Check for updates

Conservation Letters

WILEY

Conservation Letters
A journal of the Society for Conservation Biology
Open Access

LETTER OPEN ACCESS

Mismatch Between Global Importance of Peatlands and the Extent of Their Protection

Kemen G. Austin[1] | Paul R Elsen[1] | Euridice N. Honorio Coronado[2] | Alfred DeGemmis[1] | Angela V. Gallego-Sala[3] | Lorna Harris[4] | Heidi E. Kretser[1,5] | Joe R. Melton[6] | Daniel Murdiyarso[7,8] | Sigit D. Sasmito[9] | Erin Swails[7] | Arief Wijaya[10] | R. Scott Winton[11] | Dan Zarin[1]

[1]Global Conservation Program, Wildlife Conservation Society, Bronx, New York, USA | [2]School of Geography and Sustainable Development, University of St. Andrews, St. Andrews, UK | [3]Geography Department, University of Exeter, Exeter, UK | [4]Wildlife Conservation Society Canada, Toronto, Canada | [5]Department of Natural Resources & the Environment, Cornell University, Ithaca, New York, USA | [6]Climate Research Division, Environment and Climate Change Canada, Victoria, British Columbia, Canada | [7]Center for International Forestry Research–World Agroforestry Situgede, Bogor, Indonesia | [8]Department of Geophysics and Meteorology, IPB University, Bogor, Indonesia | [9]Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University, Douglas, Queensland, Australia | [10]WRI Indonesia, Jakarta, Indonesia | [11]Environmental Studies Department, University of California Santa Cruz, Santa Cruz, California, USA

Correspondence: Kemen G. Austin (kaustin@wcs.org)

Received: 8 July 2024 | **Revised:** 26 November 2024 | **Accepted:** 6 December 2024

Funding: This study was supported by the funding from Ballmer Group for data analysis and manuscript preparation. E.N.H.C. acknowledges support from a NERC Knowledge Exchange Fellowship (NE/V018760/1). A.V.G.S. acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant 865403).

Keywords: area-based conservation | climate | peat | peatlands | protected areas | rights–based conservation

ABSTRACT

Global peatlands store more carbon than all the world's forests biomass on just 3% of the planet's land surface. Failure to address mounting threats to peatland ecosystems will jeopardize critical climate targets and exacerbate biodiversity loss. Our analysis reveals that 17% of peatlands are protected globally—substantially less than many other high-value ecosystems. Just 11% percent of boreal and 27% of temperate and tropical peatlands are protected, while Indigenous peoples' lands encompass at least another one-quarter of peatlands globally. Peatlands in protected areas and Indigenous peoples' lands generally face lower human pressure than outside those areas. Yet, almost half of temperate and tropical peatlands in protected areas still experience medium to high human pressure. Country submissions of Nationally Determined Contributions under the Paris Agreement and National Biodiversity Strategy and Action Plans under the Kunming–Montreal Global Biodiversity Framework could help catalyze actions and secure funding for peatland conservation, including support for the Indigenous stewardship that is critical to protect many of the world's highest priority peatland areas.

1 | Introduction

A disproportionate amount of Earth's terrestrial carbon is stored in peat-forming wetland ecosystems. These peatlands occur on just 3% of global land but store 600 gigatons of carbon in their soil, more carbon than in all the world's forest biomass (Yu et al. 2010; UNEP 2022; Pan et al. 2024). Peatlands are also critical water reservoirs, storing 10% of nonglacial freshwater globally and bolstering water security (Xu et al. 2018a). They play a vital role in water regulation, storing water quickly following precipitation events and releasing water gradually during dry periods, buffering the effects of floods and droughts (Loisel and Gallego-Sala 2022).

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2025 The Author(s). Conservation Letters published by Wiley Periodicals LLC.

Peatlands also support globally significant and locally critical ecosystem services including regional air temperature control, food and fiber, cultural and recreational values, and habitat for endemic species (IUCN 2021).

Nonetheless, peatlands are subject to widespread drainage and degradation due to commercial agriculture, forestry, mining, roads and other infrastructure expansion, and peat extraction for fuel and horticulture. Globally, peatlands are also negatively impacted by climate change itself (Leifeld and Menichetti 2018; Dargie et al. 2019), including increased decomposition and carbon loss due to warmer temperatures and drier climate conditions, permafrost thaw, and fire (Turetsky et al. 2015; Gibson et al. 2018; Harris et al. 2023). Recent estimates suggest that global peatlands emit 1.3–1.9 Gt carbon dioxide equivalent (CO_2e) annually from human-caused degradation (Leifeld, Wüst-Galley, and Page 2019), or 2%–4% of all global anthropogenic greenhouse gas emissions. Emissions from human-caused and natural peat fires likely contribute another 0.2–1.5 Gt CO_2e annually (Prosperi et al. 2020; Wilkinson et al. 2023). Notably, once emitted to the atmosphere, the carbon lost from peatlands cannot be restored on timescales that matter for preventing dangerous climate change (Goldstein et al. 2020), although peatland restoration can prevent further losses of carbon to the atmosphere (Nugent et al. 2019).

Sustaining peatlands' essential role in global climate regulation requires large-scale and long-term efforts to protect and rehabilitate peatlands globally. The conservation and sustainable management of nearly all remaining undegraded peatlands, and the recovery of nearly all degraded peatlands, are essential to limiting warming to 1.5°C (Roe et al. 2019). This will require a portfolio of conservation approaches anchored in the ecological, social, cultural, economic, and political contexts of peatland regions and landscapes. These interventions may include expanding and strengthening management of area-based conservation approaches, regulations to limit degrading land uses, and recognizing Indigenous peoples' rights and governance. Durable finance mechanisms to incentivize peatland conservation and restoration efforts, as well as adaptation initiatives to manage increasing climate risks, are also urgently needed (UNEP 2022).

Several emerging international policy frameworks have the potential to elevate peatlands in national and local conservation priorities and action plans. These include the Global Stocktake process under the Paris Agreement, in which countries will provide additional detail for achieving 2030 mitigation targets, as well as more detail on National Adaptation Plans (NAPs; UNFCCC 2024). National governments are also in the process of developing strategies consistent with the Kunming–Montreal Global Biodiversity Framework (GBF) objective to maintain or enhance the integrity of all ecosystem types, including peatlands. Yet, data on the extent of peatlands that may be benefitting from existing conservation approaches are needed to inform the scale of additional action required to reach key climate and biodiversity targets for these ecosystems.

