm⁻³ for more frequently burnt locations. Volkova *et al.* (2021a) also report an increase in peat bulk density (0–10 cm depth) from 0.124 ± 0.01 g cm⁻³ for secondary peat swamp forest burnt in 1997 to 0.154 ± 0.01 g cm⁻³ for secondary peat swamp forest burnt both in 1997 and in two more recent fires (2014, 2015). It would be best practice to obtain site-specific peat bulk density values that adequately reflect site characteristics, including fire history. In addition, Volkova *et al.* (2020b) and Krisnawati *et al.* (2021) both report a likely increase in peat carbon content with successive fires, although using the *Wetlands Supplement* approach, any such modification would be reflected in a change in site-specific GHG EFs. A further consideration raised by Volkova *et al.* (2021b) is that for fires on vegetated peatlands, a portion of the peat mass that is combusted at or close to the peat surface will be comprised of roots, rhizomes and plant litter. Given the somewhat greater variation in the fuel consumption data compared to the data on fire GHG emissions, there is a greater probability that these values may be more impacted by data limitations for regions outside of Southeast Asia.

Table 4 Proposed Tier 1 default values for fuel consumption by peatland fires

Climate	Subcategory	Fuel consumption (t DM ha ⁻¹)	
		Mean (95% CI)	n
Tropical	Peat swamp forest (may have been subject to peripheral drainage/selective logging)*	323 (196 – 462)	4 ^{i, ii, iii, iv}
Tropical	Deforested, drained fern-/scrub-dominated (may have burnt at least once previously)**	179 (106 – 252)	5 ^{v, vi, vii, viii}
Tropical	Deforested, drained fern-/scrub-dominated (burnt previously at least twice)	54 (24 – 84)	3 ^{iv, ix}

Notes:

DM = dry matter.

CI = confidence interval.

n = sample size.

* The Simpson *et al.* (2016) value is a mean of depth of burn across both forest and previously burnt peatland but is included here in the forest category. An argument could be made to move this study into the second category (peat swamp forest that has previously burnt), or to include the study in both the first and second strata (at the risk of pseudo-replication).

** The fire history of the site used by Volkova *et al.* (2021a) is not provided. Vegetation cover suggests it had previously burnt at least once, but perhaps more frequently.

Sources:

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

ⁱⁱ Ballhorn, U., Siegert, F., Mason, M. & Limin, S. 2009. Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. *Proceedings of the National Academy of Sciences*, 106(50): 21213–21218. <https://doi.org/10.1073/pnas.0906457106>

ⁱⁱⁱ Simpson, J.E., Wooster, M.J., Smith, T.E., Trivedi, M., Vernimmen, R.R., Dedi, R., Shakti, M. & Dinata, Y. 2016. Tropical peatland burn depth and combustion heterogeneity assessed using UAV photogrammetry and airborne LiDAR. *Remote Sensing*, 8(12): 1000. <https://doi.org/10.3390/rs8121000>

^{iv} Konecny, K., Ballhorn, U., Navratil, P., Jubanski, J., Page, S.E., Tansey, K., Hooijer, A., Vernimmen, R. & Siegert, F. 2016. Variable carbon losses from recurrent fires in drained tropical peatlands. *Global Change Biology*, 22(4):1469–1480. <https://doi.org/10.1111/gcb.13186>

^v Usop, A., Hashimoto, Y., Takahashi, H. & Hayasaka, H. 2004. Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia. *Tropics*, 4 (1): 1–19. <https://doi.org/10.3759/tropics.14.1>

^{vi} Saharjo, B.H. & Munoz, C.P. 2005. Controlled burning in peat lands owned by small farmers: a case study in land preparation. *Wetlands Ecology and Management*, 13: 105–110. <https://doi.org/10.1007/s11273-003-5110-z>

^{vii} Hamada, D., Limin, S. & Hatano, R. 2012. A small scale field experiment of peat burning in a tropical peatland located in Central Kalimantan, Indonesia. In: *Proceedings of the 14th International Peat Congress, Stockholm, Sweden, June 3–8*. Extended Abstract No. 82. <https://peatlands.org/assets/uploads/2019/06/Hamada-82.pdf>

^{viii} Volkova, L., Adinugroho, W.C., Krisnawati, H., Imanuddin, R. & Weston, C.J. 2021. Loss and recovery of carbon in repeatedly burned degraded peatlands of Kalimantan, Indonesia. *Fire*, 4(4): 64. <https://doi.org/10.3390/fire4040064>

^{ix} Graham, L.L., Applegate, G.B., Thomas, A., Ryan, K.C., Saharjo, B.H. & Cochrane, M.A. 2022. A field study of tropical peat fire behaviour and associated carbon emissions. *Fire*, 5(3): 62. <https://doi.org/10.3390/fire5030062>

Table 5 Wetlands Supplement Tier 1 default values for fuel consumption by peatland fires

Climate	Subcategory	Fuel consumption (t DM ha ⁻¹)
		Mean (95% CIs)
Tropical	Wildfire (undrained)	No data
Tropical	Wildfire (drained)	353 (170 – 536) ^{i, ii, iii}
Tropical	Prescribed fire (agricultural land management)	155 (82 – 228) ^{iv, v}

Notes:

DM = dry matter.

CI = confidence interval.

Sources:
ⁱ Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D.V., Jaya, A. & Limin, S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, 420(6911): 61–65. <https://doi.org/10.1038/nature01131>
ⁱⁱ Usop, A., Hashimoto, Y., Takahashi, H. & Hayasaka, H. 2004. Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia. *Tropics*, 4 (1): 1–19. <https://doi.org/10.3759/tropics.14.1>
ⁱⁱⁱ Ballhorn, U., Siegert, F., Mason, M. & Limin, S. 2009. Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. *Proceedings of the National Academy of Sciences*, 106(50): 21213–21218. <https://doi.org/10.1073/pnas.0906457106>
^{iv} Saharjo, B.H. & Munoz, C.P. 2005. Controlled burning in peat lands owned by small farmers: a case study in land preparation. *Wetlands Ecology and Management*, 13: 105–110. <https://doi.org/10.1007/s11273-003-5110-z>
^v Saharjo, B.H. & Nurhayati, A.D. 2003. The changes in chemical and physical properties of fibric peat following burning. *Jurnal Tanah dan Lingkungan*, 5: 1–6.

Combustion factor

Using the *Wetlands Supplement* approach requires use of a dimensionless $C_f = 1$ that implies that all fuel has been combusted. No change in the value of C_f is proposed here, given that:

- the amount of burned peat is accounted for by depth of burn and peat dry bulk density; and
- the effects of combustion completeness are considered through the application of suitable EFs (G_{ef}) that are representative of smouldering conditions and hence of combustion completeness.

Nevertheless, it is accepted that there can be considerable spatial and temporal variability in mass of peat fuel combusted owing to heterogeneity of the burnt peat surface, and the value for the mass of fuel available (M_b) can contribute to uncertainty in emissions reporting (see Graham *et al.*, 2020).

For studies reporting carbon loss, as opposed to GHG emissions, from peatland fires, it will be necessary to apply appropriate data for peat carbon content which, as noted above, may vary with site fire history (Volkova *et al.*, 2021a, 2021b; Krisnawati *et al.*, 2021).



Flux tower on peat in South America

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3.3 Implications for emissions reporting

3.3.1 Evaluation of available categorical emission factors

The *Wetlands Supplement* developed Tier 1 EFs for the boreal, temperate and tropical climate zones, and for most major drained land-use categories (such as Forest Land, Cropland, Grassland, Wetlands managed for peat extraction). For the boreal and temperate climate zones, it was possible to disaggregate some land-use categories by the nutrient status of the type of peatland (“nutrient-poor” bog versus “nutrient-rich” fen). For tropical organic soil, some land-use categories were further disaggregated according to the specific crop or tree type present (such as rice, sago, oil palm, short-rotation tree species for pulp production). Both the subcategories developed and the EFs obtained were heavily influenced by the geographical distribution of published studies providing relevant data, with boreal and temperate data overwhelmingly derived from Europe and North America, and tropical data exclusively derived from Southeast Asia. These regional biases are partly a reflection of the regions where large-scale peatland drainage has occurred but are also related to where most peatland researchers were based at that time. It is now clear that some important geographic regions and land-use categories were under-represented or even omitted from the *Wetlands Supplement*.

For the cool climate zone, it remains the case that most published data on emissions for drained organic soils come from Europe and North America. However, an increasing number of studies are now available for other regions including East Asia and South America. These studies could either support a more representative update of the IPCC default Tier 1 EFs or form the basis for new region-specific EFs in the future once more data become available. The Peat-Emit project did not attempt to update current Tier 1 EFs for temperate and boreal peatlands. Given the large number of studies published for Europe, North America and other relevant countries (such as Japan and New Zealand) since 2013, such an update would be a major undertaking and would best be carried out as part of an official IPCC update of the *Wetlands Supplement*. Clearly, if updated guidance is to be presented, this should include explicit consideration of previously under-represented regions such as South America and Africa. However, in the absence of new field measurement studies, any future update will face the same data gaps as the Peat-Emit project in developing stand-alone EFs for these regions. This remains the key challenge for many countries in implementing emissions reporting for organic soils. In this study, temperate, boreal and polar Köppen-Geiger climate zones were aggregated into a single cool climate zone within the geographic scope of the review. Further disaggregation by climate was simply not practical due to the constraints imposed by continuing data limitations in these regions (outside of Europe and North America). The cool climate zone definition used here also includes organic soils formed under cool conditions at high altitudes in the tropical latitudes (for example, in the Andes, Qinghai-Tibetan Plateau, and highlands of Central/East Africa, Indonesia and Papua New Guinea), which were not represented in the *Wetlands Supplement*. It should be noted that high-altitude ecosystems may have distinct characteristics, but again, data availability was insufficient to robustly disaggregate climatic and altitudinal influences, so a single overarching cool climate zone was deemed to be the most defensible approach for the current study.

One other major gap in the current *Wetlands Supplement* guidance is the lack of methods to account for emissions from organic soil ecosystems that have been modified through land-use pressures that do not involve active drainage (such as livestock grazing, palm harvesting, reed harvesting and fire management). These activities can lead to vegetation change, peat drying and erosion, all of which can lead to emissions (or at least to reduced rates of peat formation). Although these “managed but undrained organic soils” fall outside the original UNFCCC mandate for the *Wetlands Supplement*, there is a strong case for including undrained organic soil affected by human activities in future IPCC emissions reporting guidance. It is also worth noting that managed undrained organic soils are extensive in many parts of the world, including Europe and North America, and that they include areas that retain some form of native plant species cover (and which would therefore typically be treated as unmanaged land) but that may nevertheless have been converted into GHG sources as a result of land use.

For the warm climate zone, there has been a marked increase in the availability of high-quality published emissions data from warm climate Southeast Asia in particular, allowing us to derive and propose updated EFs for existing land-use categories and propose new EFs for additional land-use subcategories in some cases for this region. There has also been an expansion in the number of studies providing data from other warm climate regions, notably from Amazonia, but with some important gaps remaining in terms of both geographic regions (such as Central Africa) and data for managed lands. As a result, it would be beneficial if EFs derived from one geographic region were transferrable to other less data-rich regions. However, some of the current IPCC Tier 1 default EFs for tropical peatlands are highly specific to Southeast Asia and represent land-use activities that are either rare or absent in other regions. As a result, a single set of pan-tropical Tier 1 EFs may not be feasible or useful and would likely require aggregation into more generic land-use categories than those currently presented in the *Wetlands Supplement*. Realistically, given differences in the types and uses of peatland in Africa, and Latin America and the Caribbean, additional flux data are likely to be needed to develop robust, regionally representative category-based EFs for these areas. This study, as well as other recently published reviews (Swails *et al.*, 2024) highlight the difficulties of developing Tier 2 EFs for regions and agroecological zones where data remain scarce. Until more primary measurement data are collected and published, this will continue to constrain future expansion of organic soil emissions reporting.

This study also identified only four new data points providing GHG emissions estimates for rewetted peatlands (all for Forest Land in warm climate Southeast Asia). This reflects a wider challenge for emissions reporting, as data from rewetted sites remain relatively scarce. The *Wetlands Supplement* did contain a separate chapter providing EFs and methodologies for rewetted organic soils. However, this was substantially less developed than the chapter on drained organic soils and relied on data from unmanaged, as opposed to rewetted, organic soils. While this use of data from unmanaged peatlands as a proxy for re-wetted peatlands was necessary at the time, it is doubtful whether they represent true analogues for rewetted sites that in many cases represent “novel” ecosystems with different emissions. For example, flooding of former agricultural peatlands could lead to above-natural CH₄ emissions, whereas rewetted sites that are rebuilding their biomass and litter carbon stocks could exhibit above-natural rates of CO₂ removal due to land-use change effects.

Data for tropical peatland fire emissions reporting are still limited. In particular, values for mass of fuel combusted (requiring data on depth of burn and peat dry bulk density) make a large contribution to the uncertainty around peat fire emissions estimates (Rodriguez Vasquez *et al.*, 2021). Studies reporting depth of burn remain limited in number and focus only on the Southeast Asian region. Nevertheless, methodologies for measuring the mass of peat fuel combusted have expanded beyond field measurements. Several studies have employed LiDAR or UAV photography. Calculation of fire emissions also requires knowledge of burnt area. This parameter is usually derived from Earth observation data, but there may be high associated uncertainty given dense clouds and smoke that can limit the accuracy of optical remote sensing approaches (Vetrita *et al.* 2021). The number of studies reporting tropical peat fire GHG emissions has increased from the one study (Christian *et al.*, 2003) that was used in the *Wetlands Supplement* to fourteen studies reported in this review. Christian *et al.* (2003) carried out laboratory measurement of gaseous emissions from burning one sample of Indonesian peat. Since that time, there have been more laboratory studies and, importantly, more field studies that provide data directly from smoke plumes and thus are more representative of *in situ* conditions than laboratory studies. The emissions data derived from both types of study are relatively consistent, providing confidence in the EFs presented in this report. It is clear from this review that peat fires are also occurring outside of the Southeast Asian region, and a general lack of data for other regions represents a major challenge for overall peat emissions reporting.

The *Wetlands Supplement* continues to provide a strong foundation for reporting emissions from drained and rewetted organic soils. The existing methodologies are broadly clear and consistent, and in principle suitable for application in developing countries. The *Wetlands Supplement* also still provides the best resource for obtaining EFs for managed land within the cool climate zone. However, an update of Tier 1 values would be beneficial, to incorporate both the new data

identified for this climate zone across Asia, and Latin America and the Caribbean, along with data from the large number of new studies from Europe, North America and other high-latitude regions that have been published since 2013. The large number of new published studies the Peat-Emit project identified for warm climate Asia supports the use of the proposed new/updated EFs (both for peat surface and fire emissions) for this region. Inclusion of the Peat-Emit project's EFs in the IPCC EFDB will be targeted to ensure that they are seen as suitable for national reporting purposes and to encourage their adoption. Their inclusion in the IPCC EFDB will require further scrutiny beyond the already rigorous independent peer-review process carried out by the Peat-Emit project TSC, which should provide end users with confidence in the suitability and robustness of the EFs produced. Given the heavy reliance of the IPCC Tier 1 default tropical EFs on data from Southeast Asia, the proposed new/updated warm climate zone EFs produced by the Peat-Emit project also represent the current best option for use elsewhere in the warm climate zone. However, this remains less than ideal, as it will often result in the use of EFs that are not strictly appropriate for transfer between regions. Similarly, the IPCC Tier 1 default EFs developed for northern temperate and boreal peatlands may not be transferrable to the cool high-altitude peatlands of the equatorial region or the high-latitude peatlands of the Southern Hemisphere. This is particularly the case for peatlands that have undergone degradation and drying due to activities other than active drainage (which is relatively rare in the region), such as grazing. Pronounced regional data gaps remain, along with a scarcity of data for some important land-use categories. This applies both to the data-rich region of Southeast Asia, where emissions data for some land-use subcategories remain sparse, and to other geographic regions where there are few or no data for some land-use categories. Limited availability of activity data to support reporting may also restrict the implementation of emissions reporting in many countries, although this issue was beyond the scope of this study. These data gaps will continue to present major challenges for some countries in trying to accurately report their emissions.

3.3.2 Potential benefits of water table-based emission factors

The current Tier 1 method for deriving organic soil EFs, as well as the Tier 2 approaches used in some countries, are founded on a category-based approach. This approach, which was followed in the preceding analysis, aggregates measured emissions/removals from multiple studies within categories that are defined by a combination of climate zone, peat type, land use and management, to obtain a mean EF and associated confidence interval. This categorical approach has the merits of relative simplicity and transparency and can be relatively easily combined with activity data (such as land-cover maps) to generate national emissions estimates. Where large numbers of measurements are available, this method allows relatively robust and granular reporting of emissions/removals as a function of land use and management. However, as this analysis has demonstrated, a categorical approach becomes far less effective when applied to less data-rich regions, or to combinations of climate, peat type and land use that are not well represented in the published literature of emissions measurements. In these circumstances, the only options are:

1. derive EFs based on very few studies, which are therefore highly susceptible to anomalous data or unrepresentative sites;
2. aggregate available data to derive more robust but very broad EFs (such as a single EF for all drained peatlands); or
3. extrapolate EFs from data-rich to less data-rich regions, which may involve transferring data between highly dissimilar ecosystems and management systems.

Clearly none of these options provide a strong basis for predicting emissions/removals for less data-rich regions. No number of reviews and data syntheses (such as the review undertaken for this project) can overcome a fundamental lack of primary measurements if a categorical approach is used.

However, another significant development since the publication of the *Wetlands Supplement* is that datasets now extend over longer timelines. For example, several eddy covariance studies have now run for over a decade, providing better data on inter-year variability in emissions related to changes in management and climatic conditions (Hirano *et al.*, 2024). Increases in both temporal and spatial coverage of data continue to provide new insights into the underlying drivers of those emissions. There is now a substantial body of evidence (starting from before the publication of the *Wetlands Supplement*) showing that both CO₂ and CH₄ emissions are strongly related to average annual water table depth for both cool and warm climate zones (Couwenberg *et al.*, 2010, 2011; Hooijer *et al.*, 2010, 2012; Hirano *et al.*, 2012, 2013; Jauhiainen *et al.*, 2012; Carlson *et al.*, 2015; Tiemeyer *et al.*, 2020; Evans *et al.*, 2021; Koch *et al.*, 2023; Deshmukh *et al.*, 2023; Jovani-Sancho *et al.*, 2023; Aben *et al.*, 2024; Hirano *et al.*, 2024). Taken together, these studies suggest that mean annual water table depth in peatlands provides a robust and widely applicable predictor of the net CO₂ balance, from unmanaged natural wetlands through to intensively managed, deeply drained croplands and forestry plantations. These relationships have been demonstrated at national, continental and global scales for both the temperate and boreal climate zones (Couwenberg *et al.*, 2011; Tiemeyer *et al.*, 2020; Evans *et al.*, 2021; Koch *et al.*, 2023; Aben *et al.*, 2024) and the tropical climate zone (Couwenberg *et al.*, 2010; Hooijer *et al.*, 2010, 2012; Hirano *et al.*, 2012, 2013; Jauhiainen *et al.*, 2012; Carlson *et al.*, 2015; Evans *et al.*, 2021; Deshmukh *et al.*, 2023; Jovani-Sancho *et al.*, 2023; Hirano *et al.*, 2024). Recently published data suggest that water table depth can also predict annual CO₂ emissions over periods of change in climate and management (Hirano *et al.*, 2024). Similarly, CH₄ emissions have been shown to be related to mean annual water table depth (albeit non-linearly with resultant challenges) in both high-latitude and tropical peatlands (Couwenberg *et al.*, 2011; Turetsky *et al.*, 2014; Evans *et al.*, 2021; Jovani-Sancho *et al.*, 2023). These findings are largely consistent with the current mechanistic understanding of peatland biogeochemistry, in that rates of peat mineralization and resulting CO₂ emissions are primarily determined by the amount of peat organic matter that is exposed to oxygen above the water table, whereas CH₄ fluxes depend on the extent to which CH₄ produced under anoxic conditions below the water table can be transported to the atmosphere (via diffusion in bubbles or via plant stems) without being exposed to oxidation above the water table. Predicting emissions of N₂O is more difficult due to the complexity of the biogeochemical processes that lead to N₂O production, but there is some evidence that emissions may be predicted based on a combination of water table depth and fertilizer application rates (Couwenberg *et al.*, 2011; Jovani-Sancho *et al.*, 2023). It is also the case that water table depth because of its influence on peat soil moisture content is a key determinant of peat fire depth of burn and hence the mass of peat fuel available for combustion, with higher water tables reducing the mass of fuel and hence total GHG emissions (Konecny *et al.*, 2016; Graham *et al.*, 2022).

One implication of this evidence is that the current category-based approach to EF derivation used in the *Wetlands Supplement* may no longer be optimal for emissions reporting because it suggests that land-use *per se* is not the main driver of emissions. Instead, taken together, this growing body of evidence suggests that the drainage depth associated with any given form of management, rather than the form of management itself, is the primary determinant of emissions for most, if not all, major GHGs. For example, CO₂ emissions from a deeply drained cropland or forestry plantation might be far higher than those from a shallow-drained area within the same land-use category, but this would not be captured in Tier 1 emissions reporting. Furthermore, the category-based approach becomes highly restrictive to the extension of emissions reporting to less data-rich regions with regionally distinct land-use categories because it would not be valid to transfer EFs for existing categories to contexts with different land uses. The current study provides many examples of this for Africa, Latin America and the Caribbean, and non-tropical Asia. An alternative approach whereby emissions can be predicted based on measured water table depth for a “new” land-use category would be far more transferrable and potentially more robust than the current category-based approach. This observation is highly significant for the implementation of GHG reporting in less data-rich regions because it offers an alternative to the highly data-dependent categorical approach for deriving Tier 1 and Tier 2 EFs. For example, if it is known that a cropland on peat in equatorial Africa with an average drainage depth of 50 cm

is likely to have very similar CO₂ emissions to an oil-palm plantation with the same drainage depth in Indonesia, a reasonable prediction of emissions can be made for the former (for which only a single GHG flux measurement was obtained in this study) based on data from the latter, for which many more measurements are available. Furthermore, because the predictive functions based on water table are continuous, they can also be used to infer emissions for land-use subcategories with different water table depths (such as shallow-drained vs deep-drained Grassland) to support improved granularity of reporting even where flux data are limited. These strengths of the water table-based approach become particularly important where the IPCC methodology is being used for other purposes (such as the assessment of individual voluntary carbon market projects or corporate emissions) because the current category-based methodology cannot capture the mitigation benefits of raising water levels within a land-use category.

To be most effective, water table-based emissions reporting would be based on direct or indirect (remotely sensed) measurements of water table depth. This would provide more accurate estimates of national emissions, reflecting large-scale changes in water management and capturing the benefits of mitigation measures within land-use categories. For example, large-scale implementation of the Indonesian water table regulations within forestry plantation areas would not result in a change in CO₂ emissions reporting based on the current Tier 1 method (a short-rotation forestry plantation with a raised water level would still fall into the same category as a deeply drained one) but would result in a reduction in reported emissions based on the water table-based method. The method could also be applied “dynamically” in the future, in line with the results of Hirano *et al.* (2024) to report changes in emissions between wet and dry years. Currently, high-resolution water table depth data are rarely available, and a robust remote sensing method for estimating water table depth across complex peat landscapes (most notably for forested peatlands) remains elusive. However, progress is being made in canal-drained tropical plantation landscapes (Vernimmen *et al.*, 2020; Hooijer *et al.*, 2024). For less data-rich developing countries in particular, it is unlikely that such data will be available. Nevertheless, a water table-based approach might still be applied to these areas provided that *characteristic* annual mean water tables for different land-use categories could be obtained. Taking the African cropland example, if a particular cropping system is known to be associated with a particular form of water management, this information (which may be readily available) could be used to estimate the annual mean water table depth, and therefore the CO₂ and CH₄ emissions. If typical fertilizer application rates were known, it might also be possible to predict N₂O emissions. This approach would not require comprehensive or continuous data on water table depth for all locations.

The water table-based approach would have a strong empirical basis in published research, would be highly transparent, and would be relatively simple to apply even to less data-rich regions. Compared to the Tier 1 categorical approach, it would support more robust and complete reporting of emissions for peatlands in developing economies where direct measurements of GHG emissions are not yet available. This approach does not remove the need to collect flux data, which could be used to validate and where necessary refine predictive equations, but it would overcome some of the current problems with extrapolating from data-rich to less data-rich regions based on unrepresentative categories. It would be highly data-efficient and therefore could help to avoid potential delays of five years or more in reporting emissions for some countries while new GHG emissions data are being collected.



Chamber measurement of greenhouse gas fluxes, Tierra del Fuego

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3.3.3 Emissions estimation for carbon crediting

Beyond national reporting, carbon credit schemes represent another potentially important use case for estimates of GHG emissions/removals for organic soils and estimates of emissions reductions resulting from changes in management and/or land use. Where projects involve either actual or avoided land-use changes in regions for which relatively robust EF data exist (such as warm climate Southeast Asia), the Peat-Emit project's proposed EFs may be used to support carbon crediting. Given that the EFs presented here draw in many cases on a much larger and more recent dataset of measurements than the *Wetlands Supplement*, they could be considered more appropriate than the current IPCC Tier 1 values in some circumstances. It is, however, important to recognize the limitations of the EF approach when applied to project-level data. Fundamentally, EFs are intended to support national-level reporting, and therefore represent the average emissions for any given combination of land-use, climate zone and peat type at a global (Tier 1) or national (Tier 2) level. Given data limitations these categories are often coarse (for example, "Cropland" may cover many different crop types, fertilizer regimes and water management practices) and may or may not accurately represent conditions and resulting emissions at an individual project site. In addition, EFs are based on larger datasets and therefore likely to be more suitable for assessing changes in CO₂ emissions and removals compared to CH₄ or N₂O emissions. Where robust region and land use-specific EFs are not yet available, as is the case for most managed peatland categories in Africa and Latin America, the application of EFs developed for other regions should not be encouraged for carbon crediting purposes due to the potential for large differences in peat types or land-management practices. When using EFs for carbon crediting, caution should always be taken to evaluate the relative robustness of the individual EFs used, and the applicability of the EFs to the specific sites in question (to ensure site management/conditions are sufficiently comparable to those in the EF sample). These challenges lead to much monitoring for carbon projects relying on site-specific measurements, often of proxy variables. The category-based Tier 1 and Tier 2 approaches are largely unable to capture the mitigation benefits of changes in land management within a land-use category as opposed to land-use change between categories, such as raising water levels within farmland or forestry plantation systems. This challenge is especially relevant for rewetting projects because "rewetted organic soil" can include a wide range of outcomes in practice. Rewetting can result in different water table depths at different sites, and even spatially variable water table depths within individual sites, reflecting the challenges of hydrological management. Emissions can therefore vary substantially between sites within the single "rewetted" land-use category used to capture the range of possible outcomes. Consequently, carbon crediting scheme methodologies have long recognized the potential utility of using water table depth as a proxy measure to estimate emissions reductions. However, the application of a water table-based approach would be substantially facilitated if robust, widely recognized and accepted regression coefficients were available. The availability of such information could help to strongly incentivize the funding and implementation of measures to reduce emissions from managed peatlands.

3.3.4 Guidance on the use of proposed new/updated emission factors

Within the Peat-Emit project EF database there is inevitably substantial variation in the robustness of different EFs. This reflects variation in the size of samples from which data were derived, the quality of input data used, and the methods used to collect the underlying data. The precision (and often accuracy) of EFs based on small sample sizes is inherently lower, and estimates of uncertainty are not possible where single data points represent the only available data for a category. Therefore, caution should be taken with the use of such EFs for either inventory reporting or carbon credit schemes. The *Wetlands Supplement* established a precedent for the use of organic soil EFs based on a single data point. However, where the sample size obtained in the Peat-Emit project's analysis is less than three, it is recommended that Tier 1 default EFs from the *Wetlands Supplement* continue to be used.

New flux data for peatlands in warm climate Southeast Asia continue to be produced at a relatively rapid rate. Therefore, when developing the classification system for this region, an optimistic approach to the disaggregation of categories was taken on the basis that this would highlight key data needs and help to direct both ongoing and future research efforts. However, this analytical decision means that a subset of EFs for this region are less robust than the majority. In addition to the minimum sample size consideration mentioned previously, it is recommended that end users make a case-by-case assessment of the suitability of individual EFs before using them. For EFs where the sample size is large, and comparable to or greater than the sample used to derive the IPCC default value, users are recommended to consider using the proposed new/updated values produced by the Peat-Emit project (such as the CO₂ EF for drained Forest Land in [Table A3.2](#)). Where the sample size is relatively small or is less than the sample used to derive the IPCC default value, an important consideration is whether the proposed new/updated value produced by the Peat-Emit project may better represent the land use in question than the equivalent IPCC default value (such as the CO₂ EF for drainage-affected Forest Land in [Table A3.2](#)). Where the sample size is relatively small or is less than the sample used to derive the IPCC default value and there is no clear improvement in the representation of the land use, users are recommended to consider using the relevant IPCC default value (such as the CH₄ EF for long-rotation, timber Plantations in [Table A3.8](#)). Such an approach to EF evaluation should help to ensure selection of the most appropriate and robust values for each use case.

More stringent inclusion criteria were applied in data-rich regions, but in less data-rich regions criteria were relaxed to maximize the use of the limited information available. Therefore, users should be aware that EFs for less data-rich regions may be less robust and may change in future if an increase in the number of higher quality studies allows reassessment of the criteria applied. The decision to include peat core studies of historical long-term carbon accumulation rates (LORCA) was made to mitigate substantially lower data availability in some regions. However, this method does not provide a direct measurement of present-day carbon stock change or CO₂ flux. Therefore, EFs that are heavily reliant on data from peat core studies should be considered less robust than EFs based on a larger proportion of flux measurements. In light of this, where relevant, CO₂ EFs are presented based on samples both including and excluding peat core data. Overall, the results outside warm climate Southeast Asia are best interpreted as a gap analysis. EFs produced for these regions should therefore be treated as indicative rather than definitive. On this basis the use of the IPCC default EF values continues to be recommended for these regions.

All the risks outlined above are best mitigated by a transparent approach, providing full details about the origins of the data included and the EF calculation approaches used. The Peat-Emit project EF database, along with this report, should allow end users to identify the studies used to derive individual EFs and provide adequate information for evaluation of the robustness of the various EFs produced. However, it should be supplemented with interpretative aids at the dissemination phase of the Peat-Emit project to assist end users with making decisions around their use. This may be especially important for carbon projects, where the use of EF values based heavily on peat core studies may not be suitable. Where end users are unsure about the appropriateness or robustness of any EF presented in this report for their purposes, they are encouraged to seek expert guidance.



**Chamber measurement of
greenhouse gas fluxes, Panama**

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3.4 Implications for organic soil emissions research

3.4.1 Research priorities

The Peat-Emit project's analysis has highlighted substantial gaps in the availability of data for organic soil terrestrial GHG emissions/removals and peatland fire emissions. Much of the terrestrial GHG emissions/removals data identified were from warm climate Southeast Asia (Table 1). Developing economies in other regions were much less well represented, and very few data were available for some regions (such as Africa). Furthermore, most of the data identified for these regions were for undrained organic soils. Peatland fire emissions data were also dominated by data from Southeast Asia (Table 1). There is therefore a clear need for additional data from the less data-rich regions (Latin America and the Caribbean, Africa, and cool climate Asia) to support countries with emissions reporting. Where ecosystems and land uses in these regions are similar to those in data-rich regions (such as Europe, North America, warm climate Asia) it is possible that additional data may simply confirm the applicability of, and support minor updates to, IPCC Tier 1 default EFs. However, there are likely to be many ecosystems and land uses in less data-rich regions that do not have direct analogues in data-rich regions (or even in other less data-rich regions). In these cases, additional data could potentially support substantial increases in the accuracy and robustness of national emissions reporting, especially if there are large differences between estimates. The collection of sufficiently robust GHG emissions data from “managed land” land-use categories in less data-rich regions should, therefore, be treated as an important research priority. When considering emissions from managed land, the extremely small amount of data available regarding GHG emissions from and removals by rewetted organic soils should also be highlighted. Given the potential benefits of peatland rewetting for emissions reductions, researchers and funders alike are encouraged to prioritize the collection of this data to strengthen the case for rewetting. Development of robust EFs for rewetted organic soil could create a substantial incentive for countries to support the development and implementation of emissions reduction projects. The collection and reporting of water table depth data is also encouraged, to support the development of water table-based estimation approaches to facilitate both the implementation of emissions reduction projects and the development of EF estimates for regions and land uses for which there continues to be limited flux data availability.

Terrestrial CH₄ emissions can be measured using both chamber and flux tower approaches. Where chamber approaches are used, CH₄ fluxes resulting from vegetation transport should also be accounted for. In ecosystems with low vegetation, enclosure of vegetation within the chamber headspace can achieve this. However, for ecosystems with tall vegetation (such as forests), estimates of net CH₄ emissions from tree stems would need to be included to capture the full NEE of CH₄. However, we currently know of no robust annual estimates of tree stem CH₄ emissions for ecosystems on organic soil and this creates an element of uncertainty in annual terrestrial CH₄ estimates for Forest Land on organic soil. Being made above the canopy, flux tower measurements do capture the full NEE of CH₄, but such studies remain very scarce. Incorporation of tree stem CH₄ emissions in annual net CH₄ emission estimates may be important for some ecosystems, and researchers working on these systems are encouraged to quantify the contribution of these emissions to overall annual emissions estimates.

Emissions of N₂O were less commonly measured and/or reported for all regions within the scope of the Peat-Emit project (Table 1). This pattern was also observable in the data obtained by the authors of the *Wetlands Supplement*. However, it is notable that N₂O emissions represent an even smaller proportion of the data available for less data-rich regions. Researchers are encouraged to estimate N₂O emissions where possible, particularly where opaque chamber measurements of CH₄ are already being made. Additional data could support:

- increased precision and accuracy of existing category-based Tier 1 EFs (Figure 10);
- more appropriate disaggregation of land-use categories and associated EFs (Figure 9); and
- the development of a predictive water table-based approach similar to that described above for CO₂ and CH₄.

Measurement technologies are improving for N_2O , which can make up a significant part of the total GHG emissions from some land-use categories, particularly fertilized land uses where sites receive high N inputs. The quantification of these emissions, their attribution between soil and fertilizer emissions, and the identification of driving variables, all remain technically challenging, leading to continuing high uncertainties in N_2O EFs. However, the resulting high probability of double counting of N_2O emissions for fertilized land uses should also strongly incentivize additional data collection to support disaggregation of these emissions and refinement of the associated EFs.

Poor availability of site-specific data for R_{het} , $Litter_{AG}$ and $Litter_{BG}$ (see Section 2.1.1 for definitions) repeatedly created challenges during the estimation of $CO_2-C_{on-site}$ using the soil flux carbon balance approach. It is important to acknowledge that the scarcity of these data reflects the challenges presented by obtaining these data. Measurements of R_{soil} are substantially less labour intensive than measurements of R_{het} . However, the use of non-site-specific conversion factors to estimate the R_{het}/R_{soil} introduces a substantial source of uncertainty into $CO_2-C_{on-site}$ estimates. Similarly, high-quality fine root mortality data are extremely scarce because obtaining them is highly labour intensive. Even though litterfall data are more easily obtained, it is likely that peer-reviewed journals might often not find this data of sufficient interest in isolation to justify publication. Collection of R_{soil} data is not discouraged, as these make up most of the flux data available for many systems and certainly represent a substantial contribution to the understanding of emissions in these cases. However, researchers making opaque chamber measurements of CO_2 emissions are strongly encouraged to consider the utility of their measurements in the context of the wider soil flux carbon balance. If R_{het} , $Litter_{AG}$ and $Litter_{BG}$ data *can* be collected (and reported) this could support substantial improvements in the robustness of $CO_2-C_{on-site}$ estimation, especially in the warm climate zone.

To support the potential refinement of methods for reporting fire emissions in the *Wetlands Supplement* there is a need for more primary GHG flux measurement studies in understudied areas (outside Southeast Asia), including studies of peatland fire emissions (laboratory-based but, preferably, also *in situ*) and of mass of fuel combusted. The proposed stratification for mass of fuel combusted that is presented in this review is based on fire frequency. Additional data would be essential to determine whether this would be an appropriate stratification approach for peatland fires outside of Southeast Asia.