In this study we assess the role of both protected areas and Indigenous peoples' lands for the conservation of peatlands and explore how anthropogenic land use pressures are unfolding within and outside these categories. A growing body of research has demonstrated that Indigenous rights and community-based management reduce deforestation and forest degradation (Sze et al. 2024) and that formal community management associations and local participation in rulemaking are linked to positive environmental and social outcomes in collectively managed forests across the tropics (Fischer et al. 2023). Here, we estimate the area of peatlands within Indigenous peoples' lands to ascertain the extent to which peatlands may be benefiting from existing community-led resource management activities.

Our assessment provides a snapshot of current global peatland protection, offers insight into the global and regional mismatch between the importance of peatlands and their current level of protection, and informs the design of coordinated solutions for an interrelated climate and biodiversity challenge with global significance.

2 | Methods

2.1 | Peatland Map

We used a continuous global map of peatland fractional coverage, termed Peat-ML (Melton et al. 2022), as the basis for our analysis. This map is the only currently available map of global peatland extent developed using a model trained on harmonized calibration data. Peat-ML represents the estimated proportion of peatlands supporting peat at least 30 cm in depth within each cell of a global 5 arcmin resolution grid. The Peat-ML model was evaluated by comparing the output to peat extent data excluded from model training, as well as to independent data not used in model development. Results suggest that Peat-ML is comparable to or more reliable than other currently available global and regional peat maps (Melton et al. 2022).

The Peat-ML product does have limitations, and we cannot assess its accuracy in regions lacking calibration and validation data. This motivated an assessment of the robustness of our analysis using alternative regional- and country-specific peatland maps. To do so, we replicated our assessment using publicly available regional maps of peatlands in Indonesia (Miettinen, Shi, and Liew 2016; Anda et al. 2021), the Amazon lowlands of Peru (Hastie et al. 2022), the Amazon Basin (Hastie et al. 2024), China (Xu et al. 2018b), and the Congo Basin (Crezee et al. 2022). By comparing the proportion of regional or national peatlands within protected areas using more than one map of the same geography, produced using diverse methods and definitions, we were able to gauge the extent to which our primary results were sensitive to the input map.

2.2 | Peatlands Within Protected Areas

To calculate the area of peatlands within global protected areas, we used a vector map of terrestrial protected areas from the World Database on Protected Areas (WDPA) downloaded in May 2023 (UNEP-WCMC and IUCN 2023). We differentiated "strict" (IUCN categories I–IV) versus "nonstrict" or "multiple use" (IUCN categories V and VI) protection categories. The strict protection category comprises areas specifically designated for the protection of nature and includes national parks, wilderness areas, nature reserves, and habitat and species management areas. The

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

nonstrict/multiple use protection category encompasses areas where a wider range of anthropogenic activities, including some sustainable uses, are permitted. We included protected areas without a reported IUCN category in the nonstrict/multiple use classification. Importantly, the classification into the strict category does not necessarily indicate more effective, equitable, or durable protection. Indeed, nonstrict/multiple use protection has been shown to be as effective as strict protection in many contexts, while also supporting activities critical for local livelihoods (Nelson and Chomitz 2011; Elleason et al. 2021).

The WDPA also includes Ramsar sites, which are a distinct subset of protected areas that merit attention in the context of peatlands. National governments have designated wetlands of international importance under the 1971 Ramsar Convention. Ramsar designated wetlands can overlap with either a strict or nonstrict/multiple use classifications in the WDPA, and we separately report the area of peatlands within Ramsar sites that overlap with either classification.

We resolved issues with overlapping polygons in the WDPA by separately grouping and dissolving all protected area categories and removing areas of nonstrict/multiple use polygons that overlapped with strict polygons. Using the Peat-ML map, we calculated the area of each cell intersecting each protected area polygon and multiplied the resulting area by its corresponding peat fraction. This approach assumed that peat soils occurred homogeneously across the Peat-ML grid cell.

We also replicated our assessment using alternative maps of protected areas in China (Fan et al. 2023) and India (Lamba et al. 2023), as these countries have protected area systems that are known to be poorly represented by the WDPA. These studies collected comprehensive spatial data on protected areas from government sources and open-source repositories of spatial data that provide substantially improved coverage and accuracy relative to the WDPA. The Fan et al. (2023) dataset includes more than 1.6 million km^2 of additional protected areas in China, relative to the WDPA, while the Lamba et al. (2023) dataset includes more than 170,000 km^2 of additional protected areas in India, relative to the WDPA. We compared the proportion of peatlands within protected areas using these alternative maps, to assess the extent to which our primary results were sensitive to the input protected area map. For China, we followed the approach of Fan et al. (2023) to assign IUCN categories to each protected area, but assigned those classified as "Geoparks" to IUCN Category V. We then reclassified all of India and China's protected areas into strict and multiple-use categories, following our above definition.

2.3 | Peatlands Within Indigenous Peoples' Lands

We next calculated the extent of peatlands occurring on lands that are under the stewardship of Indigenous peoples, using a global dataset representing some of these areas (Garnett et al. 2018). This map defines Indigenous peoples as "peoples in independent countries who are regarded as indigenous on account of their descent from the populations which inhabited the country, or a geographical region to which the country belongs, at the time of conquest or colonization or the establishment of present state boundaries and who, irrespective of their legal status, retain some or all of their own social, economic, cultural and political institutions" (ILO 1989). The map is based on a compilation of various input data sources including cadastral records in the case of state-recognized tenure, participatory mapping exercises, models derived from census data, and academic publications. Areas not identified as Indigenous peoples' lands in this map do not necessarily indicate an absence of Indigenous peoples or their lands. Rather, these may be areas where a connection to an Indigenous community cannot be determined from publicly available spatial datasets, or where rights have not yet been formally recognized.

This dataset has been instructive in demonstrating Indigenous peoples' influence on globally significant natural resources such as primate habitat (Estrada et al. 2022), terrestrial mammal ranges (O'Bryan et al. 2021), forest-dependent vertebrate habitat (Sze et al. 2024), Key Biodiversity Areas (Simkins et al. 2023), irrecoverable carbon stocks (Noon et al. 2022), high integrity forests (Sze et al. 2022), utilized plant species diversity (Pironon et al. 2024), and in the management of invasive species (Seebens et al. 2024).