3.4.2 Methodological developments since the *Wetlands Supplement*

In the decade since the publication of the *Wetlands Supplement*, there has been a general increase in the number and quality of published studies for most regions (Table 1). There has also been a major increase in the number of published CO_2 (and to a lesser degree CH_4 and N_2O) flux studies utilizing state-of-the-art measurement methods (such as flux towers, automated chambers and field GHG analysers). Within the regions reviewed by the Peat-Emit project, the increase in flux tower data is particularly notable for warm climate Asia, although some studies have also now been published including flux tower measurements from Africa, China and South America. While all methods for GHG emissions measurement have methodological limitations, this expanded range of measurement techniques can provide greater overall confidence in the resulting EFs, as they are now less reliant on one or two methods for any given region or land-use category. However, there do appear to be systematic differences in average emissions obtained for the same land-use category using different methods. This raises concerns about possible methodological biases, which could have far-reaching implications for current emissions reporting for organic soils. Resolving the differences between estimates produced using different methods should therefore be a priority for all stakeholders. Studies presenting and comparing the estimates from different methods on the same site at the same time will therefore be extremely important to understand the mechanisms underlying the differences in estimates produced by different methods. Researchers should therefore, where funding and practicalities allow, consider designing studies that use multiple methodologies. In practice, it is likely that studies combining subsidence measurements with a single

flux measurement method (chamber or flux tower) would be most feasible because subsidence measurements are relatively low cost and can be made more simply and at lower frequency in the field than chamber measurements. Where possible, this multi-methodology research approach is strongly encouraged, as resolution of this issue is essential to ensure that the EFs used for organic soils are robust and accurate.

3.4.3 Methodological standards

The methodologies used to estimate GHG emissions from organic soil in the publications identified during this study are variable in their robustness, reflecting a wide array of practical considerations. During the process of constructing the Peat-Emit project EF database, a set of criteria was developed and used to support decision-making around the inclusion of studies. This is presented in [Appendix 6](#) as a set of suggested criteria for the assessment of study suitability for EF derivation. Primarily these criteria, along with the suggested protocol for EF derivation outlined in [Appendix 5](#), are presented to support other researchers working to derive organic soil EFs and begin a discussion about how subjective decision-making processes around study inclusion might be formalized. However, these criteria could also be interpreted as general guidelines for the methodological standards that researchers should consider adhering to if they wish their data to be suitable for inclusion in EF databases. Particularly for less data-rich regions, it was necessary to use less stringent (*minimum*) criteria, to maximize the benefits that could be obtained from the limited available data. However, when reviewing the evidence for both data-rich and less data-rich regions, studies were encountered that had collected valuable data but that could not be justifiably used to generate annual emissions estimates due to limitations in their sampling designs. It is important to acknowledge that developing annual emissions estimates is not always a primary motivation in study design. However, researchers working to estimate GHG emissions from organic soils are encouraged to consider the inclusion criteria presented in [Appendix 6](#) when designing and reporting future studies, in case tolerably small adjustments to planned study designs could allow for inclusion.

Of course, these recommendations are made with an awareness that field studies and the associated publications often reflect researchers' best efforts in the face of substantial practical and financial barriers to data collection. Due to their water-logged nature, many less-disturbed peatlands represent remote and difficult terrain, which can pose challenges for making regular sampling visits. These characteristics can also present difficulties around maintaining, ensuring the security of, and providing power for technical equipment. These difficulties can be further exacerbated by climatic extremes (such as winter for high-latitude/high-altitude peatlands and the wet season for tropical peatlands), which can in some cases make access and sampling impossible for long periods. Financial considerations can also limit access to technical equipment, sampling frequency, and the duration of studies. Where expensive automated sampling equipment is not available, this can be partially mitigated by increased sampling effort, but this still incurs costs, as it places demands on staff time and resources, especially where extensive travel is required to access remote sites. Furthermore, where analytical equipment is not available "in house", costs for sending samples away for analysis can be substantial. Therefore, research plans following the Peat-Emit project's recommendations may not be practically or economically viable in all cases.

Barriers also exist to the dissemination of data. Many journals actively select for studies that present novel findings from novel contexts and/or use novel methods. A large portion of data collection that would be suitable for EF derivation must, by definition, not be novel, due to the need for multiple data points from given land-use categories and regions. Although novel high-tech methods may be employed, the scale of data collection required also clearly depends largely upon the widespread use of more affordable, low(er)-tech, established methods with lower barriers to entry, especially in developing economies. Researchers, for whom English may not be a first language, may also face publication biases around English language standard (Politzer-Ahles *et al.*, 2020), presenting an additional barrier

to dissemination. It is entirely understandable therefore, that when faced with these barriers, researchers may feel compelled to prioritize other outcomes than the inclusion of their data in EF databases. Shorter-duration studies that focus on novel mechanisms or ecosystems, may provide superior risk-to-reward ratios, given that equipment failure or other unforeseen events could result in large resource and time investments in monitoring studies producing limited outcomes. Funders and publishers would need to modify their practices for these constraints to be alleviated, although they of course face their own demands and constraints.

For the field-based assessment of peatland fire emissions and the mass of fuel consumed, the constraints discussed above in relation to the measurement of peat surface emissions are further amplified by health and safety considerations. These include the need to measure *in situ* smoke plumes during periods when ambient air conditions are extremely unhealthy or even dangerous to human health. In addition, obtaining accurate measurement of the amount of peat combusted would ideally require a “before–after–control–impact” (BACI) sampling approach, which may be challenging in remote landscapes where the exact location and timing of peat fires is difficult if not impossible to predict. Experimental peat burns, such as those described by Hu *et al.* (2024), could offer one approach to improved knowledge of the controls on the mass of peat consumed during a fire, but it would be challenging to replicate this approach across a sufficient breadth of land uses and management regimes to provide definitive Tier 1 default values.



Jelutung plantation agroforestry, Indonesia

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3.5 Recommendations for key stakeholders

3.5.1 Recommendations for the Recommendations for the United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change

Over a decade has now elapsed since the publication of the *Wetlands Supplement*, and there has been a large amount of new research published on organic soil emissions during this period. It is therefore recommended that the IPCC consider a limited update of the *Wetlands Supplement* chapters applicable to organic soil emissions/removals (Chapters 2 and 3) within the next five years. This would be similar to the update of some chapters in the *2019 Refinement*.

This update could include some adjustment of existing methods, but a major focus should be the collation of new data to support the refinement of Tier 1 organic soil EFs and improve their spatial representation. Rather than developing Tier 2 EFs for under-represented regions, it would be far preferable to extend the coverage of Tier 1 EFs to include all peat types, climatic conditions and management activities globally. This would require:

1. extending the geographic coverage of cool climate (temperate and boreal) Tier 1 EFs beyond (predominately) Europe and North America to include cool climate high-altitude and high-latitude peatlands in Asia, Africa and Latin America;
2. extending the geographic coverage of warm climate (tropical) Tier 1 EFs beyond (exclusively) Southeast Asia to include Africa, Latin America and the Caribbean, and Oceania; and
3. extending the range of emissions-inducing anthropogenic activities considered for all climate zones to include management activities other than active drainage (such as grazing or biomass harvesting) that may degrade organic soils and contribute to high GHG emissions.

While beyond the scope of the Peat-Emit project, it is important to note that a similar update of methods and EFs for the other wetland types included in the *Wetlands Supplement* might also be required.

The *Wetlands Supplement* is a long and complex document. The development of simpler summaries or tools (such as the EX-ACT tool developed by FAO to support the Indonesian government) is therefore recommended to support countries and simplify the implementation of existing methods. However, some caution would be necessary to ensure that such tools do not lead inventory compilers to apply EFs developed for other geographic regions, peat types and land-use categories that are not applicable to the conditions in their country.

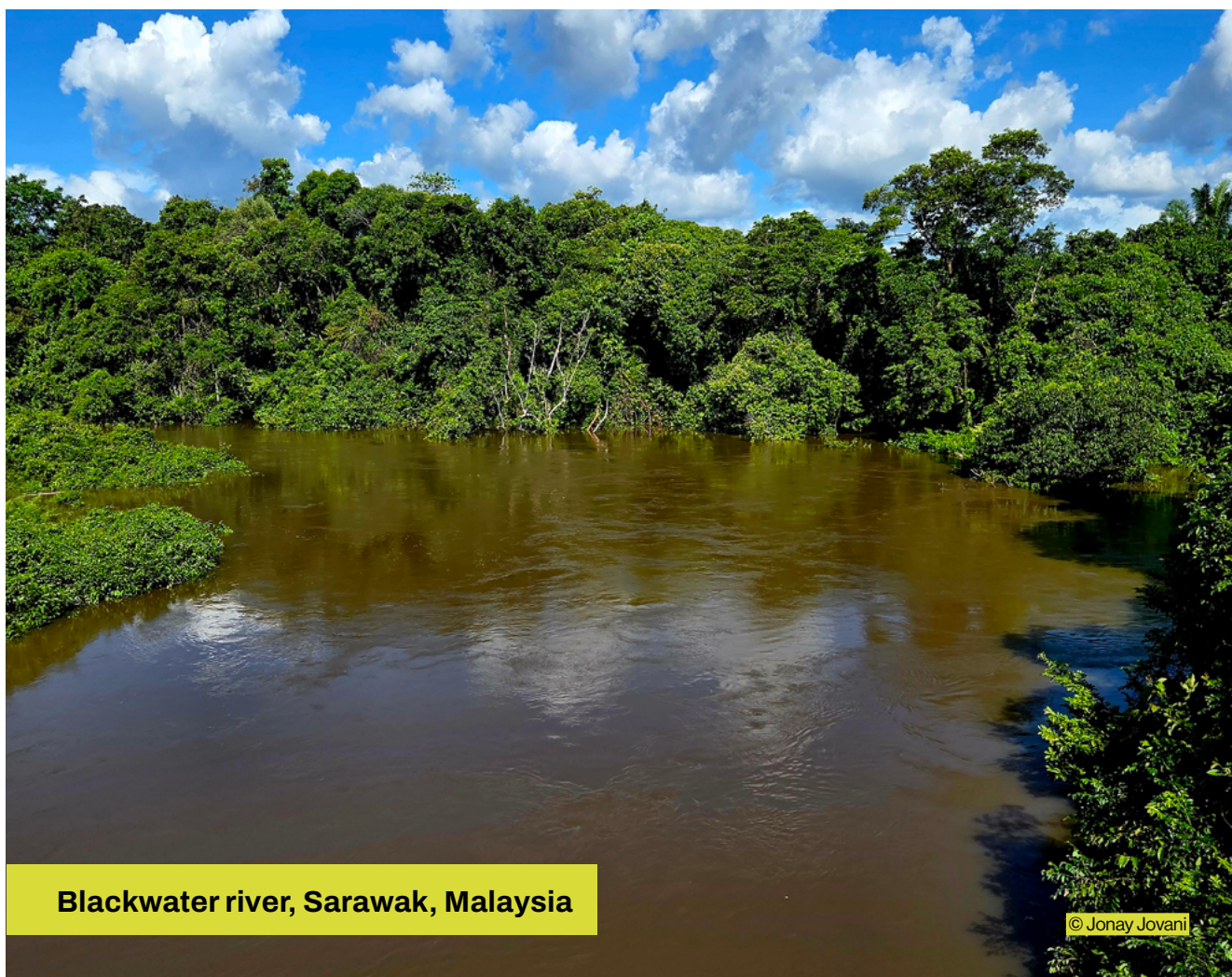
3.5.2 Recommendations for inventory compilers

National inventory compilers, both in countries that already report organic soil emissions and those that do not, are encouraged to consider using the proposed new/updated EFs developed by the Peat-Emit project, where appropriate and where relevant to their countries. It was not possible to obtain reliable new EFs for all potential land-use (or land-cover) categories, especially in Latin America and the Caribbean, and Africa. Therefore, compilers are also encouraged to consider using a water table-based approach (outlined in [Section 3.3.2](#)) as an alternative method to report emissions for categories that lack Tier 1 EFs. This approach has already been used for national inventory reporting in Germany (see Tiemeyer *et al.*, 2020). More work is needed to address the constraints currently limiting the wider application of this approach and on any further scientific or practical developments needed to support countries with implementing it.

3.5.3 Recommendations for carbon market developers

Carbon project developers are encouraged to ensure that they collect the data required to measure and verify project outcomes in line with current IPCC-based methodologies (such as Verra standards). At the simplest level, this may simply require the accurate categorization of sites in line with IPCC “Tier 1” methodology, but the updated and disaggregated EFs presented in this study (particularly for warm climate Southeast Asia) may allow for more granular reporting of emissions changes, for example as a result of improvements in forest condition. Wherever possible, it is recommended that project developers collect additional data (such as water table depth) that would be needed to support a more refined approach to emissions reporting in the future. This would, for example, enable emissions reductions resulting from enhancing peat condition *within* a category (such as drained Plantations) to be recognized, even if interventions do not lead to a full land-use category change (for example, to rewetted Forest Land). This approach would also help to “future proof” projects against changes in reporting methodology in the future, if these move from a category-based to a continuous measurement-based approach.

As global voluntary carbon markets move beyond avoided emissions to incorporate emissions reductions and carbon sequestration, accurate measurements of water table depth changes and (if possible) direct measurements of GHG fluxes before and after interventions may be required to measure, report and verify that anticipated carbon benefits have been achieved. While remotely sensed data are likely to be required to measure, report and verify project outcomes at scale, ground observations will still be invaluable for ensuring that remote sensing data accurately reflect the true site conditions.



3.5.4 Recommendations for researchers

It is recommended that all researchers making measurements of GHG emissions and removals by peatlands take reasonable efforts to ensure that the data they collect and report are suitable for inclusion in future EF assessments. Specifically, researchers should seek wherever possible to account for the methodological criteria set out in [Appendix 6](#) when designing studies to estimate emissions/removals for organic soils to facilitate inclusion of data in EF databases. A focus on the sampling design (duration, frequency, timing and replication) is particularly encouraged. Similarly, the estimation of all elements of the carbon and GHG budget (including all three major GHGs and waterborne carbon) is encouraged wherever funding and circumstances permit. All studies should record key ancillary data (such as water table depth) and ensure that these data are explicitly reported either directly in publications or are made available in supporting material (rather than, for example, only presenting such data in graphs) to ensure that the relevant information can be extracted. Given the highly uneven distribution of published peatland research to date, the collection of GHG flux measurements is particularly encouraged in understudied regions and peat types. A shift in research focus to include more managed areas (including rewetted organic soils) rather than (or in addition to) pristine areas is also recommended. Finally, an increase in research on peatland fires is encouraged, particularly outside Southeast Asia.

3.5.5 Recommendations for funding organizations

Potential funders of peatland research include government departments and research councils, charitable and philanthropic funds, and commercial organizations. All prospective funders are encouraged to support peatland research, particularly in relation to GHG emissions and their mitigation, and consider the criteria presented in [Appendix 6](#) when evaluating research proposals and plans.

Major peatland regions of Africa, Latin America and elsewhere are currently under-researched (and in some cases almost unresearched). Therefore, funding of new work in these regions is strongly encouraged. Where countries in these regions lack the resources to fund peatland research themselves, it is strongly recommended that any externally funded projects should involve the participation of local researchers and seek to build capacity for future in-country research and monitoring. A targeted international funding call to fill identified global gaps in peatland GHG data coverage based on specified measurement protocols would be particularly valuable, especially if designed to inform a future refinement of the *Wetlands Supplement*.

Research councils in more developed economies tend to often fund novel, highly mechanistic studies, often within the funding country, which collect data over short periods and under either pristine or highly controlled (and often artificial) experimental conditions. These data are rarely useful for EF assessment. Grant review panels are therefore encouraged to consider the utility rather than just the novelty of research proposals and to support more work in highly managed ecosystems. While this research might be considered less cutting edge, it is likely to have more value for quantifying and ultimately reducing peatland GHG emissions.



Indonesia's peatlands

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4. Conclusion

Just over a decade has passed since the publication of the *Wetlands Supplement*, and the Peat-Emit project has identified a substantial volume of additional data from which estimates can be made of GHG emissions from and removals by peatlands in developing economies. Perhaps the most immediately usable output of the Peat-Emit project is a proposed suite of new/updated terrestrial GHG EFs for warm climate Asia (equivalent to tropical Southeast Asia). This represents a substantial advance on the suite of EFs provided by the *Wetlands Supplement* due to a rapid expansion of the available data for this region in the intervening years. The reviews of terrestrial GHG EFs for less data-rich regions and emissions associated with peatland fires also provide critical insight into the severity of ongoing data limitations and strongly emphasize the importance of new data collection to improve estimates of GHG emissions from organic soils.

The guidance provided here for assessing study suitability ([Appendix 6](#)) can act as a valuable support tool for researchers looking to contribute to improved emissions reporting by ensuring their data are suitable for use in EF assessments. Although outside the scope of the Peat-Emit project, there has also been a substantial increase in available peatland GHG emissions/removals data for developed economies (for example, in Europe and North America). Several countries in Europe now have relatively advanced peatland methodologies for national GHG inventory reporting because of this increase in data availability. Notable challenges remain, particularly in reconciling differences in emissions estimates produced by different measurement techniques. However, integrating the Peat-Emit project's new data with additional recent datasets from developed economies would create a strong foundation for a much-needed update of the *Wetlands Supplement*, or at least the chapters regarding GHG emissions from organic soils.

The Peat-Emit project EF database, like the *Wetlands Supplement* before it, could remain relevant for a decade or more. However, encouragingly, the scale and quality of research into peatland emissions have been increasing rapidly in recent years. As international and national policies continue to further prioritize climate change mitigation and adaptation, we are hopeful that governments, non-governmental organizations (NGOs) and private institutions will be increasingly supportive of further peatland emissions research. In particular, there is rising demand for data on emissions from and removals by rewetted organic soils (such as for carbon finance schemes). Combined with the need to address substantial data gaps for national reporting and develop country-specific EFs, this could generate enough new data to support more frequent updates.



Estimating organic soil GHG emissions in less data-rich regions using lower cost variables like water table depth offers a promising, cost-effective and data-efficient solution to current reporting constraints. Ideally, water table-based approaches could complement existing category-based approaches to emissions reporting, which would allow the benefits of both approaches to be obtained. Development of water table-based approaches should be treated as an essential priority. These methods could both enhance emissions reporting accuracy while awaiting further data collection, as well as substantially improve scientific support for less data-rich, developing economies.

The availability of organic soil GHG emissions/removals data has improved substantially since the *Wetlands Supplement*. The Peat-Emit project outputs can already support improved reporting accuracy for warm climate Southeast Asia, and the substantial data gaps identified by this evidence review should provide a strong incentive to expand peatland flux data collection efforts. Improved management and rewetting of organic soils have substantial potential to deliver GHG emissions reductions, creating an exciting opportunity for research to support governments, civil society and private interests in delivering climate change mitigation results. The Peat-Emit project will both immediately contribute to delivering urgently needed scientific support and provide a platform to support the ongoing work across research, policy, and practice that will allow these essential benefits to be realized.





Peatlands in the Tahuayo river, Loreto, Peru

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On the ground, a peatland in Bocas del Toro, Panama

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Appendices

Appendix 1. Search strings

Table A1.1 Search strings used for warm climate Asia

Category	Terms
Population (All searches)	Peat* OR peatland OR "organic soils" OR wetland OR histosol OR swamp OR gambut
Region (All searches)	Tropical OR tropic OR neotropic OR "Southeast Asia" OR Indonesia OR Malaysia OR Brunei OR Papua OR Borneo OR Bornean OR Sumatra OR Kalimantan OR Sarawak OR Sabah OR Thailand OR Vietnam OR Singapore OR Philippines OR Laos OR "Timor-Leste" OR Cambodia OR Burma OR Myanmar
Outcome (Search 1: Carbon dioxide emissions)	"carbon dioxide" OR co2 OR "soil respiration" OR "heterotrophic respiration" OR "ecosystem respiration" OR GPP OR "gross primary prod*" OR NPP OR "net primary prod*" OR nee OR "net ecosystem exchange" OR "biomass export" OR "litter fall" OR litterfall OR "fine root biomass" OR "fine root turnover" OR "fine root mortality" OR necb OR "net ecosystem carbon balance" OR "carbon balance" OR "c balance" OR "peat accumulation" OR "carbon accumulation" OR "c accumulation" OR "emission factor"
Outcome (Search 2: Methane emissions)	methane OR ch4 OR "emission factor"
Outcome (Search 3: Nitrous oxide emissions)	"nitrous oxide" OR n2o OR "emission factor"
Outcome (Search 4: Eddy covariance method)	"eddy covariance" OR "ecosystem respiration" OR GPP OR "gross primary prod*" OR NPP OR "net primary prod*" OR nee OR "net ecosystem exchange" OR necb OR "net ecosystem carbon balance" OR "carbon balance" OR "c balance" OR "peat accumulation" OR "carbon accumulation" OR "c accumulation"
Outcome (Search 5: Subsidence rate method)	Subsidence OR "peat motion"

Notes:

These were "title, keyword and abstract" searches.

Note that categories (Population/Region/Outcome) were linked using the "AND" operator. There were five separate searches, with a different outcome string used for each.

The asterisk (*) is a wildcard symbol that searches for words sharing the same initial characters.

Quotation marks ("") combine multiple words into a single search term, requiring both to be present and adjacent.

"OR" is not an abbreviation; it is the capitalized form of the word "or", formatted for emphasis.

Search strings reproduce the query terms used, including colloquial, historical and non-standard country names.

Source: Authors' own elaboration

Table A1.2 Search string used for Latin America and the Caribbean

Category	Terms
Population	peat* OR wetland* OR "organic soil*" OR "suelo orgánico" OR "suelos orgánicos" OR "solo orgânico" OR "solos orgânicos" OR "sol organique" OR "sols organiques" OR histosol OR muck OR turba OR turbera* OR humedal* OR turfa OR turfeira* OR tourbe* OR tourbiere* OR tourbière* OR bog* OR fen* OR mire* OR swamp* OR moor* OR bofedal* OR oconal* OR aguajal* OR vereda* OR murundu* OR pomponal* OR morichal* OR pantano* OR pantanal OR brejo* OR paramo* OR vega* OR mallin*
Region	"South America" OR "Central America" OR "Latin America" OR Caribbean OR Anguilla OR "Antigua and Barbuda" OR Argentina OR Aruba OR Bahamas OR Barbados OR Belize OR Bolivia OR Brazil OR "British Virgin Islands" OR "Caribbean Netherlands" OR "Cayman Islands" OR Chile OR Colombia OR "Costa Rica" OR Cuba OR Curaçao OR Dominica OR "Dominican Republic" OR Ecuador OR "El Salvador" OR "Falkland Islands" OR "French Guiana" OR Grenada OR Guadeloupe OR Guatemala OR Guyana OR Haiti OR Honduras OR Jamaica OR Martinique OR Mexico OR Montserrat OR Nicaragua OR Panama OR Paraguay OR Peru OR "Puerto Rico" OR "Saint Barthélemy" OR "Saint Kitts and Nevis" OR "Saint Lucia" OR "Saint Martin" OR "Saint Vincent and the Grenadines" OR "Sint Maarten" OR Suriname OR "Trinidad and Tobago" OR "Turks and Caicos Islands" OR Uruguay OR "United States Virgin Islands" OR Venezuela OR Amazon* OR navarino OR "Tierra del Fuego" OR Patagonia
Outcome	co2 OR "carbon dioxide" OR "soil respiration" OR "heterotrophic respiration" OR "ecosystem respiration" OR GPP OR "gross primary prod*" OR NPP OR "net primary prod*" OR nee OR "net ecosystem exchange" OR "carbon export" OR "c export" OR "biomass export" OR "litter fall" OR litterfall OR "fine root biomass" OR "fine root turnover" OR "fine root mortality" OR hojarasca OR musgo OR "raíces finas" OR necb OR "net ecosystem carbon balance" OR "eddy covariance" OR "carbon balance" OR "c balance" OR "peat accumulation" OR "carbon accumulation" OR "c accumulation" OR lorca OR ch4 OR methane OR n2o OR "nitrous oxide" OR GHG* OR "greenhouse gas*" OR subsidence OR fire OR combustion OR burn* OR "emission factor*" OR "carbon turnover" OR "c turnover" OR "carbon dynamics" OR "c dynamics"

Notes:

This was a "title, keyword and abstract" search.

Note that categories were linked using the "AND" operator.

The asterisk (*) is a wildcard symbol that searches for words sharing the same initial characters.

Quotation marks (") combine multiple words into a single search term, requiring both to be present and adjacent.

Terms in bold italics are additional terms added to the updated search string following the TSC meeting.

"OR" is not an abbreviation; it is the capitalized form of the word "or", formatted for emphasis.

Search strings reproduce the query terms used, including colloquial, historical and non-standard country names.

Source: Authors' own elaboration

Table A1.3 Search string used for Africa

Category	Terms
Population	peat* OR wetland* OR "organic soil*" OR "sol organique" OR "sols organiques" OR histosol OR muck OR tourbe* OR tourbiere* OR tourbière* OR floodplain* OR marsh* OR delta* OR bog* OR fen* OR mire* OR swamp* OR moor* OR dambo* OR ubongo* OR mobongo*
Region	Africa* OR Algeria OR Angola OR Benin OR Bénin OR Botswana OR "Burkina Faso" OR Burundi OR Cameroon OR Cameroun OR "Cape Verde" OR "Central African Republic" OR "République centrafricaine" OR Chad OR Tchad OR Comoros OR Comores OR "Democratic Republic of the Congo" OR "République Démocratique du Congo" OR "Republic of the Congo" OR "République du Congo" OR Djibouti OR Egypt OR "Equatorial Guinea" OR "Guinée équatoriale" OR Eritrea OR Eswatini OR Ethiopia OR Gabon OR "République gabonaise" OR "The Gambia" OR Ghana OR Guinea OR Guinée OR Guinea-Bissau OR "Ivory Coast" OR "Côte d'Ivoire" OR Kenya OR Lesotho OR Liberia OR Libya OR Madagascar OR Malawi OR Mali OR Mauritania OR Mauritius OR Morocco OR Mozambique OR Namibia OR Niger OR Nigeria OR Rwanda OR "São Tomé and Príncipe" OR Senegal OR Sénégal OR Seychelles OR Sierra Leone OR Somalia OR "South Africa" OR "South Sudan" OR Sudan OR Tanzania OR Togo OR "République togolaise" OR Tunisia OR Uganda OR Zambia OR Zimbabwe OR Congo OR Cuvette OR Okavango OR Sudd OR Rugezi OR "East African highlands" OR "Yala swamp"
Outcome	co2 OR "carbon dioxide" OR "soil respiration" OR "heterotrophic respiration" OR "ecosystem respiration" OR GPP OR "gross primary prod*" OR NPP OR "net primary prod*" OR nee OR "net ecosystem exchange" OR "carbon export" OR "c export" OR "biomass export" OR "litter fall" OR litterfall OR "fine root biomass" OR "fine root turnover" OR "fine root mortality" OR necb OR "net ecosystem carbon balance" OR "eddy covariance" OR "carbon balance" OR "c balance" OR "peat accumulation" OR "carbon accumulation" OR "c accumulation" OR lorca OR ch4 OR methane OR n2o OR "nitrous oxide" OR GHG* OR "greenhouse gas*" OR subsidence OR fire OR combustion OR burn* OR "emission factor*" OR "carbon turnover" OR "c turnover" OR "carbon dynamics" OR "c dynamics"

Notes:

This was a "title, keyword and abstract" search.

Note that categories were linked using the "AND" operator.

The asterisk (*) is a wildcard symbol that searches for words sharing the same initial characters.

Quotation marks (") combine multiple words into a single search term, requiring both to be present and adjacent.

Terms in bold italics are additional terms added to the updated search string following the TSC meeting.

"OR" is not an abbreviation; it is the capitalized form of the word "or", formatted for emphasis.

Search strings reproduce the query terms used, including colloquial, historical and non-standard country names.

Source: Authors' own elaboration

Table A1.4 Search string used for cool climate Asia

Category	Terms
Population	peat* OR wetland* OR “organic soil*” OR histosol OR muck OR bog* OR fen* OR mire* OR swamp* OR moor* OR marsh*
Region	Asia OR China OR “Democratic People's Republic of Korea” OR Fiji OR “Hong Kong” OR Kiribati OR Mongolia OR “Republic of Korea” OR Korea OR Samoa OR “Solomon Islands” OR “Taiwan Province of China” OR Taiwan OR Vanuatu OR Afghanistan OR Bangladesh OR Bhutan OR India OR Iran OR Maldives OR Nepal OR Pakistan OR “Sri Lanka” OR Bahrain OR Iraq OR Israel OR Jordan OR Kuwait OR Lebanon OR Oman OR Qatar OR “Saudi Arabia” OR Palestine OR Syria* OR Türkiye OR Turkey OR “United Arab Emirates” OR UAE OR Yemen OR Himalaya* OR Ruergai OR Tibet* OR “Qinghai-Tibet*” OR Zoige OR Yungui OR Yangtze OR Lancang OR “Yellow River” OR “Fujian-Guangdong” OR Andaman OR Nicobar
Outcome	co2 OR “carbon dioxide” OR “soil respiration” OR “heterotrophic respiration” OR “ecosystem respiration” OR GPP OR “gross primary prod*” OR NPP OR “net primary prod*” OR nee OR “net ecosystem exchange” OR “carbon export” OR “c export” OR “biomass export” OR “litter fall” OR “litterfall” OR “fine root biomass” OR “fine root turnover” OR “fine root mortality” OR necb OR “net ecosystem carbon balance” OR “eddy covariance” OR “carbon balance” OR “c balance” OR “peat accumulation” OR “carbon accumulation” OR “c accumulation” OR lorca OR ch4 OR methane OR n2o OR “nitrous oxide” OR GHG* OR “greenhouse gas*” OR subsidence OR fire OR combustion OR burn* OR “emission factor*” OR “carbon turnover” OR “c turnover” OR “carbon dynamics” OR “c dynamics”
Region (Exclusion)	“Southeast Asia” OR “SE Asia” OR Borneo OR Brunei OR Burma OR Cambodia OR “East Timor” OR Indonesia OR Kalimantan OR Lao OR Laos OR Malaysia OR Myanmar OR Papua OR Philippines OR Sabah OR Sarawak OR Singapore OR Sumatra OR Thailand OR “Timor-Leste” OR Vietnam

Notes: This was a “title, keyword and abstract” search.

Note that categories were linked using the “AND” operator apart from the Region (Exclusion) terms which were preceded by an “AND NOT” operator, to exclude results containing these terms.

The asterisk (*) is a wildcard symbol that searches for words sharing the same initial characters.

Quotation marks (“”) combine multiple words into a single search term, requiring both to be present and adjacent.

“OR” is not an abbreviation; it is the capitalized form of the word “or”, formatted for emphasis.

Search strings reproduce the query terms used, including colloquial, historical and non-standard country names.

Source: Authors' own elaboration

Table A1.5 Search string used for tropical Florida, United States

Category	Terms
Population	peat* OR wetland* OR "organic soil*" OR histosol* OR muck* OR bog* OR fen* OR mire* OR swamp* OR moor* OR marsh* OR slough* OR Cypress OR "Taxodium distichum"
Region	Florida OR Everglades
Outcome	co2 OR "carbon dioxide" OR "soil respiration" OR "heterotrophic respiration" OR "ecosystem respiration" OR GPP OR "gross primary prod*" OR NPP OR "net primary prod*" OR nee OR "net ecosystem exchange" OR "carbon export" OR "c export" OR "biomass export" OR "litter fall" OR "litterfall" OR "fine root biomass" OR "fine root turnover" OR "fine root mortality" OR necb OR "net ecosystem carbon balance" OR "eddy covariance" OR "carbon balance" OR "c balance" OR "peat accumulation" OR "carbon accumulation" OR "c accumulation" OR lorca OR ch4 OR methane OR n2o OR "nitrous oxide" OR GHG* OR "greenhouse gas*" OR subsidence OR fire OR combustion OR burn* OR "emission factor*" OR "carbon turnover" OR "c turnover" OR "carbon dynamics" OR "c dynamics"

Notes: This was a "title, keyword and abstract" search.

Note that categories were linked using the "AND" operator.

The asterisk (*) is a wildcard symbol that searches for words sharing the same initial characters.

Quotation marks (") combine multiple words into a single search term, requiring both to be present and adjacent.

"OR" is not an abbreviation; it is the capitalized form of the word "or", formatted for emphasis.

Search strings reproduce the query terms used, including colloquial, historical and non-standard country names.

Source: Authors' own elaboration

Table A1.6 Search string used for peatland fires

Category	Terms
Population	(Fire OR smouldering OR smoldering) AND (peat OR peatland OR "organic soils" OR histosol OR swamp OR gambut)
Region	Emissions OR "emissions factor" OR "greenhouse gas" OR "depth of burn" OR "fuel load"

Notes:

Note that categories are linked using the "AND" operator.

Quotation marks (") combine multiple words into a single search term, requiring both to be present and adjacent.

"OR" is not an abbreviation; it is the capitalized form of the word "or", formatted for emphasis.

Search strings reproduce the query terms used, including colloquial, historical and non-standard country names.

Source: Authors' own elaboration

Appendix 2. Soil flux carbon balance parameters

As mentioned in [Section 2.1.1](#), estimates of carbon inputs from Litter_{AG} and Litter_{BG} were combined with CO₂ emissions from the R_{het} to estimate CO₂-C_{on-site} under the soil flux carbon balance approach.

Average Litter_{AG} and below-ground inputs from Litter_{BG} from sites in warm climate Asia are presented in [Table A2.1](#). Similar challenges were encountered to those described in the *Wetlands Supplement*. Fine root mortality data were derived from a single PhD thesis (Basuki, 2017), which contained data from several subcategories of Forest Land and Plantations:

- drained forest;
- previously burned fern-/sedge-dominated peatland; and
- oil palm plantations.

This was also the only study found for warm climate Asia, that reported site-specific values for all the parameters required to calculate CO₂-C_{on-site} under the soil flux carbon balance approach. Similarly, measurements of R_{het} were very scarce, with most publications for the region measuring only R_{soil}. As with fine root mortality data, this scarcity is due to the relatively greater difficulty of measuring R_{het} over longer time periods. A summary of the existing data is presented in [Table A2.2](#). The average value for the R_{het}/R_{soil} for each land-use category was used to adjust data from papers reporting only R_{soil}.

Even fewer data points were available for Litter_{AG} (6), Litter_{BG} (3) and the R_{het}/R_{soil} (3) for warm climate Latin America and the Caribbean ([Table A2.3](#)). However, there were three sites for which site-specific values of all three parameters were reported and for which CO₂-C_{on-site} could be calculated using these exclusively. These sites were the only sites for which Litter_{BG} and the R_{het}/R_{soil} were reported in this region. However, they are also relatively closely co-located, part of the same project and all within *Mauritia flexuosa* palm swamps (experiencing various degrees of degradation due to palm cutting). It is therefore very important to highlight the relatively strong influence of a small number of data points (from a single research group and ecotype) in the calculation of CO₂-C_{on-site} for warm climate Forest Land CO₂ EFs in Latin America and the Caribbean.

At the time of this project, no soil carbon flux balance method studies or studies reporting relevant input values were identified for organic soil ecosystems in Africa or in-scope cool climate regions (Asia or Latin America and the Caribbean).

Table A2.1 Above-ground and below-ground litter input values used in soil flux carbon balance calculations for sites in warm climate Asia

Land use	Subcategory	Litter _{AG}		Litter _{BG}	
		Value	n	Value	n
Forest Land	Drainage-affected forest (<0.5 km from drain/canal)	4.68 ^{viii}	1	1.33 ^{ix}	6
	Selectively logged forest ^{i, ii, iii}	3,9	4	1.33 ^{ix}	6
	Drained forest ^{iv, v}	5,09	7	1,33	6
	Previously burned forest (bare peat)	0.00 ^{xi}	–	0.00 ^{xi}	–
	Previously burned forest (fern-/sedge-dominated) ^v	1,83	3	5.70	3
	Previously burned forest (scrub-dominated)	4.32 ^x	–	1.33 ^{ix}	6
	Previously burned forest (tree-dominated) ^{vi}	3,97	1	1.33 ^{ix}	6
Plantations	Plantation, short-rotation, pulp ^{vii, viii}	2,84	4	1.33 ^{ix}	6
	Plantation, long-rotation, timber ^{ix, x}	1,92	4	1.33 ^{ix}	6
	Plantation, oil palm, industrial	1.20 ^{xii}	3	0.20 ^{xii}	3
	Plantation, oil palm, smallholder ^{vi}	1.20	3	0.20	3
	Plantation, agricultural, shallow-drained (e.g. sago)	1.20 ^{xii}	3	0.20 ^{xiii}	3
	Plantation, agricultural, deep-drained (e.g. fruit trees)*	1.92 ^{xiv}	4	1.33 ^{ix}	6
	Plantation, other ^{vi, vii}	2,88	4	1.33 ^B	6
Cropland	Shallow-drained, short-rotation (e.g. rice)	1.06 ^{xiii}	3	1.50 ^{xiii}	3
	Deep-drained, short-rotation (e.g. vegetables)	0.00 ^{xi}	–	0.00 ^{xi}	–
Rewetted	Rewetted forest	4,68	1	1.33 ^{ix}	6

Notes:

n = number of sites reporting relevant measurements.

* Values not from organic soil.

For above-ground litter (Litter_{AG}) and below-ground litter (Litter_{BG}), numbers in bold mean that the values were derived as part of this review for those land-use subcategories. By contrast, values in italics mean that no data for that land-use subcategory was available and the values were considered to be the same as those from a “similar” land-use subcategory,

^{viii} Same as “Rewetted forest”.

^{ix} Same as “Drained forest”.