We excluded assessment of Indigenous peoples' lands in Canada, as the available spatial data do not adequately reflect the context of Indigenous peoples' lands and rights, or the extent of Indigenous homelands and traditional territories (Artelle et al. 2019; Townsend, Moola, and Craig 2020). We recognize that similar data quality limitations may obscure the true scale of Indigenous stewardship of peatlands in other regions of the world. However, as Canada is home to one-quarter of global peatlands, any underestimation of Canada will have dramatic implications for our findings. We therefore chose to omit this region from our assessment and acknowledge that our global estimate is very conservative as a result.

2.4 | Human Pressure on Peatlands

We overlaid a map of the Human Impact Index (HII) for the year 2020 with the map of peatland extent to estimate the area of peatlands potentially impacted by and at risk from some anthropogenic activities (Williams et al. 2020; Sanderson et al. 2022). The HII represents cumulative anthropogenic pressures including population density, land use and infrastructure, and accessibility (Venter et al. 2016), reported as a global dataset of 1×1 km grid cells ranging in value from 0 to 6400. We applied a threshold to these values to discretize them into low (< 400), medium (400–700), and high (> 700) human pressure, following previous studies (Elsen, Monahan, and Merenlender 2020; Williams et al. 2020).

Importantly, the HII does not reflect future pressures on peatlands, such as planned industry and infrastructure expansion, and therefore underrepresents the area of peat at risk of degradation from human activities. Nor does the HII represent all pressures on peatlands, including many that are relevant in the boreal context such as logging, oil and gas wells, mining, pipelines, and seismic lines (Dabros, Pyper, and Castilla 2018; Horton, Lehtinen, and Kummu 2022; Klotz et al. 2023). Neverthe-

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

less, the HII provides one gauge of human pressure in peatlands across different conservation contexts and at a global scale.

3 | Results

Of the 4.02 million km^2 of peatlands globally, only 0.68 million km^2 (17%) are within protected areas (Table 1). Of the peatlands within protected areas, just over half (0.37 million km^2) fall within the strict protection category and slightly less than half (0.31 million km^2) fall within the nonstrict/multiple use protection category. One-fifth of protected peatlands (0.15 million km^2) are designated as Ramsar wetlands of international importance, roughly 70% of which overlap with the nonstrict/multiple use protection category.

Approximately 0.27 million km^2 (11%) of boreal peatlands are within protected areas, compared to 0.15 million km^2 (27%) of temperate and 0.26 million km^2 (27%) of tropical peatlands. Of those, 8%, 16%, and 8% of boreal, temperate, and tropical peatlands, respectively, are within strictly protected areas. Most Ramsar sites are in the tropics, where 9% of peatlands have Ramsar designation, compared to < 2% in temperate and boreal regions.

Peatland protection varies widely by region and country. In South America, Oceania, and Africa, > 30% of peatlands fall within some official protected designation, inclusive of Ramsar categories. Among the 28 countries with more than 15,000 km^2 of peatlands (comprising 91% of global peatlands), 1%–87% of peatlands fall in protected areas, and 0%–35% fall within strict protection areas (Table A1). Our estimates of the proportion of peat within protected areas and Ramsar sites are robust to alternative regional peatland maps (Table A2).

When comparing our findings to those produced with alternative maps of protected areas for China and India, we estimate a larger area of peatlands within protected areas using more comprehensive country-specific data on protected area extent. In China, we estimate there are 19,295 km^2 of peatlands within protected areas using the Fan et al. (2023) dataset, relative to 2,237 km^2 using the WDPA dataset. In India, we estimate that there are 2347 km^2 of peatlands within PAs using the Lamba et al. (2023) dataset, relative to 536 km^2 using the WDPA dataset. While significant at a country scale, in aggregate these data improvements increase the global proportion of peatlands within protected areas from 16.9% to 17.4%.

Globally, 1.1 million km^2 (27%) of peatlands are within Indigenous peoples' lands (Table 1). This proportion is roughly similar across the boreal (29%) and tropical (29%) biomes and is smaller in the temperate (16%) biome. More than 85% of peatlands within Indigenous peoples' lands (0.94 million km^2) do not fall within other types of protected areas.

Twenty-two percent of global peatlands are under high human pressure according to the HII, 12% under medium pressure, 61% under low pressure, and 5% are in areas without reported HII data (Figure 1). This finding is driven in part by the large expanses of relatively low population density in boreal peatlands, where most

TABLE 1 | Area and proportion of peatlands protected by category, within Indigenous peoples' lands, and designated as Ramsar wetlands of international importance, by biome.

	Total peatland area (million km^2)	Proportion of peatlands in all protection categories	Proportion of peatlands in strict protection category	Proportion of peatlands in nonstrict/multiple use protection category	Proportion of peatlands with Ramsar designation and strict protection	Proportion of peatlands with Ramsar designation and nonstrict/multiple use protection	Proportion of peatlands in Indigenous peoples' lands
Boreal	2.49	11%	8%	2%	1%	0%	29%[a]
Temperate	0.55	27%	16%	11%	1%	1%	16%
Tropical	0.99	27%	8%	19%	1%	9%	29%
Global	4.02	17%	9%	8%	1%	3%	27%

[a]Not including Canada.