^x Uses Litter_{AG} mean for “Selectively logged forest”, “Drained forest” and “Previously burned forest (tree-dominated)”.

^{xi} Assume zero carbon inputs as all biomass removed or bare peat.

^{xii} Same as “Plantation, oil palm, smallholder”.

^{xiii} Value from Hergoualc’h and Verchot (2014).

^{xiv} Same as “Plantation, long-rotation, timber”.

Superscript numbers in parentheses in the subcategory column refer to the papers used to develop the values.

Sources:

ⁱ Sulistiyanto, Y. 2005. Nutrient dynamics in different sub-types of peat swamp forest in Central Kalimantan, Indonesia. University of Nottingham, United Kingdom.

ⁱⁱ Saragi-Sasmito, M.F., Murdiyarso, D., June, T. & Sasmito, S.D. 2019. Carbon stocks, emissions, and aboveground productivity in restored secondary tropical peat swamp forests. *Mitigation and Adaptation Strategies for Global Change*, 24: 521–533. <https://doi.org/10.1007/s11027-018-9793-0>

ⁱⁱⁱ Darusman, T., Murdiyarso, D., Impron, I., Chaniago, I.A. & Lestari, D.P. 2022. Carbon Dynamics in Rewetted Tropical Peat Swamp Forests. *Climate*, 10 (3): 35. <https://doi.org/10.3390/cli10030035>

- ^{iv} **Hergoualc'h, K., Hendry, D.T., Murdiyarso, D. & Verchot, L.V.** 2017. Total and heterotrophic soil respiration in a swamp forest and oil palm plantations on peat in Central Kalimantan, Indonesia. *Biogeochemistry*, 135: 203–220. <https://doi.org/10.1007/s10533-017-0363-4>
- ^v **Basuki, I.** 2017. Carbon Dynamics in Response to Land Cover Change in Tropical Peatlands, Kalimantan, Indonesia.
- ^{vi} **Jaya, A., Sancho, J.J., Page, S., Sjorgensen, S., Evans, C., Purwanto, Sosilawaty & Sulistiyanto, Y.** 2022. Litter production and leaf litter decomposition rate in secondary peat swamp forests in Central Kalimantan, Indonesia. *IOP Conference Series: Earth and Environmental Science*. 1025: 012024. <https://doi.org/10.1088/1755-1315/1025/1/012024>
- ^{vii} **Junaedi, A., Hardiwinoto, S., Supriyo, H. & Mindawati, N.** 2020. Litter productivity and leaf litter nutrient return of three native tree species in drained tropical peatland, Riau-Indonesia. *IOP Conference Series: Earth and Environmental Science*. 533: 012007. <https://doi.org/10.1088/1755-1315/533/1/012007>
- ^{viii} **Sumawinata, B., Djajakirana, G., Suwardi & Darmawan.** 2019. Understanding nutrient cycles as a key to sustainable forest plantation on tropical peatland in Indonesia. *IOP Conf. Ser.: Earth Environ. Sci.* 393: 012029. <https://doi.org/10.1088/1755-1315/393/1/012029>
- ^{ix} **Tongkaemkaew, U., Sukkul, J., Sumkhan, N., Panklang, P., Brauman, A. & Ismail, R.** 2018. Litterfall, litter decomposition, soil macrofauna, and nutrient content in rubber monoculture and rubber-based agroforestry plantations. *Forest and Society* 2(2): 138–149. <https://doi.org/10.24259/fs.v2i2.4431>
- ^x **Zhu, X., Jiang, X., Kumar Singh, A., Zeng, H., Chen, C., Lu, E. & Liu, W.** 2022. Reduced litterfall and decomposition alters nutrient cycling following conversion of tropical natural forests to rubber plantations. *Ecological Indicators*, 138: 108819. <https://doi.org/10.1016/j.ecolind.2022.108819>

Table A2.2 Summary of published values for the heterotrophic proportion of soil respiration for warm climate Asia

Land use	Suggested Tier 1 category	R_{het}/R_{soil}	Mean R_{het}/R_{soil}
Forest Land	Drainage-affected forest (<0.5 km from drain/canal)	47.5 ⁱ	47.5
	Selectively logged forest	61.5 ⁱⁱ	69.9
	Selectively logged forest	78.4 ⁱⁱⁱ	
	Previously burned forest (tree-dominated)	84.0 ⁱ	77.1
	Drained forest	87.1 ^{iv}	
	Drained forest	74.3 ^{iv}	
	Drained forest	72.1 ^{iv}	
	Drained forest	79.8 ^{iv}	
	Drained forest	86.8 ^{iv}	
	Drained forest	77.3 ^{iv}	
	Drained forest	55.0 ^v	
	Previously burned forest (fern-/sedge-dominated)	65.7 ^{iv}	75.2
	Previously burned forest (fern-/sedge-dominated)	83.5 ^{iv}	
	Previously burned forest (fern-/sedge-dominated)	76.4 ^{iv}	
Plantations	Plantation, short-rotation, pulp	49.7 ⁱⁱ	59.9
	Plantation, short-rotation, pulp	70.2 ⁱⁱ	42.8
	Plantation, long-rotation, timber	42.8 ^{vi}	
	Plantation, oil palm, industrial	71.3 ^{vii}	76.3
	Plantation, oil palm, industrial	86.7 ⁱ	
	Plantation, oil palm, industrial	67.0 ^{viii}	
	Plantation, oil palm, industrial	87.6 ^{ix}	
	Plantation, oil palm, industrial	70.7 ^{ix}	
	Plantation, oil palm, smallholder	85.5 ^{vii}	
	Plantation, oil palm, smallholder	71.8 ^v	
Cropland*	Shallow-drained, short-rotation (e.g. rice)	64.7 ^x	68.1
	Shallow-drained, short-rotation (e.g. rice)	71.5 ^x	

Notes: Values presented as percentages.

The average values of the heterotrophic proportion of soil respiration (R_{het}/R_{soil}) were used to adjust values from papers reporting only R_{soil} when calculating CO_2 -C_{on-site}.

Note some averages include data from more than one suggested Tier 1 category.

Sources:

ⁱ Comeau, L.-P. 2016. Carbon dioxide fluxes and soil organic matter characteristics on an intact peat swamp forest, a drained and logged forest on peat, and a peatland oil palm plantation in Jambi, Sumatra, Indonesia. University of Aberdeen, United Kingdom.

ⁱⁱ Basuki, S. & Munoz, C.P. 2012. Emission of CO_2 and CH_4 from plantation forest of *Acacia crassiparva* on peatlands in Indonesia, Proceedings of the 14th International Peat Congress, Stockholm.

ⁱⁱⁱ Saragi-Sasmito *et al.* (2019)

^{iv} Basuki, I. 2017. Carbon Dynamics in Response to Land Cover Change in Tropical Peatlands, Kalimantan, Indonesia.

^v Hergoualc'h, K., Hendry, D.T., Murdiyarso, D. & Verchot, L.V. 2017. Total and heterotrophic soil respiration in a swamp forest and oil palm

plantations on peat in Central Kalimantan, Indonesia. *Biogeochemistry*, 135: 203–220. <https://doi.org/10.1007/s10533-017-0363-4>

^{vi} Wakhid, N., Hirano, T., Okimoto, Y., Nurzakiah, S. & Nursyamsi, D. 2017. Soil carbon dioxide emissions from a rubber plantation on tropical peat. *Science of The Total Environment*, 581–582: 857–865. <https://doi.org/10.1016/j.scitotenv.2017.01.035>

^{vii} Dariah, A., Marwanto, S. & Agus, F. 2014. Root- and peat-based CO₂ emissions from oil palm plantations. *Mitigation and Adaptation Strategies for Global Change*, 19: 831–843. <https://doi.org/10.1007/s11027-013-9515-6>

^{viii} Ishikura, K., Hirano, T., Okimoto, Y., Hirata, R., Kiew, F., Melling, L., Aeries, E.B., Lo, K.S., Musin, K.K., Waili, J.W., Wong, G.X. & Ishii, Y. 2018. Soil carbon dioxide emissions due to oxidative peat decomposition in an oil palm plantation on tropical peat. *Agriculture, Ecosystems & Environment*, 254: 202–212. <https://doi.org/10.1016/j.agee.2017.11.025>

^{ix} Manning, F.C., Kho, L.K., Hill, T.C., Cornulier, T. & Teh, Y.A. 2019. Carbon Emissions From Oil Palm Plantations on Peat Soil. *Frontiers in Forests and Global Change*, 2: 37. <https://doi.org/10.3389/ffgc.2019.00037>

^x Min, S. & Rulík, M. 2020. Comparison of Carbon Dioxide (CO₂) Fluxes between Conventional and Conserved Irrigated Rice Paddy Fields in Myanmar. *Sustainability* 12: 5798. <https://doi.org/10.3390/su12145798>

Table A2.3 Summary of published litterfall, fine root mortality, and heterotrophic proportion of soil respiration values for warm climate Forest Land in Latin America and the Caribbean

Habitat description	$R_{\text{het}}/R_{\text{soil}}$ (%)	Litter _{AG} (t C ha ⁻¹ yr ⁻¹)	Litter _{BG} (t C ha ⁻¹ yr ⁻¹)
Pole forest (intact)	–	4.85 ⁱ	–
Palm swamp (intact)	–	4.36 ⁱⁱ	–
Palm swamp (intact)	59.5 ⁱⁱ	4.90 ⁱⁱ	3.37 ⁱⁱⁱ
Palm swamp (moderately degraded by cutting)	93.8 ⁱⁱ	5.10 ⁱⁱ	1.95 ⁱⁱⁱ
Palm swamp (highly degraded by cutting)	96.0 ⁱⁱ	2.00 ⁱⁱ	1.54 ⁱⁱⁱ
Forested floodplain (disturbed by development)	–	5.05 ^{iv}	–

Notes:

Litter_{AG} = litterfall.

Litter_{BG} = fine root mortality.

$R_{\text{het}}/R_{\text{soil}}$ = heterotrophic proportion of soil respiration.

Sources:

ⁱ Dargie, G.C., del Aguila-Pasquel, J., Córdova Oroche, C.J., Irarica Pacaya, J., Reyna Huaymacari, J., Baker, T.R., Hastie, A., Honorio Coronado, E.N., Lewis, S.L., Roucoux, K.H., Mitchard, E.T., Williams, M., Draper, F.C.H. & Lawson, I.T. 2024. Net primary productivity and litter decomposition rates in two distinct Amazonian peatlands. *Global Change Biology*, 30: e17436. <https://doi.org/10.1111/gcb.17436>

ⁱⁱ Hergoualc'h, K., van Lent, J., Dezzio, N., Verchot, L.V., van Groenigen, J.W., López Gonzales, M. & Grandez-Rios, J. 2024. Major carbon losses from degradation of *Mauritia flexuosa* peat swamp forests in western Amazonia. *Biogeochemistry*, 167: 327–345. <https://doi.org/10.1007/s10533-023-01057-4>

ⁱⁱⁱ Dezzio, N., Grandez-Rios, J., Martius, C. & Hergoualc'h, K. 2021. Degradation-driven changes in fine root carbon stocks, productivity, mortality, and decomposition rates in a palm swamp peat forest of the Peruvian Amazon. *Carbon Balance and Management*, 16: 33. <https://doi.org/10.1186/s13021-021-00197-0>

^{iv} Cejudo, E., Hernández, M.E., Campos, A., Infante-Mata, D. & Moreno-Casasola, P. 2022. Leaf litter production and soil carbon storage in forested freshwater wetlands and mangrove swamps in Veracruz, Gulf of Mexico. *Mires and Peat*, 28: 15. <https://doi.org/10.19189/MaP.2020.OMB.StA.1994>

Appendix 3 Terrestrial greenhouse gas emission factors

The EF tables that have been produced are presented below and are grouped by GHG in the order: CO₂, CH₄, N₂O. Wherever possible, the proposed new/updated Tier 1 EFs produced by the Peat-Emit project have been presented alongside the *Wetlands Supplement* default values to facilitate comparison. The *Wetlands Supplement* did not provide EFs for “unmanaged” land or undrained organic soil on “managed” land. Therefore, proposed EFs presented for these lands in these categories are new, and no Tier 1 EFs exist for undrained organic soil for direct comparison. However, the Tier 1 EFs for rewetted organic soil from the *Wetlands Supplement* drew on a substantial amount of data from undrained organic soil and can be compared to the values produced by the Peat-Emit project for undrained organic soil to identify potential outliers. In some cases, for warm climate Asia, EFs could be disaggregated beyond the Tier 1 categories used in the *Wetlands Supplement*. In these cases, these EFs are presented separately as subcategories of the original Tier 1 category. In other cases (especially in Latin America and the Caribbean, and Africa) there were insufficient data to derive separate regional EFs, even for relatively coarse land-use categories; this is made explicit by the term “No data”. In many cases this highlights an evidence gap. Alternatively, it may indicate the absence of that land use on peat within the region.

For each of the 21 tables in this appendix, the following points should be noted:

- Data for CO₂ are presented as t CO₂-C ha⁻¹ yr⁻¹.
- Data for CH₄ are presented as kg CH₄ ha⁻¹ yr⁻¹.
- Data for N₂O are presented as kg N₂O-N ha⁻¹ yr⁻¹.
- CI = 95 percent confidence interval.
- n = sample size.
- Allocation of land to management categories is at “inventory compilers” discretion.
- Drained organic soil includes all hydrologically modified sites except rewetted sites.
- Plantations can be reported under Forest Land or Cropland categories according to national land-use definitions.

Table A3.1.A Terrestrial carbon dioxide emission factors for the warm climate zone (excluding peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	–2.0 (–5.5–1.6)	6
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	–3.7 (–17.7–10.2)	3
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	5.1 (–8.8–18.9)	3
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	5.3 (0.7–9.5)	21	Drainage-affected (<0.5 km from canal/drain)	–2.3 (–5.3–0.8)	4
						Selectively logged	3.7 (1.5–5.9)	20
						Drained	4.7 (3.1–6.3)	43
						Previously burned (bare peat)	16.4 (5.8–27.0)	7
						Previously burned (fern-/sedge-dominated)	3.3 (0.4–6.3)	22
						Previously burned (scrub-dominated)	8.9 (2.4–15.4)	7
						Previously burned (tree-dominated)	2.5 (–1.3–6.4)	5
		Plantations	Drained, short rotations	20 (16–24)	13	Short-rotation, pulp	19.0 (16.2–21.9)	17
			Drained, unknown or long rotations	15 (10–21)	21	Long-rotation, timber	5.5 (1.8–9.1)	9
						Agricultural, deep-drained (e.g. fruit trees)	10.3	2
						Other	0.5 (–2.7–3.6)	4
		Cropland	Drained, oil palm	11 (5.6–17)	10	Oil palm, industrial	10.2 (8.9–11.5)	35
						Oil palm smallholder	11.6 (9.2–13.9)	29
			Shallow-drained (<0.3 m)	1.5 (–2.3–5.4)	5	Agricultural, shallow-drained (e.g. sago)	3.6 (1.1–6.0)	5
			Drained, paddy rice	9.4 (–0.2–6.6)	6	Shallow-drained, short-rotation (e.g. rice)	6.3 (–1.6–14.3)	4
		Grassland	Drained	9.6 (4.5–17)	–	Grassland	No data	–
		Wetlands	Managed for extraction	2.0 (0.1–7.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	2.8 (–7.7–13.3)	3
		Wetlands				Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.1.B Terrestrial carbon dioxide emission factors for the warm climate zone (including peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	–1.7 (–2.7–0.8)	19
		Grassland	Grassland	Not included	–	Grassland	–0.7	1
		Wetlands	Wetlands	Not included	–	Wetlands	–2.2 (–3.9–0.5)	12
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	5.1 (–8.8–18.9)	3
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	5.3 (0.7–9.5)	21	Drainage-affected (<0.5 km from canal/drain)	–2.3 (–5.3–0.8)	4
						Selectively logged	3.7 (1.5–5.9)	20
						Drained	4.7 (3.1–6.3)	43
						Previously burned (bare peat)	16.4 (5.8–27.0)	7
						Previously burned (fern-/sedge-dominated)	3.3 (0.4–6.3)	22
						Previously burned (scrub-dominated)	8.9 (2.4–15.4)	7
						Previously burned (tree-dominated)	2.5 (–1.3–6.4)	5
		Plantations	Drained, short rotations	20 (16–24)	13	Short-rotation, pulp	19.0 (16.2–21.9)	17
			Drained, unknown or long rotations	15 (10–21)	21	Long-rotation, timber	5.5 (1.8–9.1)	9
						Agricultural, deep-drained (e.g. fruit trees)	10.3	2
						Other	0.5 (–2.7–3.6)	4
		Cropland	Drained, oil palm	11 (5.6–17)	10	Oil palm, industrial	10.2 (8.9–11.5)	35
						Oil palm smallholder	11.6 (9.2–13.9)	29
			Shallow-drained (<0.3 m)	1.5 (–2.3–5.4)	5	Agricultural, shallow-drained (e.g. sago)	3.6 (1.1–6.0)	5
			Drained, paddy rice	9.4 (–0.2–6.6)	6	Shallow-drained, short-rotation (e.g. rice)	6.3 (–1.6–14.3)	4
		Wetlands	Cropland and fallow, drained	14 (6.6–26)	10	Deep-drained, short-rotation (e.g. vegetables)	15.3 (12.7–17.9)	40
			Grassland	9.6 (4.5–17)	–	Grassland	No data	–
	Rewetted	Forest Land	Managed for extraction	2.0 (0.1–7.0)	–	Managed for extraction	No data	–
		Wetlands	Rewetted organic soils	0	–	Rewetted forest	2.8 (–7.7–13.3)	3
						Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.2 Terrestrial carbon dioxide emission factors for warm climate Asia