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

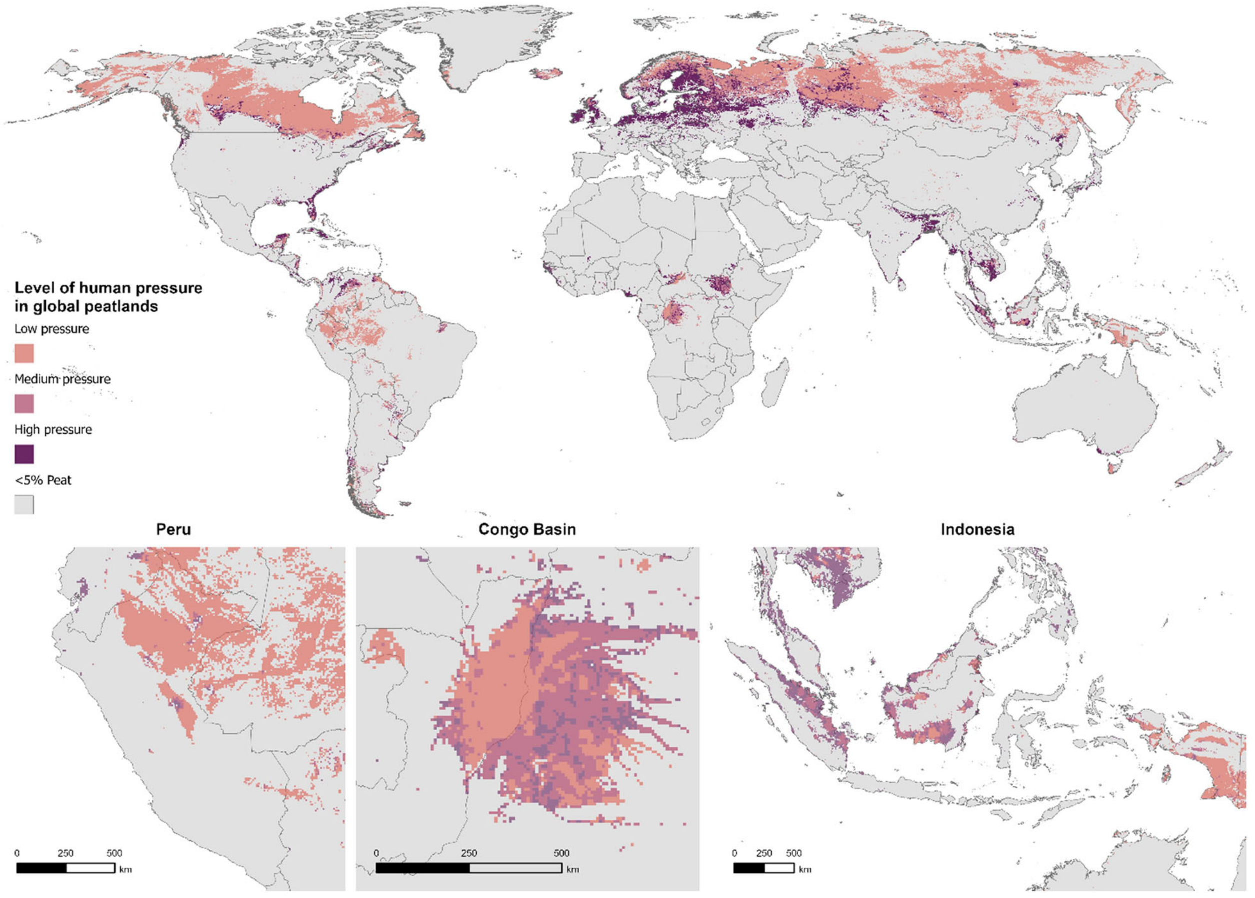

FIGURE 1 | Human pressure in global peatlands, visualized here using a 5% peat fraction threshold on the Peat-ML map. Human pressure measured using the Human Impact Index, discretized into low (< 400), medium (400–700), and high (> 700) categories.

(77%) peatlands are under low human pressure according to the HII data.

There are substantially more peatlands with high (47%) and medium (8%) human pressure in the temperate biome, particularly in Europe and along the east coast of the United States. In the tropics, a large portion of peatlands fall within high (44%) and medium (19%) human pressure categories across Southeast Asia, South Asia, Central America, the Caribbean, and West and East Africa.

The pattern of human pressure in peatlands varies by biome and protection category (Figure 2). As expected, human pressure is somewhat higher in unprotected peatlands and somewhat lower in protected areas, globally. Yet nearly one-third of global peatlands, and nearly half of temperate and tropical peatlands in protected areas and Indigenous peoples' lands, still experience medium to high human pressure.

4 | Discussion

Less than one-fifth of peatlands (17%) fall within the global protected area network, a proportion substantially lower than other high value ecosystems such as mangroves, 42% of which are within official protected areas globally (Spalding and Leal 2021), saltmarshes (50%) (Ocean+ Habitats 2024), and tropical forests (38%) (WRI 2024).

Importantly, our estimates of protected peatlands include Ramsar sites, which comprise roughly one-fifth of protected peatlands globally and nearly two-fifths of protected peatlands in the tropics. Yet Ramsar sites typically lack strong government commitment, evidenced by the absence of domestic legislation, legal frameworks, or management plans in these sites (Kingsford et al. 2021). Our results therefore suggest a large opportunity not only to expand protection and sustainable management of global peatlands but also to strengthen protections for peatlands, particularly in the tropics where Ramsar designation is more prevalent.

The extent and stringency of protection for peatlands vary by country (Table A1), and peatland protection and sustainable management will require diverse approaches and policy pathways. In the Republic of Congo, more than 40,000 km^2 or nearly 90% of peatlands fall within protected areas. But most of this falls within a designated Ramsar site that has not yet been backed up by strong government commitments. A crucial next step will be strengthening protection of these peatlands, potentially via new regulations and the design, funding, and implementation of community-led peat management programs (Dargie et al. 2019). In Indonesia, nearly 28,000 km^2 or just 15% of peatlands are within protected areas. Expanding area-based protections for peatlands as part

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

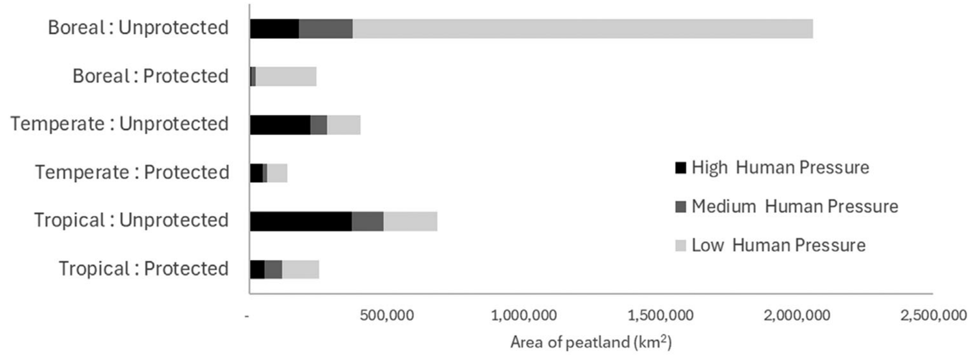

FIGURE 2 | The area of peatlands in high, medium, and low Human Impact Index (HII) tiers, by biome and protection category. Protection includes all categories of protected areas including Ramsar sites.

of a comprehensive national peatlands strategy that includes restoration initiatives, land use planning approaches, and non-area based regulations (Widyatmanti et al. 2022) will be necessary for managing peat fires and meeting climate targets nationally (Terzano et al. 2023). Avoiding peatland degradation and fires is an important component of the Indonesian Nationally Determined Contribution (NDC), providing significant policy support for these efforts (Republic of Indonesia 2022). In Peru, 12% of peatlands are within a Ramsar site, another 7% are within other forms of multiple-use protection, and 2% are within strictly protected areas. Peru's NDC includes several strategies for improving peatland management, including the establishment of new conservation areas, promotion of sustainable management of nontimber forest products, implementation of fishery management programs, and recognition of knowledge, sustainable management practices, and values of Indigenous peoples related to peatlands (Gobierno del Peru 2020).