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	5.3 (0.7–9.5)	21	Drainage-affected (<0.5 km from canal/drain)	–2.3 (–5.3–0.8)	4
						Selectively logged	3.7 (1.5–5.9)	20
						Drained	4.7 (3.1–6.3)	43
						Previously burned (bare peat)	16.4 (5.8–27.0)	7
						Previously burned (fern-/sedge-dominated)	3.3 (0.4–6.3)	22
						Previously burned (scrub-dominated)	8.9 (2.4–15.4)	7
						Previously burned (tree-dominated)	2.5 (–1.3–6.4)	5
		Plantations	Drained, short rotations	20 (16–24)	13	Short-rotation, pulp	19.0 (16.2–21.9)	17
			Drained, unknown or long rotations	15 (10–21)	21	Long-rotation, timber	5.5 (1.8–9.1)	9
						Agricultural, deep-drained (e.g. fruit trees)	10.3	2
						Other	0.5 (–2.7–3.6)	4
			Drained, oil palm	11 (5.6–17)	10	Oil palm, industrial	10.2 (8.9–11.5)	35
		Cropland	Shallow-drained (<0.3 m)	1.5 (–2.3–5.4)	5	Oil palm smallholder	11.6 (9.2–13.9)	29
			Drained, paddy rice	9.4 (–0.2–6.6)	6	Agricultural, shallow-drained (e.g. sago)	3.6 (1.1–6.0)	5
			Cropland and fallow, drained	14 (6.6–26)	10	Shallow-drained, short-rotation (e.g. rice)	6.3 (–1.6–14.3)	4
						Deep-drained, short-rotation (e.g. vegetables)	15.3 (12.7–17.9)	40
		Grassland	Drained	9.6 (4.5–17)	–	Grassland	No data	–
		Wetlands	Managed for extraction	2.0 (0.1–7.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	2.8 (–7.7–13.3)	3
		Wetlands				Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.3.A Terrestrial carbon dioxide emission factors for warm climate Latin America and the Caribbean (excluding peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	–2.0 (–5.5–1.6)	6
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	0.4	1
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	5.1 (–8.8–18.9)	3
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	5.3 (0.7–9.5)	21	Drainage-affected (<0.5 km from canal/drain)	No data	–
						Selectively logged	No data	–
						Drained	No data	–
						Previously burned (bare peat)	No data	–
						Previously burned (fern-/sedge-dominated)	No data	–
						Previously burned (scrub-dominated)	No data	–
						Previously burned (tree-dominated)	No data	–
		Plantations	Drained, short rotations	20 (16–24)	13	Short-rotation, pulp	No data	–
			Drained, unknown or long rotations	15 (10–21)	21	Long-rotation, timber	No data	–
						Agricultural, deep-drained (e.g. fruit trees)	No data	–
						Other	No data	–
			Drained, oil palm	11 (5.6–17)	10	Oil palm, industrial	No data	–
		Cropland	Shallow-drained (<0.3 m)	1.5 (–2.3–5.4)	5	Oil palm smallholder	No data	–
						Agricultural, shallow-drained (e.g. sago)	No data	–
			Drained, paddy rice	9.4 (–0.2–6.6)	6	Shallow-drained, short-rotation (e.g. rice)	No data	–
		Wetlands	Cropland and fallow, drained	14 (6.6–26)	10	Deep-drained, short-rotation (e.g. vegetables)	10.4 (8.2–12.5)	3
			Grassland	9.6 (4.5–17)	–	Grassland	No data	–
		Wetlands	Managed for extraction	2.0 (0.1–7.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

¹Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.3.B Terrestrial carbon dioxide emission factors for warm climate Latin America and the Caribbean (including peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	-1.8 (-2.8– -0.8)	18
		Grassland	Grassland	Not included	–	Grassland	-0.7	1
		Wetlands	Wetlands	Not included	–	Wetlands	-1.5 (-2.3– -0.7)	9
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	5.1 (-8.8–18.9)	3
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	5.3 (0.7–9.5)	21	Drainage-affected (<0.5 km from canal/drain)	No data	–
						Selectively logged	No data	–
						Drained	No data	–
						Previously burned (bare peat)	No data	–
						Previously burned (fern-/sedge-dominated)	No data	–
						Previously burned (scrub-dominated)	No data	–
						Previously burned (tree-dominated)	No data	–
		Plantations	Drained, short rotations	20 (16–24)	13	Short-rotation, pulp	No data	–
			Drained, unknown or long rotations	15 (10–21)	21	Long-rotation, timber	No data	–
						Agricultural, deep-drained (e.g. fruit trees)	No data	–
						Other	No data	–
		Cropland	Drained, oil palm	11 (5.6–17)	10	Oil palm, industrial	No data	–
			Shallow-drained (<0.3 m)	1.5 (-2.3–5.4)	5	Oil palm smallholder	No data	–
						Agricultural, shallow-drained (e.g. sago)	No data	–
						Shallow-drained, short-rotation (e.g. rice)	No data	–
			Drained, paddy rice	9.4 (-0.2–6.6)	6	Deep-drained, short-rotation (e.g. vegetables)	10.4 (8.2–12.5)	3
		Grassland	Cropland and fallow, drained	14 (6.6–26)	10	Grassland	No data	–
						Grassland	No data	–
		Wetlands	Managed for extraction	2.0 (0.1–7.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.4.A Terrestrial carbon dioxide emission factors for warm climate Africa (excluding peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	–5.8	2
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	5.3 (0.7–9.5)	21	Drainage-affected (<0.5 km from canal/drain)	No data	–
						Selectively logged	No data	–
						Drained	No data	–
						Previously burned (bare peat)	No data	–
						Previously burned (fern-/sedge-dominated)	No data	–
						Previously burned (scrub-dominated)	No data	–
						Previously burned (tree-dominated)	No data	–
		Plantations	Drained, short rotations	20 (16–24)	13	Short-rotation, pulp	No data	–
			Drained, unknown or long rotations	15 (10–21)	21	Long-rotation, timber	No data	–
						Agricultural, deep-drained (e.g. fruit trees)	No data	–
						Other	No data	–
		Cropland	Drained, oil palm	11 (5.6–17)	10	Oil palm, industrial	No data	–
			Shallow-drained (<0.3 m)	1.5 (–2.3–5.4)	5	Oil palm smallholder	No data	–
			Drained, paddy rice	9.4 (–0.2–6.6)	6	Agricultural, shallow-drained (e.g. sago)	No data	–
			Cropland and fallow, drained	14 (6.6–26)	10	Shallow-drained, short-rotation (e.g. rice)	No data	–
		Grassland	Drained	9.6 (4.5–17)	–	Deep-drained, short-rotation (e.g. vegetables)	10.2	1
						Grassland	No data	–
		Wetlands	Managed for extraction	2.0 (0.1–7.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.4.B Terrestrial carbon dioxide emission factors for warm climate Africa (including peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	–1.1	1
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	–4.5 (–16.6–17.7)	3
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	5.3 (0.7–9.5)	21	Drainage-affected (<0.5 km from canal/drain)	No data	–
						Selectively logged	No data	–
						Drained	No data	–
						Previously burned (bare peat)	No data	–
						Previously burned (fern-/sedge-dominated)	No data	–
						Previously burned (scrub-dominated)	No data	–
						Previously burned (tree-dominated)	No data	–
		Plantations	Drained, short rotations	20 (16–24)	13	Short-rotation, pulp	No data	–
			Drained, unknown or long rotations	15 (10–21)	21	Long-rotation, timber	No data	–
						Agricultural, deep-drained (e.g. fruit trees)	No data	–
						Other	No data	–
		Cropland	Drained, oil palm	11 (5.6–17)	10	Oil palm, industrial	No data	–
			Shallow-drained (<0.3 m)	1.5 (–2.3–5.4)	5	Oil palm smallholder	No data	–
						Agricultural, shallow-drained (e.g. sago)	No data	–
			Drained, paddy rice	9.4 (–0.2–6.6)	6	Shallow-drained, short-rotation (e.g. rice)	No data	–
			Cropland and fallow, drained	14 (6.6–26)	10	Deep-drained, short-rotation (e.g. vegetables)	10.2	1
		Grassland	Drained	9.6 (4.5–17)	–	Grassland	No data	–
		Wetlands	Managed for extraction	2.0 (0.1–7.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.5.A Terrestrial carbon dioxide emission factors for cool climate Asia (excluding peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	–0.6	1
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	–0.7 (–1.9–0.6)	6
	Drained	Forest Land	Drained, including shrubland and drained land that may not be classified as forest (Boreal)	0.37 (–0.11–0.84)	63	Forest Land	No data	–
		Cropland	Drained, nutrient-poor (Boreal)	0.25 (–0.23–0.73)	59	Cropland	No data	–
			Drained, nutrient-rich (Boreal)	0.93 (0.54–1.3)	62			
			Drained (Temperate)	2.6 (2.0–3.3)	8			
		Grassland	Drained (Boreal)	5.7 (2.9–8.6)	8	Grassland	3.8	1
			Drained, nutrient-poor (Temperate)	5.3 (3.7–6.9)	7			
			Deep-drained, nutrient-rich (Temperate)	6.1 (5.0–7.3)	39			
			Shallow-drained, nutrient-rich (Temperate)	3.6 (1.8–5.4)	13			
		Wetlands	Managed for extraction	2.8 (1.1–4.2)	20	Managed for extraction	No data	–
	Rewetted	Any land use	Nutrient-poor (Boreal)	–0.34 (–0.59–0.09)	26	Any land use	No data	–
			Nutrient-rich (Boreal)	–0.55 (–0.77–0.34)	39			
			Nutrient-poor (Temperate)	–0.23 (–0.64–0.18)	43			
			Nutrient-rich (Temperate)	0.5 (–0.71–1.71)	15			

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.5.B Terrestrial carbon dioxide emission factors for cool climate Asia (including peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	-0.4 (-0.5– -0.3)	12
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	-0.7 (-1.9–0.6)	6
	Drained	Forest Land	Drained, including shrubland and drained land that may not be classified as forest (Boreal)	0.37 (-0.11–0.84)	63	Forest Land	No data	–
		Cropland	Drained, nutrient-poor (Boreal)	0.25 (-0.23–0.73)	59	Cropland	No data	–
			Drained, nutrient-rich (Boreal)	0.93 (0.54–1.3)	62			
			Drained (Temperate)	2.6 (2.0–3.3)	8			
		Grassland	Drained (Boreal)	5.7 (2.9–8.6)	8	Grassland	3.8	1
			Drained, nutrient-poor (Temperate)	5.3 (3.7–6.9)	7			
			Deep-drained, nutrient-rich (Temperate)	6.1 (5.0–7.3)	39			
			Shallow-drained, nutrient-rich (Temperate)	3.6 (1.8–5.4)	13			
		Wetlands	Managed for extraction	2.8 (1.1–4.2)	20	Managed for extraction	No data	–
	Rewetted	Any land use	Nutrient-poor (Boreal)	-0.34 (-0.59– -0.09)	26	Any land use	No data	–
			Nutrient-rich (Boreal)	-0.55 (-0.77– -0.34)	39			
			Nutrient-poor (Temperate)	-0.23 (-0.64–0.18)	43			
			Nutrient-rich (Temperate)	0.5 (-0.71–1.71)	15			

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.6.A Terrestrial carbon dioxide emission factors for cool climate Latin America and the Caribbean (excluding peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	–4.9	1
		Grassland	Grassland	Not included	–	Grassland	1	1
		Wetlands	Wetlands	Not included	–	Wetlands	–0.7	2
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	0.3	1
	Drained	Forest Land	Drained, including shrubland and drained land that may not be classified as forest (Boreal)	0.37 (-0.11–0.84)	63	Forest Land	No data	–
		Cropland	Drained, nutrient-poor (Boreal)	0.25 (-0.23–0.73)	59	Cropland	No data	–
			Drained, nutrient-rich (Boreal)	0.93 (0.54–1.3)	62			
			Drained (Temperate)	2.6 (2.0–3.3)	8			
		Grassland	Drained (Boreal)	5.7 (2.9–8.6)	8	Grassland	No data	–
			Drained, nutrient-poor (Temperate)	5.3 (3.7–6.9)	7			
			Deep-drained, nutrient-rich (Temperate)	6.1 (5.0–7.3)	39			
			Shallow-drained, nutrient-rich (Temperate)	3.6 (1.8–5.4)	13			
		Wetlands	Managed for extraction	2.8 (1.1–4.2)	20	Managed for extraction	No data	–
	Rewetted	Any land use	Nutrient-poor (Boreal)	–0.34 (-0.59– -0.09)	26	Any land use	No data	–
			Nutrient-rich (Boreal)	–0.55 (-0.77– -0.34)	39			
			Nutrient-poor (Temperate)	–0.23 (-0.64–0.18)	43			
			Nutrient-rich (Temperate)	0.5 (-0.71–1.71)	15			

Source:

¹Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions

Table A3.6.B Terrestrial carbon dioxide emission factors for cool climate Latin America and the Caribbean (including peat core data)

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	–4.9	1
		Grassland	Grassland	Not included	–	Grassland	–0.2 (–0.6–0.2)	8
		Wetlands	Wetlands	Not included	–	Wetlands	–0.4 (–0.5–0.3)	46
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	0.3	1
	Drained	Forest Land	Drained, including shrubland and drained land that may not be classified as forest (Boreal)	0.37 (–0.11–0.84)	63	Forest Land	No data	–
		Cropland	Drained, nutrient-poor (Boreal)	0.25 (–0.23–0.73)	59	Cropland	No data	–
			Drained, nutrient-rich (Boreal)	0.93 (0.54–1.3)	62			
			Drained (Temperate)	2.6 (2.0–3.3)	8			
		Grassland	Drained (Boreal)	5.7 (2.9–8.6)	8	Grassland	No data	–
			Drained, nutrient-poor (Temperate)	5.3 (3.7–6.9)	7			
			Deep-drained, nutrient-rich (Temperate)	6.1 (5.0–7.3)	39			
			Shallow-drained, nutrient-rich (Temperate)	3.6 (1.8–5.4)	13			
		Wetlands	Managed for extraction	2.8 (1.1–4.2)	20	Managed for extraction	No data	–
	Rewetted	Any land use	Nutrient-poor (Boreal)	–0.34 (–0.59–0.09)	26	Any land use	No data	–
			Nutrient-rich (Boreal)	–0.55 (–0.77–0.34)	39			
			Nutrient-poor (Temperate)	–0.23 (–0.64–0.18)	43			
			Nutrient-rich (Temperate)	0.5 (–0.71–1.71)	15			

Source:

¹Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.7 Terrestrial methane emission factors for the warm climate zone

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	440 (43–836)	15
		Grassland	Grassland	Not included	–	Grassland	131	1
		Wetlands	Wetlands	Not included	–	Wetlands	1024 (21–2027)	6
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	1694 (–4649–8038)	3
		Grassland	Grassland	Not included	–	Grassland	116	1
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	4.9 (2.3–7.5)	7	Drainage-affected (<0.5 km from canal/drain)	48 (–14–110)	4
						Selectively logged	42 (0–85)	11
						Drained	62 (22–101)	26
						Previously burned (bare peat)	No data	–
						Previously burned (fern-/sedge-dominated)	446 (–45–938)	4
						Previously burned (scrub-dominated)	21	2
						Previously burned (tree-dominated)	20 (–13–52)	4
		Plantations	Drained	2.7 (–0.9–6.3)	5	Short-rotation, pulp	2 (–5–9)	6
						Long-rotation, timber	2 (–7–11)	3
						Agricultural, deep-drained (e.g. fruit trees)	No data	–
						Other	2 (–6–10)	3
						Oil palm, industrial	10 (–2–22)	10
		Cropland	Drained	26.2 (7.2–45.3)	6	Oil palm smallholder	2 (1–3)	15
						Agricultural, shallow-drained (e.g. sago)	27 (–22–76)	6
						Shallow-drained, short-rotation (e.g. rice)	205 (–149–558)	4
						Deep-drained, short-rotation (e.g. vegetables)	11 (4–19)	23
						Grassland	7 (0.3–13.7)	–
		Wetlands	Managed for extraction	Not included	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	55 (9–179)	11	Rewetted forest	75	1
		Wetlands				Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.8 Terrestrial methane emission factors for warm climate Asia

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	4.9 (2.3–7.5)	7	Drainage-affected (<0.5 km from canal/drain)	48 (–14–110)	4
						Selectively logged	42 (0–85)	11
						Drained	62 (22–101)	26
						Previously burned (bare peat)	No data	–
						Previously burned (fern-/sedge-dominated)	446 (–45–938)	4
						Previously burned (scrub-dominated)	21	2
						Previously burned (tree-dominated)	20 (–13–52)	4
		Plantations	Drained	2.7 (–0.9–6.3)	5	Short-rotation, pulp	2 (–5–9)	6
						Long-rotation, timber	2 (–7–11)	3
						Agricultural, deep-drained (e.g. fruit trees)	No data	–
						Other	2 (–6–10)	3
		Oil palm	Oil palm	0	1	Oil palm, industrial	10 (–2–22)	10
						Oil palm smallholder	2 (1–3)	15
						Agricultural, shallow-drained (e.g. sago)	27 (–22–76)	6
		Cropland	Rice	143.5 (63.2–223.7)	6	Shallow-drained, short-rotation (e.g. rice)	205 (–149–558)	4
			Cropland	7 (0.3–13.7)	5	Deep-drained, short-rotation (e.g. vegetables)	11 (4–19)	23
		Grassland	Drained	7 (0.3–13.7)	–	Grassland	–9	–
		Wetlands	Managed for extraction	Not included	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	55 (9–179)	11	Rewetted forest	75	1
		Wetlands				Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.9 Terrestrial methane emission factors for warm climate Latin America and the Caribbean

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	440 (43–836)	15
		Grassland	Grassland	Not included	–	Grassland	131	1
		Wetlands	Wetlands	Not included	–	Wetlands	824 (–1008–2657)	4
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	1694 (–4649–8038)	3
		Grassland	Grassland	Not included	–	Grassland	116	1
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	4.9 (2.3–7.5)	7	Forest Land	No data	–
			Drained	2.7 (–0.9–6.3)	5			
		Plantations	Oil palm	0	1	Plantations	No data	–
			Sago palm	26.2 (7.2–45.3)	6			
		Cropland	Rice	143.5 (63.2–223.7)	6	Cropland	No data	–
			Cropland	7 (0.3–13.7)	5			
		Grassland	Drained	7 (0.3–13.7)	–	Grassland	–9	1
		Wetlands	Managed for extraction	Not included	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	55 (9–179)	11	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

ⁱ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.10 Terrestrial methane emission factors for warm climate Africa

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	1424	2
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	4.9 (2.3–7.5)	7	Forest Land	No data	–
			Drained	2.7 (-0.9–6.3)	5			
		Plantations	Oil palm	0	1	Plantations	No data	–
			Sago palm	26.2 (7.2–45.3)	6			
		Cropland	Rice	143.5 (63.2–223.7)	6	Cropland	No data	–
			Cropland	7 (0.3–13.7)	5			
		Grassland	Drained	7 (0.3–13.7)	–	Grassland	No data	–
		Wetlands	Managed for extraction	Not included	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	55 (9–179)	11	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.11 Terrestrial methane emission factors for cool climate Asia

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	310 (–58–677)	9
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	89	2
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	242 (–91–575)	4
	Drained	Forest Land	Drained, nutrient-poor (Boreal)	7.0 (2.9–11)	47	Forest Land	No data	–
			Drained, nutrient-rich (Boreal)	2.0 (–1.6–5.5)	83			
			Drained (Temperate)	2.5 (–0.6–5.7)	13			
		Cropland	Drained	0 (–2.8–2.8)	38	Cropland	No data	–
		Grassland	Drained (Boreal)	1.4 (–1.6–4.5)	12	Grassland	No data	–
			Drained, nutrient-poor (Temperate)	1.8 (0.7–2.9)	9			
			Deep-drained, nutrient-rich (Temperate)	16 (2.4–29)	44			
			Shallow-drained, nutrient-rich (Temperate)	39 (–2.9–81)	16			
		Wetlands	Wetlands	Not included	–	Wetlands	16 (–14–46)	4
			Managed for extraction	6.1 (1.6–11)	15	Managed for extraction	No data	–
	Rewetted	Any land use	Nutrient-poor (Boreal)	55 (9–179)	39	Any land use	No data	–
			Nutrient-rich (Boreal)	183 (0–657)	35			
			Nutrient-poor (Temperate)	123 (4–593)	42			
			Nutrient-rich (Temperate)	288 (0–1141)	37			

Source:

ⁱ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.12 Terrestrial methane emission factors for cool climate Latin America and the Caribbean

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	–4 (–10–2)	3
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	17	2
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	3 (–6–12)	3
		Wetlands	Wetlands	Not included	–	Wetlands	156 (– 44–356)	7
	Drained	Forest Land	Drained, nutrient-poor (Boreal)	7.0 (2.9–11)	47	Forest Land	No data	–
			Drained, nutrient-rich (Boreal)	2.0 (–1.6–5.5)	83			
			Drained (Temperate)	2.5 (–0.6–5.7)	13			
		Cropland	Drained	0 (–2.8–2.8)	38	Cropland	No data	–
		Grassland	Drained (Boreal)	1.4 (–1.6–4.5)	12	Grassland	No data	–
			Drained, nutrient-poor (Temperate)	1.8 (0.7–2.9)	9			
			Deep-drained, nutrient-rich (Temperate)	16 (2.4–29)	44			
			Shallow-drained, nutrient-rich (Temperate)	39 (–2.9–81)	16			
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
			Managed for extraction	6.1 (1.6–11)	15	Managed for extraction	No data	–
	Rewetted	Any land use	Nutrient-poor (Boreal)	55 (9–179)	39	Any land use	No data	–
			Nutrient-rich (Boreal)	183 (0–657)	35			
			Nutrient-poor (Temperate)	123 (4–593)	42			
			Nutrient-rich (Temperate)	288 (0–1141)	37			

Source:

ⁱValues for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.13 Terrestrial nitrous oxide emission factors for the warm climate zone

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	1.3	1
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	0.8	2
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	2.4 (1.3–3.5)	10	Drainage-affected (<0.5 km from canal/drain)	2.7	1
						Selectively logged	0.8 (–0.5–2.1)	5
						Drained	4.9 (1.9–7.9)	20
						Previously burned (bare peat)	No data	–
						Previously burned (fern-/sedge-dominated)	0	2
						Previously burned (scrub-dominated)	2.4 (0.0–4.7)	4
						Previously burned (tree-dominated)	4.4 (–13.3–22.1)	3
						Short-rotation, pulp	No data	–
						Long-rotation, timber	5.3 (–2.4–12.9)	3
						Agricultural, deep-drained (e.g. fruit trees)	No data	–
		Plantations	Other				1.2 (–0.2–2.7)	3
						Oil palm, industrial	24.2 (13.0–35.4)	13
						Oil palm smallholder	18.5 (–1.2–38.3)	15
						Agricultural, shallow-drained (e.g. sago)	5.2	1
		Cropland	Rice	0.4 (–0.1–0.8)	6	Shallow-drained, short-rotation (e.g. rice)	0.5 (–1.0–2.0)	4
			Cropland			Deep-drained, short-rotation (e.g. vegetables)	103.1 (18.2–187.9)	34
		Grassland	Drained	5.0 (2.3–7.7)	8	Grassland	No data	–
		Wetlands	Managed for extraction	3.6 (0.2–5.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

¹Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.14 Terrestrial nitrous oxide emission factors for warm climate Asia

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	2.4 (1.3–3.5)	10	Drainage-affected (<0.5 km from canal/drain)	2.7	1
						Selectively logged	0.8 (–0.5–2.1)	5
						Drained	4.9 (1.9–7.9)	20
						Previously burned (bare peat)	No data	–
						Previously burned (fern-/sedge-dominated)	0	2
						Previously burned (scrub-dominated)	2.4 (0.0–4.7)	4
						Previously burned (tree-dominated)	4.4 (–13.3–22.1)	3
						Short-rotation, pulp	No data	–
						Long-rotation, timber	5.3 (–2.4–12.9)	3
						Agricultural, deep-drained (e.g. fruit trees)	No data	–
		Plantations	Forest Land and cleared Forest Land (shrubland), drained	2.4 (1.3–3.5)	10	Other	1.2 (–0.2–2.7)	3
						Oil palm, industrial	24.2 (13.0–35.4)	13
						Oil palm smallholder	18.5 (–1.2–38.3)	15
						Agricultural, shallow-drained (e.g. sago)	5.2	1
		Cropland	Rice	0.4 (–0.1–0.8)	6	Shallow-drained, short-rotation (e.g. rice)	0.5 (–1.0–2.0)	4
			Cropland	5.0 (2.3–7.7)	8	Deep-drained, short-rotation (e.g. vegetables)	103.1 (18.2–187.9)	34
		Grassland	Drained	5.0 (2.3–7.7)	8	Grassland	No data	–
		Wetlands	Managed for extraction	3.6 (0.2–5.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

¹Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.15 Terrestrial nitrous oxide emission factors for warm climate Latin America and the Caribbean

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	1.3	1
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	0.8	2
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Forest Land and cleared Forest Land (shrubland), drained	2.4 (1.3–3.5)	10	Forest Land	No data	–
		Plantations	Forest Land and cleared Forest Land (shrubland), drained	2.4 (1.3–3.5)	10	Plantations	No data	–
			Oil palm	1.2	1			
			Sago palm	3.3	1			
		Cropland	Rice	0.4 (-0.1–0.8)	6	Cropland	No data	–
			Cropland	5.0 (2.3–7.7)	8			
		Grassland	Drained	5.0 (2.3–7.7)	8	Grassland	No data	–
		Wetlands	Managed for extraction	3.6 (0.2–5.0)	–	Managed for extraction	No data	–
	Rewetted	Forest Land	Rewetted organic soils	0	–	Rewetted forest	No data	–
		Wetlands				Rewetted wetlands	No data	–

Source:

ⁱValues for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.16 Terrestrial nitrous oxide emission factors for cool climate Asia

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
	Drained	Forest Land	Drained, nutrient-poor (Boreal)	0.22 (0.15–0.28)	43	Forest Land	No data	–
			Drained, nutrient-rich (Boreal)	3.2 (1.9–4.5)	75			
			Drained (Temperate)	2.8 (-0.57–6.1)	13			
		Cropland	Drained	13 (8.2–18)	36	Cropland	No data	–
		Grassland	Drained (Boreal)	9.5 (4.6–14)	16	Grassland	No data	–
			Drained, nutrient-poor (Temperate)	4.3 (1.9–6.8)	7			
			Deep-drained, nutrient-rich (Temperate)	8.2 (4.9–11)	47			
			Shallow-drained, nutrient-rich (Temperate)	1.6 (0.56–2.7)	13			
		Wetlands	Wetlands	Not included	–	Wetlands	0.8 (0.3–1.3)	4
			Managed for extraction	0.3 (-0.03–0.64)	4	Managed for extraction	No data	–
	Rewetted	Any land use	Rewetted organic soils	0	–	Any land use	No data	–

Source:

¹ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Table A3.17 Terrestrial nitrous oxide emission factors for cool climate Latin America and the Caribbean

Management	Drainage	Land use	Wetlands Supplement			This study		
			Category	EF (95% CI)	n	Category	EF (95% CI)	n
Unmanaged land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	0.8 (–1.8–3.3)	4
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
Managed land	Undrained	Forest Land	Forest Land	Not included	–	Forest Land	No data	–
		Grassland	Grassland	Not included	–	Grassland	No data	–
		Wetlands	Wetlands	Not included	–	Wetlands	4.0	1
	Drained	Forest Land	Drained, nutrient-poor (Boreal)	0.22 (0.15–0.28)	43	Forest Land	No data	–
			Drained, nutrient-rich (Boreal)	3.2 (1.9–4.5)	75			
			Drained (Temperate)	2.8 (–0.57–6.1)	13			
		Cropland	Drained	13 (8.2–18)	36	Cropland	No data	–
		Grassland	Drained (Boreal)	9.5 (4.6–14)	16	Grassland	No data	–
			Drained, nutrient-poor (Temperate)	4.3 (1.9–6.8)	7			
			Deep-drained, nutrient-rich (Temperate)	8.2 (4.9–11)	47			
			Shallow-drained, nutrient-rich (Temperate)	1.6 (0.56–2.7)	13			
		Wetlands	Wetlands	Not included	–	Wetlands	No data	–
			Managed for extraction	0.3 (–0.03–0.64)	4	Managed for extraction	No data	–
	Rewetted	Any land use	Rewetted organic soils	0	–	Any land use	No data	–

Source:

ⁱ Values for this study are the authors' own elaboration based on the Pet-Emit EF database published alongside this report: Freeman, B., Monsen-Elvik, E., Jovani, J., Page, S., Rams Beltrán, E., Nuutinen, M., Warren, M. & Evans, C. (forthcoming). Peat-Emit – EF database: Terrestrial GHG emissions.

Appendix 4. Fire emissions input data

Table A4.1 Emissions factors for CO₂, CO and CH₄ derived from *ex situ* laboratory and *in situ* field measurements of tropical peat combustion

Sampling location	Sampling method	Number of samples	Method	Emission factors (g kg ⁻¹ dry matter burned)			MCE	Notes
				CO ₂	CO	CH ₄		
South Sumatra, Indonesia ⁱ	Lab	1 peat sample	FTIR	1703	210	20.8	0.84	Basis for IPCC Tier 1 EFs
South Kalimantan, Indonesia ⁱⁱ	Lab	3 peat samples	FTIR	1637 ±204	233 ±72	12.8 ±6.6	0.82 ±0.07	
Central Kalimantan, Indonesia ⁱⁱⁱ	Field	4 smoke plumes	CRS	1594 ±61	255 ±39	7.4 ±2.3	0.8	
Central Kalimantan, Indonesia ^{iv}	Field	35 smoke plumes	FTIR	1564 ±77	291 ±49	9.5 ±4.7	0.77 ±0.05	
Coastal central Sumatra, Indonesia ^v	Ship-board	5 biomass burning episodes	Infrared & CRS	1663 ±54	205 ±23	7.6 ±1.6	0.84	Estimated average EFs
West Kalimantan, Indonesia ^{vi}	Lab	17 peat samples	CO/CO ₂ monitors	1831 ±131	138 ±72	17 ±1.2	0.89 ±0.06	Smouldering emissions
Central Kalimantan, Indonesia ^{vii}	Field	21 smoke plumes	CELAS & FTIR	1775 ±64	279 ±44	7.9 ±2.4	0.77–0.83	'Close-to-source' peat only fires
Pahang & Selangor, Peninsula Malaysia ^{viii}	Field	10 smoke plumes	FTIR	1579 ±58	251 ±39	11.0 ±6.1	0.80 ±0.03	
Indonesia ^{ix}	Lab	1 peat sample	FTIR	n.d.	n.d.	10.4	0.83	
Sarawak, Malaysia ^x	Lab	4 peat samples	CO & CO ₂ monitors & FTIR	1331 ±78	171 ±22	6.7 ±0.9	0.83 ±0.03	
Putnam Co., Florida, United States ^x	Lab	7 peat samples	CO & CO ₂ monitors & FTIR	1194	355	9.8	0.69	Average values*
Sumatra & Central Kalimantan, Indonesia ^{xi}	Field	25 smoke plumes	FTIR & whole air sampling	1544	315	9.8	0.72 ±0.02	
Central Kalimantan, Indonesia ^{xii}	Field	7 smoke plumes	FTIR	1590 ±42	237 ±26	5.4 ±1.3	0.78–0.85	
Rokan Hilir, Sumatra, Indonesia ^{xiii}	Field	27 smoke plumes	FTIR	1591 ±243	206 ±85	4.3 ±2.4	0.75–0.84	Data for fire spread/smouldering stage only
Overall average ±95% CIs				1584 ±91	242 ±32	10.0 ±2.3		

Notes:

Values presented with standard deviations or as ranges depending on original study reporting. Overall average presented with 95 percent CIs.

n.d. = not determined

*Averages of EFs for 4 peat samples with 25 percent fuel moisture content (FMC) and 3 samples with 60 percent FMC

Data for the Everglades National Park in Florida, United States excluded as values represented a mix of flaming and smouldering.

FTIR = fourier transform infrared spectrometer

CRS = cavity ring-down spectrometer

CELAS = cavity-enhanced laser absorption spectrometer

MCE = modified combustion efficiency.

Sources:

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Table A4.2 Peat fuel consumption values

Sampling location	Land use/cover	Sampling method	Sample size	Depth of burn (m)	Dry bulk density (g cm ⁻³)	Mass of fuel consumed (t DM ha ⁻¹)	Notes
Central Kalimantan, Indonesia ⁱ	Lightly degraded PSF	Post-fire field measurement at burn scars	43	0.51 ±0.05	0.1 ^A	510 ±50	1997 fire season
Central Kalimantan, Indonesia ⁱⁱ	Fern-dominated (deforested)	Pre-/post-fire assessment of fuel load	9	n.d.	n.d.	83 ±1.8	Experimental burning in plots
Riau, Indonesia ⁱⁱⁱ	Degraded shrub and fern-dominated	Post-fire field measurement	4	19.5 ±8.5	0.1 ^A	195 ±85	Controlled burning with different above ground fuel loads to simulate agricultural land clearing fires
Central Kalimantan, Indonesia ^{iv}	Degraded PSF	LiDAR comparison of burnt vs unburnt peat surfaces	n.a.	0.33 ±0.18	0.1 ^A	330 ±180	2006 fire season
Central Kalimantan, Indonesia ^v	Degraded fern scrub	Field measurement	n.a.	0.075 ±0.062	0.22	165 ±136	Experimental burning in a small plot
Central Kalimantan, Indonesia ^{vi}	Degraded PSF & fern scrub	LiDAR comparison of burnt surfaces with 1990 peat surface; field BD data	n.a.	Fire 1: 0.17 Fire 2: 0.10 Fire 3: 0.6 Fire 4+: 0.02	Fire 1: 0.121 ±0.018 Fire 2+: 0.115 ±0.020	Fire 1: 206 Fire 2: 115 Fire 3: 69 Fire 4+: 23	Eight fire seasons ^B
Jambi, Indonesia ^{vii}	Degraded PSF & previously burnt fern scrub	Structure from motion photogrammetry applied to post-fire imagery collected using an UAV	n.a.	0.23 ±0.19	0.106 ^A	244 ±201	2015 fire season
Central Kalimantan, Indonesia ^{viii}	Degraded, previously burnt fern scrub	Field measurement at active fires	30	0.21 –0.24	0.15	315–360	2019 fire season
Central Kalimantan, Indonesia ^{ix}	Degraded, previously burnt fern scrub	Field measurement at active fires	5	0.05 ±0.036	0.14 ±0.02	70 ±50	2015 fire season

Notes:

Values presented with standard deviations or as ranges depending on original study reporting.

DM = dry matter.

PSF = peat swamp forest.

^A Assumed value for bulk density based on literature values.

^B Fire events in 1997, 2001, 2002, 2004, 2005, 2006, 2009 and 2011.

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Appendix 5. Suggested protocol for emission factor development

This section details a suggested protocol for the aggregation, analysis and presentation of peatland GHG emissions/removals data. We outline concise guidance on a series of fundamental steps that can support the production of robust EFs for organic soil. This is intended to support both individuals and organizations working to produce new EFs and end users of published EFs needing to evaluate the process used to produce any given set of estimates. This information can also be used by organizations developing EFs (such as IPCC or national governments) or using EFs (such as NGOs, business, voluntary carbon standards) to evaluate the EF derivation approaches developed by themselves or their collaborators.

Step 1. Define the population and region/s of interest

The population and region of interest should be clearly defined based on the study's scope. This can range from a broad, global perspective (such as global peatlands) to more specific geographic or categorical classifications including:

- regional level (such as “Southeast Asian peatlands”);
- national level (such as “Indonesian peatlands”); and
- land-use or land-cover category (such as “peat swamp forests”).

Clearly specifying the population and region ensures that the analysis aligns with the study objectives and facilitates meaningful comparisons across different environmental and geographical contexts.

Step 2. Define the outcome/s of interest

The outcomes of interest should be clearly outlined in accordance with the *2006 IPCC Guidelines*, the *2019 Refinement* and the *Wetlands Supplement*.

Step 3. Develop search strings to identify relevant publications

To systematically identify relevant publications, search strings should be designed to capture studies that align with the population(s), region(s), and outcome(s) of interest, as defined in [Step 1](#) and [Step 2](#). Search terms can be identified through previously known literature, subject expertise and by seeking out local knowledge for regionally specific terms. It should be considered whether non-English language searches could be expected to substantially increase data capture, and whether these are possible within project constraints. Where large numbers of publications are returned, comprehensive search strings may be disaggregated into component searches (such as CO₂, CH₄, N₂O outcomes) to facilitate efficient screening.

Step 4. Undertake a bibliographic database search

Title, abstract and keyword searches should be conducted at a minimum. Database limitations should be considered (for example, some databases may not capture university thesis repositories in some regions), and searches of multiple databases may be undertaken where required. The database search/es can be augmented/supported by “snowballing” from identified publications, by prior knowledge of the literature, and by targeted searches for authors/sites identified by other means (for example, TSC input for this project).

Step 5. Screen search results for relevance

Publications should be sequentially screened for relevance by title, abstract and full text. At each level, publications should be excluded if there is evidence that they do not include relevant data. Where relevance is unclear, publications should be retained for the next level of screening to minimize false negatives.

Step 6. Screen search results for study suitability

As the objective is the development of new/updated EFs for inland organic soils, the remaining publications must be further screened to assess the suitability of the presented data for this purpose. A detailed description of potential criteria for study inclusion is presented in [Appendix 6](#). This includes both “recommended” criteria to be used for data-rich regions, categories and outcomes, and “minimum” criteria to be used for less data-rich contexts, and/or where the benefits of inclusivity may outweigh the costs of including less robust studies.