At least one-quarter of global peatlands overlap with Indigenous peoples' lands, most of which do not overlap with other forms of official protection. This estimate is conservative, as we excluded Indigenous peoples' lands in Canada, home to one-quarter of global peatlands, from our assessment (Artelle et al. 2019). A growing body of research has demonstrated that Indigenous land rights and community-based management result in positive environmental outcomes, such as reduced deforestation and forest degradation (Sze et al. 2022), and increased biodiversity as a result of fire management (Hoffman et al. 2021). Formal community management associations and local participation in rulemaking have been shown to have strong links to positive environmental and social outcomes in collectively managed forests across the tropics (Fischer et al. 2023). Peatlands within Indigenous peoples' lands, including those mapped in this study as well as those in Canada, those which are not included in the Garnett et al.'s (2018) dataset, and those which have not yet been recognized, may therefore benefit from existing management activities. Where this is not already the case, our findings point to a large opportunity to increase protection, sustainable management, and stewardship of global peatlands by recognizing local authority, building or strengthening management institutions, advancing participation in governance of peatlands, and supporting Indigenous-led stewardship such as via Indigenous Protected and Conserved Areas (Townsend, Moola, and Craig 2020; ECCC 2021; Harris et al. 2022).

Crucially, improved data and monitoring systems are needed to guide implementation and adaptive management of peatlands in the context of climate mitigation and biodiversity conservation strategies (Dinerstein et al. 2019). Nationally and locally specific information on peatland extent and distribution; protected areas; and Indigenous peoples' lands, rights, and stewardship (particularly in Canada) and the relationship between human pressure and the integrity of peatland ecosystems are essential to build on this global analysis. For example, we find that integrating country-specific maps of protected areas in China and India substantially increase our estimates of the area of peatlands within protected areas. We note that our estimates may be similarly improved in other countries without up-to-date or comprehensive protected area representation in the WDPA. In Argentina, for example, the Peninsula Mitre National Park was established in 2022 and protects 2400 km^2, or 84%, of the nation's peatlands (Alberts 2022). Yet, the spatial boundaries of this park have not yet been incorporated into the WDPA. Improving completeness, accuracy, and accessibility of these management data will be one crucial step to more accurate tracking of peat conservation goals (Elsen, Monahan, and Merenlender 2018). In parallel, systems for regular and frequent tracking of indicators of peatland health such as water table depth, soil moisture, rates of subsidence, and greenhouse gas fluxes are urgently needed to evaluate the impacts of and adaptively manage programs aimed at maintaining or enhancing the integrity of peatlands (Minasny et al. 2024).

Fortunately, several current international policy processes have the potential to drive national and subnational actions to protect, restore, sustainably manage, monitor, and align corresponding finance for peatlands. Following the 2023 Global Stocktake to track progress toward meeting the goals of the Paris Agreement, countries will both strengthen 2030 mitigation targets and develop the next generation of NDCs, by early 2025 (Srouji et al. 2024). Under the Global Stocktake process, country governments will also be updating and finalizing NAPs outlining finance, technology, and capacity needs to strengthen resilience and reduce vulnerability to climate change impacts (Hussein et al. 2024). In 2023, countries were also encouraged to submit national commitments to the Sustainable Development Goals, including priority areas for investment to catalyze progress (United Nations 2024).

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Countries that are Party to the Convention on Biological Diversity are also updating their National Biodiversity Strategy and Action Plans to reflect targets that are consistent with the GBF (CBD 2024). The GBF commits Party governments to maintain or enhance the integrity of all ecosystem types, including peatlands, through measures such as spatial planning (GBF Target 1); increasing coverage of ecologically representative and well-connected area-based conservation measures such as protected areas, other effective area-based conservation measures, and Indigenous and Traditional Territories (GBF Target 3); and minimizing the impacts of climate change through mitigation and adaptation actions (GBF Target 8). These international policy frameworks have the potential to elevate the importance of high value ecosystems, including inland freshwater ecosystems such as peatlands, in national and local conservation priorities.

In addition, governments are increasingly centering human rights–based approaches, agreeing to implement broader and more inclusive consultation and including free, prior, and informed consent ahead of any policy intervention affecting Indigenous peoples or local communities. Advancing these and related efforts is especially critical in the case of peatlands, given the large role that Indigenous peoples already have for the stewardship of these ecosystems.

This study provides a snapshot of the state of peatland protection globally and highlights opportunities to improve conservation and sustainable management of these unique and irreplaceable ecosystems. Expanding peatland conservation efforts, including via area-based approaches, strengthening of Indigenous peoples' rights, and via other tailored programs and policies adapted to unique contexts and informed or led by local communities, will be essential to meeting critical climate and biodiversity targets.

Acknowledgments

This study was supported by the funding from Ballmer Group for data analysis and manuscript preparation. E.N.H.C. acknowledges support from a NERC Knowledge Exchange Fellowship (NE/V018760/1). A.V.G.S. acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant 865403). The authors would like to thank A. Lambda for making the data on India's protected areas available and T. Mu for help in preprocessing the data on China's protected areas.

Data Availability Statement

A netCDF format version of the Peat-ML dataset is available at https://doi.org/10.5281/zenodo.5794336 (Melton et al. 2022). Shapefile data on protected areas are publicly available for download at www.protectedplanet.net. The data on the extent of Indigenous peoples' lands are available by request from the authors of the original publication (Garnett et al. 2018).The designations of geographical entities in this dataset do not imply the expression of any view or opinion whatsoever concerning the legal status of any country, territory, or area or of its authorities or concerning the delimitation of its frontiers or boundaries.

References

Alberts, E. C. 2022. "*Peat on Land and Kelp at Sea as Argentina Protects Tip of Tierra del Fuego*." Mongabay Environmental News. https://news.mongabay.com/2022/12/peat-on-land-and-kelp-at-sea-as-argentina-protects-tip-of-tierra-del-fuego/.

Anda, M., S. Ritung, E. Suryani, et al. 2021. "Revisiting Tropical Peatlands in Indonesia: Semi-Detailed Mapping, Extent and Depth Distribution Assessment." *Geoderma* 402: 115235.

Artelle, K. A., M. Zurba, J. Bhattacharyya, et al. 2019. "Supporting Resurgent Indigenous-Led Governance: A Nascent Mechanism for Just and Effective Conservation." *Biological Conservation* 240: 108284.

CBD. 2024. "National Biodiversity Strategies and Action Plans (NBSAPs)." Convention on Biological Diversity. https://www.cbd.int/nbsap.

Crezee, B., G. C. Dargie, C. E. N. Ewango, et al. 2022. "Mapping Peat Thickness and Carbon Stocks of the Central Congo Basin Using Field Data." *Nature Geoscience* 15: 639–644.

Dabros, A., M. Pyper, and G. Castilla. 2018. "Seismic Lines in the Boreal and Arctic Ecosystems of North America: Environmental Impacts, Challenges, and Opportunities." *Environmental Reviews* 26: 214–229.

Dargie, G. C., I. T. Lawson, T. J. Rayden, et al. 2019. "Congo Basin Peatlands: Threats and Conservation Priorities." *Mitigation and Adaptation Strategies for Global Change* 24: 669–686.

Dinerstein, E., C. Vynne, E. Sala, et al. 2019. "A Global Deal for Nature: Guiding Principles, Milestones, and Targets." *Science Advances* 5: eaaw2869.

ECCC. 2021. National Inventory Report 1990–2019: Greenhouse Gas Sources and Sinks in Canada. National Inventory Report. Ottawa, Canada: Environment and Climate Change Canada, Government of Canada.

Elleason, M., Z. Guan, Y. Deng, A. Jiang, E. Goodale, and C. Mammides. 2021. "Strictly Protected Areas Are Not Necessarily More Effective Than Areas in Which Multiple Human Uses Are Permitted." *Ambio* 50: 1058–1073.

Elsen, P. R., W. B. Monahan, and A. M. Merenlender. 2018. "Reply to You et al.: The World Database on Protected Areas Is an Invaluable Resource for Global Conservation Assessments and Planning." *Proceedings of the National Academy of Sciences of the United States ofAmerica* 115: E9029–E9030.

Elsen, P. R., W. B. Monahan, and A. M. Merenlender. 2020. "Topography and Human Pressure in Mountain Ranges Alter Expected Species Responses to Climate Change." *Nature Communications* 11: 1974.

Estrada, A., P. A. Garber, S. Gouveia, et al. 2022. "Global Importance of Indigenous Peoples, Their Lands, and Knowledge Systems for Saving the World's Primates From Extinction." *Science Advances* 8: eabn2927.

Fan, X., W. Xu, Z. Zang, and Z. Ouyang. 2023. "Representativeness of China's Protected Areas in Conserving Its Diverse Terrestrial Ecosystems." *Ecosystem Health and Sustainability* 9: 0029.

Fischer, H. W., A. Chhatre, A. Duddu, N. Pradhan, and A. Agrawal. 2023. "Community Forest Governance and Synergies Among Carbon, Biodiversity and Livelihoods." *Nature Climate Change* 13: 1340–1347.

Garnett, S. T., N. D. Burgess, J. E. Fa, et al. 2018. "A Spatial Overview of the Global Importance of Indigenous Lands for Conservation." *Nat Sustain* 1: 369–374.

Gibson, C. M., L. E. Chasmer, D. K. Thompson, W. L. Quinton, M. D. Flannigan, and D. Olefeldt. 2018. "Wildfire as a Major Driver of Recent Permafrost Thaw in Boreal Peatlands." *Nature Communications* 9: 3041.

Gobierno del Peru. 2020. *Contribuciones Determinadas a Nivel Nacional del Peru*. Estudio Técnico Periodo 2021–2030. Peru: Gobierno del Peru.

Goldstein, A., W. R. Turner, S. A. Spawn, et al. 2020. "Protecting Irrecoverable Carbon in Earth's Ecosystems." *Nature Climate Change* 10: 287–295.

Harris, L. I., D. Olefeldt, N. Pelletier, et al. 2023. "Permafrost Thaw Causes Large Carbon Loss in Boreal Peatlands While Changes to Peat Quality Are Limited." *Global Change Biology* 29: 5720–5735.

Harris, L. I., K. Richardson, K. A. Bona, et al. 2022. "The Essential Carbon Service Provided by Northern Peatlands." *Frontiers in Ecology and the Environment* 20: 222–230.

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Hastie, A., E. N. Honorio Coronado, J. Reyna, et al. 2022. "Risks to Carbon Storage From Land-Use Change Revealed by Peat Thickness Maps of Peru." *Nature Geoscience* 15: 369–374.

Hastie, A., J. E. Householder, E. N. H. Coronado, et al. 2024. "A New Data-Driven Map Predicts Substantial Undocumented Peatland Areas in Amazonia." *Environmental Research Letters* 19: 094019.

Hoffman, K. M., E. L. Davis, S. B. Wickham, et al. 2021. "Conservation of Earth's Biodiversity Is Embedded in Indigenous Fire Stewardship." *Proceedings of the National Academy of Sciences of the United States of America* 118: e2105073118.

Horton, A. J., J. Lehtinen, and M. Kummu. 2022. "Targeted Land Management Strategies Could Halve Peatland Fire Occurrences in Central Kalimantan, Indonesia." *Communications Earth & Environment* 3: 204.

Hussein, F., M. Adow, C. Okereke, G. Olorunfemi, H. Otchwemah, and C. Thangata 2024. "*Understanding the Paris Agreement's 'Global Goal on Adaptation'*." World Resources Institute. https://www.wri.org/insights/global-goal-on-adaptation-explained.

ILO. 1989. *Convention C169—Indigenous and Tribal Peoples Convention, 1989 (No. 169)*. Convention 169. Jakarta: International Labour Organization.

IUCN. 2021. *Peatlands and Climate Change*. Issues Brief. Switzerland: International Union for Conservation of Nature.

Kingsford, R. T., G. Bino, C. M. Finlayson, et al. 2021. "Ramsar Wetlands of International Importance–Improving Conservation Outcomes." *Frontiers in Environmental Science* 9: 643367.

Klotz, L. A., O. Sonnentag, Z. Wang, J. A. Wang, and M. Kang. 2023. "Oil and Natural Gas Wells Across the NASA ABoVE Domain: Fugitive Methane Emissions and Broader Environmental Impacts." *Environmental Research Letters* 18: 035008.

Lamba, A., H. C. Teo, R. Sreekar, Y. Zeng, L. R. Carrasco, and L. P. Koh. 2023. "Climate Co-Benefits of Tiger Conservation." *Nature Ecology & Evolution* 7: 1104–1113.

Leifeld, J., and L. Menichetti. 2018. "The Underappreciated Potential of Peatlands in Global Climate Change Mitigation Strategies." *Nature Communications* 9: 1071.