Step 7. Extract the required data

Data availability may vary between publications. However, where available, data should be extracted on all the variables described in [Table A5.1](#). The data requirements vary depending on the outcome variable/s reported. The suggested data requirements reflect both data needed to evaluate the suitability of studies for inclusion in the EF database ([Steps 6](#)) and for the subsequent calculation of EFs. It is therefore feasible that in practice, [Steps 6](#) and [Steps 7](#) may be carried out simultaneously. However, we have separated them here for clarity.

Step 8. Classify sites appropriately

Sites should be classified by climate, region, management, drainage status and land use. The classification process should categorize sites at a resolution that meets the needs of end users. A balance must be maintained between meeting the need for more specific EFs to improve the granularity of reporting and ensuring that the EFs are based on a sufficiently robust dataset. While more specific EFs can lead to greater accuracy and refined estimations, they must be derived from adequate, high-quality data to ensure statistical reliability and policy relevance. If EFs are too narrowly defined without sufficient supporting data, the resulting estimates may lack credibility and introduce uncertainty into reporting. Conversely, overly generalized EFs may fail to capture important regional or ecosystem-specific variations. Therefore, the approach should aim to optimize specificity while maintaining data sufficiency, consistency, and scientific rigor to produce reliable and actionable estimates.

Step 9. Calculate emission factors

In this analysis, a simple equally weighted arithmetic mean is used as the EF estimate for each category. There may be merit to the development of weighting approaches to account for differences in study duration, spatial coverage/replication, methodological robustness, or differences between methods. However, any such approaches that involve an element of subjective assessment must make explicit the assumptions and biases underlying the approach, so that the resulting EFs can be evaluated appropriately by end users.

Step 10. Make emission factors available to end users

When EF estimates are published, an indicator of the uncertainty associated with each EF estimate should also be provided along with the size of the sample used to produce it. Authors should clearly describe the approach and provide the input values, and sources used to derive the EFs and highlight any challenges faced that may affect the

robustness of EF estimates produced. Where any values represent potential anomalies due to small sample sizes, classification challenges or limitations associated with the quality of studies (or their reporting), authors should highlight these clearly. Ultimately the presentation of any EFs produced should be done in a way that allows end users to make a reasonable assessment of the suitability of the EFs for their purposes.

Table A5.1 Suggested data to be reported by and extracted from studies to be used for emission factor derivation

Study type	Variables
All studies	Lead author, publication year, country, geographical region, study site name, latitude, longitude, present land use/cover description, land use/cover history, dominant vegetation, climate zone, depth of organic layer, soil description/classification, distance to drainage system, water table depth, measurement method, start/end dates of study period, measurement frequency/schedule.
GHG flux studies	Flux calculation methodology used, number of replicates, spatial coverage/representativeness, net ecosystem exchange, ecosystem respiration, gross primary productivity, soil respiration, heterotrophic respiration, litter inputs, fine root mortality, biomass harvest carbon export, methane emissions, nitrous oxide emissions.
Subsidence rate studies	Mean subsidence rate, bulk density (upper and lower peat), organic carbon content (upper and lower peat), number and location of measurement points.
Peat core studies	Long-term rate of observed carbon accumulation (LORCA), peat depth, peat basal age, number of measurement locations.
Fire emissions studies	Methodology used, types and numbers of measurements, values for emission factors (carbon dioxide, carbon monoxide and methane), modified combustion efficiency, peat bulk density, peat organic carbon content, peat fuel moisture content, depth of burn.

Source: Authors' own elaboration

Appendix 6. Suggested criteria for assessing study suitability

This section details a set of suggested criteria developed during the Peat-Emit project for the evaluation of study suitability when aggregating data for peatland GHG EF estimation. The information presented in this section serves several purposes:

1. It is intended to provide an insight into the decision-making processes undertaken during the Peat-Emit project, to inform end users in making their assessments of the EFs produced.
2. It is intended to provide a source of guidance for authors who may wish to publish studies supporting future EF derivation projects.
3. It can be used by journals and funders to encourage researchers to develop study designs and publications that include the relevant measurements and information required to support EF derivation.

There is inevitably a degree of subjectivity in defining such criteria, as some thresholds will be somewhat arbitrary and reliant on expert judgement. There will also be cases where a study may be limited in one area, but strengths elsewhere may be sufficient to outweigh this. Therefore, these criteria should not necessarily be treated as pass/fail. There will always be a degree of expert judgement required to assess the relative balance of strengths and weaknesses. It is acknowledged that no set of suggested criteria is ever likely to represent a definitive solution, but it is hoped that this section will support and facilitate the development of a wider dialogue around the optimal approach for assessing the suitability of studies for use in EF estimation. Ultimately any approach must seek to balance scientific robustness, practical realities and the needs of end users.

After an initial screening to confirm that studies report a relevant population, region, and outcome (see [Steps 5, Appendix 5](#)), the remaining publications must undergo further evaluation to assess the suitability of their data for deriving EFs (see [Steps 6, Appendix 5](#)). This secondary screening should consider key aspects such as study design, methodology, and reporting quality, ensuring that only validated and reliable data are included in EF databases. The application of appropriately rigorous inclusion criteria will help to ensure that the resulting EF estimates will be scientifically robust and suitable for accurate reporting.

Suggested general criteria for assessing the suitability of studies for use in EF derivation are presented in [Table A6.1](#). More specific suggested criteria are then presented for studies reporting CO₂ emissions measured using flux towers ([Table A6.2](#)), transparent chambers ([Table A6.3](#)), and opaque chambers ([Table A6.4](#)), CH₄ and N₂O emissions ([Table A6.5](#)), subsidence rates ([Table A6.6](#)), long-term carbon accumulation rates ([Table A6.7](#)) and data related to peatland fires and fire emissions ([Table A6.8, Table A6.9](#)).

We present both *recommended* and *minimum* suggested criteria for assessing study suitability. For data-rich regions/categories/outcomes, we would suggest that more stringent *recommended* criteria should be used. However, for less data-rich contexts, the benefits of relaxing the study suitability criteria to increase data availability may outweigh the potential costs due to associated reductions in data quality. Therefore, less stringent *minimum* criteria may be used only in cases, where:

- an insufficient number of studies meet the *recommended* criteria to adequately populate a dataset; and
- the urgency of need for, and potential benefits from an EF estimate justify the *temporary* use of a less robust value, until more data are available.

Table A6.1 General criteria for assessing the suitability of studies

Consideration	Minimum	Recommended
Environmental description	Description of location, climate, present land cover/use, and dominant vegetation.	In addition to minimum criteria: Precise location (latitude/longitude or coordinates) provided. Land-use history included.
Soil description	Soils classified as peat, histosols or organic soils by study authors.	In addition to minimum criteria: Thickness and carbon content of organic layer presented, and nature of underlying material described.
Hydrology	Narrative description of drainage management or flooding conditions/patterns.	In addition to minimum criteria: Water table depth presented. Ideally as annual average value. Distance to drainage system reported.
Method reporting	Most necessary information for study suitability evaluation is reported (or identifiable from other sources). Necessary information is reported but may be imprecise (e.g. overview of sampling timeline without clear dates), requiring expert judgement.	All necessary information for study suitability evaluation is reported.
Data type	Secondary reports of data from field studies. accompanied by adequate site/methodological information to allow reasonable assessment of study suitability.	Primary data from field studies.
Outcome type	Indirect measure of outcome of interest (e.g. long-term carbon accumulation rate as a proxy for net balance of greenhouse gas fluxes).	Direct measure of outcome of interest (e.g. chamber or eddy covariance measurements of greenhouse gas fluxes).
Outcome reporting	Mean value reported or calculable.	Mean, standard deviation and sample size reported.
Outcome availability	Relevant values can be disaggregated from non-target population values (e.g. mineral soils) or unrealistic values (e.g. experimental fertilizer treatments).	<i>Same as minimum.</i>

Source: Authors' own elaboration

Table A6.2 Suitability criteria for studies reporting carbon dioxide flux measurements using flux towers

Consideration	Minimum	Recommended
Duration	≥7 months (Tropical) ≥9 months (Non-tropical)	≥1 year
Temporal frequency	Continuous measurements at 20 Hz or 10 Hz with high frequency data averaged every 30 minutes.	<i>Same as minimum.</i>
Temporal spacing	Gaps are allowed. Gap-filling performed using eddy covariance techniques.	<i>Same as minimum.</i>
Temporal coverage	Covers at least 6 calendar months (can be a composite of several periods over multiple calendar years).	Covers all calendar months, ideally as a single continuous period.
Seasonal coverage	1 tower	Captures all seasonal variation.
Spatial replication	Homogeneous land use within footprint. If fluxes from several land uses are captured within the flux tower footprint, these must be filtered / disaggregated.	<i>Same as minimum.</i>
Spatial variation	Includes all major seasonal variations, with approximately representative proportional coverage unlikely to result in excessive bias.	<i>Same as minimum.</i>
Calculation method	For carbon dioxide (CO ₂) emissions: In 'steady state' sites, annual NEE or net ecosystem productivity (NEP) may be used to represent the soil CO ₂ EFs. However, in non-steady state sites, changes in biomass carbon stocks must be accounted for when NEP is used to derive a peat CO ₂ -C _{on-site} EF.	<i>Same as minimum.</i>
Carbon imports/exports	For CO ₂ emissions: Must be accounted for if present. Literature values or approximations may be used.	For CO ₂ emissions: Must be accounted for if present. Empirically measured site-specific values available.

Source: Authors' own elaboration

Table A6.3 Suitability criteria for studies reporting carbon dioxide flux measurements using transparent chambers

Consideration	Minimum	Recommended
Duration	≥7 months (Tropical) ≥9 months (Non-tropical)	≥1 year
Temporal frequency	Minimum 5 measurements for tropical sites. Minimum 6 measurements for non-tropical sites. Where measures are spread over multiple calendar years, frequency can be lower if temporal and seasonal coverage are acceptable.	≥1 measurement per month
Temporal spacing	No gaps > 3 months. Where measurements are spread over multiple calendar years, gaps can be larger if temporal and seasonal coverage are acceptable.	No gaps > 1 month
Temporal coverage	Covers at least 5 calendar months (can be a composite of several periods over multiple calendar years).	Covers all calendar months (or higher resolution), ideally as a single continuous period.
Seasonal coverage	Includes all major seasonal variations, with approximately representative proportional coverage unlikely to result in excessive bias.	Includes all seasonal variation.
Diurnal variation	Measurement time consistent.	Empirically characterized.
Temp variation	Consistent time of day for measurements.	Multiple measurements per chamber, from sunrise until mid-afternoon.
PAR variation	Light (transparent) and dark (opaque) measurements only.	Multiple measurements per chamber from sunrise until mid-afternoon. Alternatively, a selection of shade cloths covering the full photosynthetically active radiation (PAR) range from dark to ambient.
Spatial replication	≥3 replicates (chambers)	Same as minimum.
Spatial variation	Measurements include the dominant landform for the site, and land use/cover category.	Measurements from all important landforms within variable sites/habitats. Habitat characterized to allow robust upscaling.
Calculation method	Mean of fluxes (upscaled). Trapezoidal integration of fluxes. Annual emissions modelled using environmental variables, with parameters estimated for the annual dataset.	Annual emissions modelled using environmental variables, with parameters estimated for individual campaigns and interpolated.
Carbon imports/exports	Must be accounted for if present. Literature values or approximations may be used.	Must be accounted for if present. Empirically measured site-specific values available.

Source: Authors' own elaboration

Table A6.4 Suitability criteria for studies reporting carbon dioxide flux measurements using opaque chambers

Consideration	Minimum	Recommended
Outcome measured	R_{soil} (no root exclusion) is acceptable if sufficient other data are available to assess the relative contribution of R_{het} and autotrophic root respiration. Studies reporting R_{eco} alone, should be excluded, as autotrophic contributions cannot be separated from R_{het} .	R_{het}
Duration	≥7 months (Tropical) ≥9 months (Non-tropical)	≥1 year
Temporal frequency	Minimum 5 measurements for tropical sites. Minimum 6 measurements for non-tropical sites. Where measures are spread over multiple calendar years, frequency can be lower if temporal and seasonal coverage are acceptable.	≥1 measurement per month
Temporal spacing	No gaps > 3 months. Where measurements are spread over multiple calendar years, gaps can be larger if temporal and seasonal coverage are acceptable.	No gaps > 1 month
Temporal coverage	Covers at least 5 calendar months (can be a composite of several periods over multiple calendar years).	Covers all calendar months (or higher resolution), ideally as a single continuous period.
Seasonal coverage	Includes all major seasonal variations, with approximately representative proportional coverage unlikely to result in excessive bias.	Includes all seasonal variation.
Diurnal variation	Measurement time consistent.	Empirically characterized.
Spatial replication	≥3 replicates (chambers)	<i>Same as minimum.</i>
Spatial variation	Measurements include the dominant landform for the site, and land use/cover category.	Measurements from all important landforms within variable sites/habitats. Habitat characterized to allow robust upscaling.
Root exclusion method	Bare peat with post-measurement visual checks to ensure that there are no roots growing.	Trenching, girdling, transect sampling (varied distance from tree/palm) or bare peat with post-measurement checks to ensure that there are no roots growing.
Calculation method	Mean of fluxes. Not upscaled based on stratified sampling.	Trapezoidal integration of fluxes. Annual emissions modelled using environmental variables. Upscaled based on stratified sampling.
Carbon inputs	Appropriate litterfall and fine root mortality values must be available from literature.	Site-specific litterfall and fine root mortality values available.

Notes: R_{eco} = ecosystem respiration. R_{het} = heterotrophic respiration. R_{soil} = soil respiration.**Source:** Authors' own elaboration

Table A6.5 Suitability criteria for studies reporting methane and nitrous oxide flux measurements

Consideration	Minimum	Recommended
Duration	≥7 months (Tropical) ≥9 months (Non-tropical)	≥1 year
Temporal frequency	Minimum 5 measurements for tropical sites. Minimum 6 measurements for non-tropical sites. Where measures are spread over multiple calendar years, frequency can be lower if temporal coverage is acceptable.	≥1 measurement per month
Temporal spacing	No gaps > 3 months. Where measurements are spread over multiple calendar years, gaps can be larger if temporal and seasonal coverage are acceptable.	No gaps > 1 month
Temporal coverage	Covers at least 5 calendar months (can be a composite of several periods over multiple calendar years).	Covers all calendar months (or higher resolution), ideally as a single continuous period.
Seasonal coverage	Includes all major seasonal variations, with approximately representative proportional coverage unlikely to result in excessive bias.	Includes all seasonal variation.
Diurnal variation	Measurement time consistent.	Empirically characterized.
Spatial replication	≥3 spatial replicates (chambers)	<i>Same as minimum.</i>
Spatial variation	Measurements (or flux tower fetch) include the dominant landform for the site, and land use/cover category.	Measurements from all important landforms within variable sites/habitats. Habitat characterized to allow robust upscaling. Flux tower fetch includes all important landforms, and is representative of wider site, and land use/cover category.
Calculation method	Mean of fluxes (upscaled).	Trapezoidal integration of fluxes. Annual emissions modelled using environmental variables.

Source: Authors' own elaboration

Table A6.6 Suitability criteria for studies reporting subsidence rate measurements

Consideration	Minimum	Recommended
Study duration	≥2 year	≥5 year
Measurement interval	≥6 months This must include two consecutive wet seasons to allow for similar groundwater conditions at the time of measurements, so that the influence of elastic changes in peat thickness are minimized.	Monthly
Levelling method	Reference points (usually plastic pipes or metal rods) must be anchored into the mineral soil layer underneath the peat. Distance from the peat surface to a fixed reference point marked in the plastic pipes / rods. Multiple methods such as extensometers, dual pressure transducers, manual measurements, time-lapse cameras.	<i>Same as minimum.</i>
Number of measurements	≥3 replicates	Measurements from all important landforms within variable sites. Transect measurements, between, canals/drains/dykes to account for different peat motion rates as a consequence of different groundwater level.
Land-use change during study period	Only measurements within the same land-use/cover category should be combined to estimate subsidence rates. If the land-use/cover category changes during a time series due to management changes (e.g. conversion of peat swamp forest to oil palm plantation) then data from periods of different land use/cover must be allocated appropriately.	<i>Same as minimum.</i>
Drainage changes during study period	Water table depth should be measured together with each manual peat measurement to assess what the effect of water level and drainage might be on peat subsidence. If the land-use/cover category changes during a time series due to drainage changes (e.g. from shallow drained to deep drained) then data from periods of different land use/cover must be allocated appropriately.	<i>Same as minimum.</i>

Source: Authors' own elaboration

Table A6.7 Suitability criteria for studies reporting carbon accumulation rates estimated from peat cores

Consideration	Minimum	Recommended
Outcome type	Long-term observed rate of carbon accumulation (LORCA)	<i>Same as minimum.</i>
Core depth	Full peat depth	Full peat depth and ≥ 100 cm
Core basal age (LORCA)	≥ 1000 years	<i>Same as minimum.</i>
C content estimation	Derived from organic matter content using a conversion factor.	Empirically determined from samples.
Site conditions	Unmanaged land and undrained organic soil	<i>Same as minimum.</i>

Source: Authors' own elaboration

Table A6.8 Suitability criteria for studies reporting greenhouse gas emissions emissions from peatland fires

Consideration	Minimum	Recommended
Measurements are for smouldering (as opposed to flaming fires)	<i>In situ</i> measurements are made in smoke plumes	MCE (modified combustion efficiency) is measured and is < 0.9 (representing smouldering combustion)
Peat organic carbon content	Appropriate literature value(s) provided	Site-specific values are provided
Peat water content	Appropriate literature value(s) provided	Site-specific values are provided (given that peat water content may affect the combustion dynamic [smouldering vs flaming] and emissions chemistry)

Source: Authors' own elaboration

Table A6.9 Suitability criteria for studies reporting the mass of dry peat fuel consumed during fires

Consideration	Minimum	Recommended
Land cover & fire history described	Description of vegetation cover and land use (if any)	Description of site fire history, in addition to vegetation cover and land use history
Degree of site disturbance described	Information on whether site is undrained vs drained	Sufficient information provided to distinguish between sites with no/low drainage or high drainage; information on water level depth prior to fire
Depth of burn	Post-fire measurements using either field data or remote sensing	Post-fire measurements using either field data or remote sensing sufficient to derive a comparison with height of pre-fire peat surface, and sufficient to account for heterogeneity of the burnt peat surface & hence depth of burn
Peat dry bulk density	Estimated from relevant literature values	Based on field measurements

Source: Authors' own elaboration

For more information, please contact:

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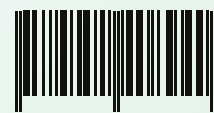
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Food and Agriculture Organization of the United Nations
Rome, Italy

With the financial support of



ISBN 978-92-5-140894-0



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CE0889EN/1/07.26