Leifeld, J., C. Wüst-Galley, and S. Page. 2019. "Intact and Managed Peatland Soils as a Source and Sink of GHGs From 1850 to 2100." *Nature Climate Change* 9: 945–947.

Loisel, J., and A. Gallego-Sala. 2022. "Ecological Resilience of Restored Peatlands to Climate Change." *Communications Earth & Environment* 3: 208.

Melton, J. R., E. Chan, K. Millard, et al. 2022. "A Map of Global Peatland Extent Created Using Machine Learning (Peat-ML)." *Geoscientific Model Development* 15: 4709–4738.

Miettinen, J., C. Shi, and S. C. Liew. 2016. "Land Cover Distribution in the Peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 With Changes Since 1990." *Global Ecology and Conservation* 6: 67–78.

Minasny, B., D. V. Adetsu, M. Aitkenhead, et al. 2024. "Mapping and Monitoring Peatland Conditions From Global to Field Scale." *Biogeochemistry* 167: 383–425.

Nelson, A., and K. M. Chomitz. 2011. "Effectiveness of Strict vs. Multiple Use Protected Areas in Reducing Tropical Forest Fires: A Global Analysis Using Matching Methods." *PLoS One* 6: e22722.

Noon, M. L., A. Goldstein, J. C. Ledezma, et al. 2022. "Mapping the Irrecoverable Carbon in Earth's Ecosystems." *Nature Sustainability* 5: 37–46.

Nugent, K. A., I. B. Strachan, N. T. Roulet, M. Strack, S. Frolking, and M. Helbig. 2019. "Prompt Active Restoration of Peatlands Substantially Reduces Climate Impact." *Environmental Research Letters* 14: 124030.

O'Bryan, C. J., S. T. Garnett, J. E. Fa, et al. 2021. "The Importance of Indigenous Peoples' Lands for the Conservation of Terrestrial Mammals." *Conservation Biology* 35: 1002–1008.

Ocean+Habitats. 2024. "Proportion of habitat within protected and conserved areas." Ocean+ Habitats.

Pan, Y., R. A. Birdsey, O. L. Phillips, et al. 2024. "The Enduring World Forest Carbon Sink." *Nature* 631: 563–569.

Pironon, S., I. Ondo, M. Diazgranados, et al. 2024. "The Global Distribution of Plants Used by Humans." *Science* 383: 293–297.

Prosperi, P., M. Bloise, F. N. Tubiello, et al. 2020. "New Estimates of Greenhouse Gas Emissions From Biomass Burning and Peat Fires Using MODIS Collection 6 Burned Areas." *Climatic Change* 161: 415–432.

Republic of Indonesia. 2022. *National Forest Reference Level for Deforestation, Forest Degradation and Enhancement of Forest Carbon Stock in the Context of Decision 12/CP.17 Para 12 UNFCCC*. National FRL Document. Republic of Indonesia: United Nations Climate Change.

Roe, S., C. Streck, M. Obersteiner, et al. 2019. "Contribution of the Land Sector to a 1.5°C World." *Nature Climate Change* 9: 817–828.

Sanderson, E. W., K. Fisher, N. Robinson, D. Sampson, A. Duncan, and L. Royte. 2022. *The March of the Human Footprint*. This is a preprint available here: https://ecoevorxiv.org/repository/view/3641/

Seebens, H., A. Niamir, F. Essl, et al. 2024. "Biological Invasions on Indigenous Peoples' Lands." *Nature Sustainability* 7: 737–746.

Simkins, A. T., P. F. Donald, A. E. Beresford, et al. 2023. "Rates of Tree Cover Loss in Key Biodiversity Areas on Indigenous Peoples' Lands." *Conservation Biology* 38, no. 3: e14195.

Spalding, M. D., and M. Leal. 2021. *The State of the World's Mangroves 2021*. Global Mangrove Alliance. https://www.mangrovealliance.org/the-state-of-the-worlds-mangroves-2021/

Srouji, J., T. Fransen, S. Boehm, D. Waskow, R. Carter, and G. Larsen. 2024. "*Next-Generation Climate Targets: A 5-Point Plan for NDCs*." World Resources Institute. https://www.wri.org/insights/next-ndcs-5-point-plan.

Sze, J. S., D. Z. Childs, L. R. Carrasco, and D. P. Edwards. 2022. "Indigenous Lands in Protected Areas Have High Forest Integrity Across the Tropics." *Current Biology* 32: 4949–4956.e3.

Sze, J. S., D. Z. Childs, L. R. Carrasco, Á. Fernández-Llamazares, S. T. Garnett, and D. P. Edwards. 2024. "Indigenous Peoples' Lands Are Critical for Safeguarding Vertebrate Diversity Across the Tropics." *Global Change Biology* 30: e16981.

Terzano, D., F. R. Trezza, M. Rezende, et al. 2023. "Prioritization of Peatland Restoration and Conservation Interventions in Sumatra, Kalimantan and Papua." *Journal for Nature Conservation* 73: 126388.

Townsend, J., F. Moola, and M.-K. Craig. 2020. "Indigenous Peoples Are Critical to the Success of Nature-Based Solutions to Climate Change." *FACETS* 5: 551–556.

Turetsky, M. R., B. Benscoter, S. Page, G. Rein, G. R. van der Werf, and A. Watts. 2015. "Global Vulnerability of Peatlands to Fire and Carbon Loss." *Nature Geoscience* 8: 11–14.

UNEP. 2022. "Global Peatlands Assessment: The State of the World's Peatlands." UN Environment Programme. http://www.unep.org/resources/global-peatlands-assessment-2022.

UNEP-WCMC and IUCN. 2023. "Protected Planet." The World Database on Protected Areas (WDPA). http://www.protectedplanet.net.

UNFCCC. 2024. "Global Stocktake." United Nations Climate Change. https://unfccc.int/topics/global-stocktake.

United Nations. 2024. "National Commitments to SDG Transformation." United Nations, Department of Economic and Social Affairs. https://sdgs.un.org/SDGSummitActions/National.

Venter, O., E. W. Sanderson, A. Magrach, et al. 2016. "Sixteen Years of Change in the Global Terrestrial Human Footprint and Implications for Biodiversity Conservation." *Nature Communications* 7: 12558.

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Widyatmanti, W., B. Minasny, D. Awanda, et al. 2022. “Codification to Secure Indonesian Peatlands: From Policy to Practices as Revealed by Remote Sensing Analysis.” *Soil Security* 9: 100080.

Wilkinson, S. L., R. Andersen, P. A. Moore, S. J. Davidson, G. Granath, and J. M. Waddington. 2023. “Wildfire and Degradation Accelerate Northern Peatland Carbon Release.” *Nature Climate Change* 13: 456–461.

Williams, B. A., O. Venter, J. R. Allan, et al. 2020. “Change in Terrestrial Human Footprint Drives Continued Loss of Intact Ecosystems.” *One Earth* 3: 371–382.

WRI. 2024. “Protected Forests.” Global Forest Review. https://research.wri.org/gfr/forest-designation-indicators/protected-forests.

Xu, J., P. J. Morris, J. Liu, and J. Holden. 2018a. “Hotspots of Peatland-Derived Potable Water Use Identified by Global Analysis.” *Nature Sustainability* 1: 246–253.

Xu, J., P. J. Morris, J. Liu, and J. Holden. 2018b. “PEATMAP: Refining Estimates of Global Peatland Distribution Based on a Meta-Analysis.” *Catena* 160: 134–140.

Yu, Z., J. Loisel, D. P. Brosseau, D. W. Beilman, and S. J. Hunt. 2010. “Global Peatland Dynamics Since the Last Glacial Maximum.” *Geophysical Research Letters* 37, no. 13: L13402.

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Appendix

TABLE A1 | Area and proportion of peatlands protected, in strict protection, in nonstrict/multiple use protection, and designated as Ramsar wetlands of international importance, by country, according to the Peat-ML map. This includes 28 countries with at least 15,000 km^2 of peatlands.

	Total peatland area (km^2)	Protected peatland area (km^2)	Strictly protected peatland area (km^2)	Nonstrict/ Multiple use protected peatland area (km^2)	Ramsar peatland area with strict protection designation (km^2)	Ramsar peatland area with nonstrict protection designation (km^2)
Russia	1,272,029	120,296	70,843	49,453	110	7426
Canada	1,127,849	135,537	126,293	9244	24,917	1680
Indonesia	191,347	27,838	18,719	9119	2690	523
United States	165,124	54,312	46,613	7699	964	33
Brazil	107,404	54,656	8641	46,015	1690	5960
Democratic Republic of the Congo	98,313	25,195	1695	23,500	274	20,795
China	70,878	2237	621	1616	596	618
Peru	62,482	13,130	1409	11,721	0	7217
Finland	49,310	6502	4926	1576	1109	131
Republic of the Congo	48,412	41,881	333	41,550	256	41,519
Colombia	44,700	8310	6965	1346	0	0
United Kingdom	41,030	16,727	7196	9531	1275	506
India	40,581	536	0	536	0	200
South Sudan	37,691	8265	4347	3919	72	2944
Venezuela	37,435	16,308	5598	10,710	53	0
Sweden	31,931	5646	4428	1218	425	227
Argentina	30,841	6789	1246	5542	142	1153
Papua New Guinea	23,353	1099	0	1099	0	933
Mexico	22,746	4370	1329	3042	1000	1571
Norway	21,458	2527	1978	548	25	0
Australia	21,272	10,441	7382	3059	151	110
Cambodia	21,183	6470	3792	2677	272	0
Myanmar	19,706	1203	1177	26	99	23
Chile	17,583	9006	4882	4124	8	9
Bangladesh	17,360	507	150	358	58	358
Germany	17,311	6195	962	5233	28	87
Ukraine	16,565	3028	767	2261	94	74
Poland	15,957	6941	211	6730	22	77

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE A2 | Comparison of the area and proportion of peatlands protected, strictly protected, and designated as a Ramsar wetland of international importance, according to alternative peat extent maps for peatlands in the Congo Basin, the Amazon lowlands of Peru, the Amazon Basin, Indonesia, and China.

Region	Reference	Total peatland area (km^2)[a]	Protected peatland area (km^2)	Proportion of peatlands in all protection categories	Strictly protected peatland area (km^2)	Proportion of peatlands in strict protection	Ramsar designated peatland area (km^2)	Proportion of peatlands with Ramsar designation
Congo Basin	Crezee et al. (2022)[b]	167,755	78,065	47%	561	0%	76,622	46%
	Peat-ML	146,725	67,077	46%	2028	1%	62,845	43%
Peru	Hastie et al. (2022)[c]	62,714	10,498	17%	832	1%	7326	12%
	Peat-ML	62,482	13,130	21%	1409	2%	7217	12%
Amazon Basin	Hastie et al. (2024)[d]	251,048	101,494	40%	19,844	8%	30,473	12%
	Peat-ML	180,723	73,331	41%	17,065	9%	14,856	8%
Indonesia	Miettinen, Shi, and Liew (2016)[e]	149,629	20,963	14%	14,216	10%	2210	1%
	Anda et al. (2021)[f]	133,919	20,783	16%	14,695	11%	2770	2%
	Peat-ML	191,347	27,838	15%	18,719	10%	3213	2%
China	Xu et al. (2018a, 2018b)[g]	123,004	8517	7%	2909	2%	6958	6%
	Peat-ML	70,878	2237	3%	621	1%	1214	2%

[a]Minor differences in the reported extent of peatlands, relative to the original publications, are due to differences in national spatial boundaries and projection systems.
[b]Data from Crezee et al. (2022), who used field data from the Republic of Congo and the Democratic Republic of the Congo to produce models of peat thickness and carbon density for the central Congo Basin. We used the unsmoothed classification representing the most likely class based on the highest probability of the five modeled land cover classes, where Classes 4 and 5 are associated with the presence of peat.
[c]Data from Hastie et al. (2022), who mapped peatlands using a combination of field and remote sensing data to produce spatially explicit estimates of peatland extent and thickness for lowland Peruvian Amazonia.
[d]Data from Hastie et al. (2024), who mapped peatlands distribution across seven countries in the Amazon Basin using 2413 ground reference data and remote sensing products.
[e]Data from Miettinen, Shi, and Liew (2016), who visually interpreted Landsat imagery to produce land cover maps including peatland distribution. The data are provided in vector format representing the presence of peat.
[f]Data from Anda et al. (2021), who mapped tropical peatland extent and depth distributions in Indonesia by employing remote sensing products and 18,232 field reference points.
[g]Data from Xu et al. (2018a, 2018b), who compiled global peatland map datasets including in China from multiple sources.

1755263x, 2025, 1, Downloaded from https://conbio.onlinelibrary.wiley.com/doi/10.1111/conl.13080 by James Cook University, Wiley Online Library on [18/02/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License