

Half of land use carbon emissions in Southeast Asia can be mitigated through peat swamp forest and mangrove conservation and restoration

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Southeast Asia (SEA) contributes approximately one-third of global land-use change carbon emissions, a substantial yet highly uncertain part of which is from anthropogenically-modified peat swamp forests (PSFs) and mangroves. Here, we report that between 2001–2022 land-use change impacting PSFs and mangroves in SEA generate approximately 691.8 ± 97.2 teragrams of CO_2 equivalent emissions annually ($\text{TgCO}_2\text{eyr}^{-1}$) or 48% of region's land-use change emissions, and carbon removal through secondary regrowth of -16.3 ± 2.0 $\text{TgCO}_2\text{eyr}^{-1}$. Indonesia (73%), Malaysia (14%), Myanmar (7%), and Vietnam (2%) combined accounted for over 90% of regional emissions from these sources. Consequently, great potential exists for emissions reduction through PSFs and mangroves conservation. Moreover, restoring degraded PSFs and mangroves could provide an additional annual mitigation potential of 94.4 ± 7.4 $\text{TgCO}_2\text{eyr}^{-1}$. Although peatlands and mangroves occupy only 5.4% of SEA land area, restoring and protecting these carbon-dense ecosystems can contribute substantially to climate change mitigation, while maintaining valuable ecosystem services, livelihoods and biodiversity.

Peatlands and mangroves collectively act as natural carbon sinks owing to atmospheric carbon uptake by photosynthesizing vegetation exceeding ecosystem respiration, with the excess accumulating under anoxic conditions as partially decomposed organic matter. Globally, peatlands store -604 ± 130 gigatonnes of carbon (GtC)^{1–3}, equivalent to

31% of the terrestrial carbon pool⁴, despite only accounting for 3% of the terrestrial surface area³. Tropical peatlands cover at least 44 million hectares (Mha) and store an estimated 105 GtC ⁵. These peatlands, found primarily at lower elevations but occasionally at higher ones, often support forest vegetation known as peat swamp forest (PSF).

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Mangroves, a form of coastal forested wetland found in tropical, subtropical, and warm temperate regions, extend across 14.7 Mha⁶, and may store between 3.1 and 12.3 GtC⁷ although there is considerable uncertainty associated with this estimate. When combined, tropical peatlands and mangroves store around 25% of global tropical forest carbon stocks⁸, while occupying <3% of land at low latitudes. However, large areas of PSFs and mangroves have been converted to alternative land-uses^{9,10}, and are now functioning as net sources rather than sinks of greenhouse gases (GHGs)^{11–13}. Emissions from peatlands and mangroves are largely from the oxidation of irrecoverable soil organic carbon—ancient (>100 years) carbon that cannot be replaced on timescales relevant to climate change mitigation strategies¹⁴. Reducing emissions through conservation and restoration of peatlands and mangroves can thus provide a cost-effective contribution to the mitigation of anthropogenic GHG emissions, thereby assisting countries with these important wetland ecosystems to meet their Nationally Determined Contributions (NDCs) as part of the Paris Agreement¹⁵.

The eleven Southeast Asian countries (Brunei, Cambodia, Timor Leste, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam) cover just 4–5% of the world's land area, but host 39% and 33% of the global extent of, respectively, tropical peatlands and mangroves^{6,16}. PSF has been commonly drained and converted into industrial tree and agricultural plantations¹³ with the forest area further reduced by fire¹⁷. Aquaculture ponds and agriculture have largely replaced mangroves¹⁸, with remnant areas degraded through timber extraction and other land uses. Habitat losses from deforestation, land-use change, drainage, and biomass burning are responsible

for a rapid depletion of carbon stocks and substantial emissions of GHGs including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O)^{11,13,19–21}. Previous assessments of CO₂ emissions following deforestation and land conversion were conducted at both global and local levels for peatland^{13,20,22–24} and mangroves^{11,21}. However, these assessments often lacked detailed information on interannual variations in emissions. This gap limits our understanding of the actionable mitigation potential through the conservation and restoration of these ecosystems. In addition, the climate change mitigation effects of restoring these ecosystems when in a degraded state or converted to other land use are still not fully understood, despite rising interest in developing restoration for carbon credit projects in these ecosystems²⁵. Understanding the climate change mitigation potential of PSFs and mangroves conservation and restoration in Southeast Asia has grown in importance as nations increasingly include these carbon-rich ecosystems in plans to achieve emissions reduction targets outlined in their NDCs^{26–29}.

Here, we present estimates of region-wide and national-level carbon dioxide equivalent (CO₂e) emissions (combined CO₂ and CH₄) associated with deforestation—defined as tree cover loss, fires, and land-use change affecting PSFs and mangroves, along with potential climate change mitigation effects (avoided emissions and carbon removal) from conservation and restoration of these important ecosystems in Southeast Asia for the past two decades (2001–2022). Annual rates of deforestation of PSFs and mangroves were determined for the period of interest, along with changes in the extent of replacement land covers (Fig. 1). Former PSFs that had been

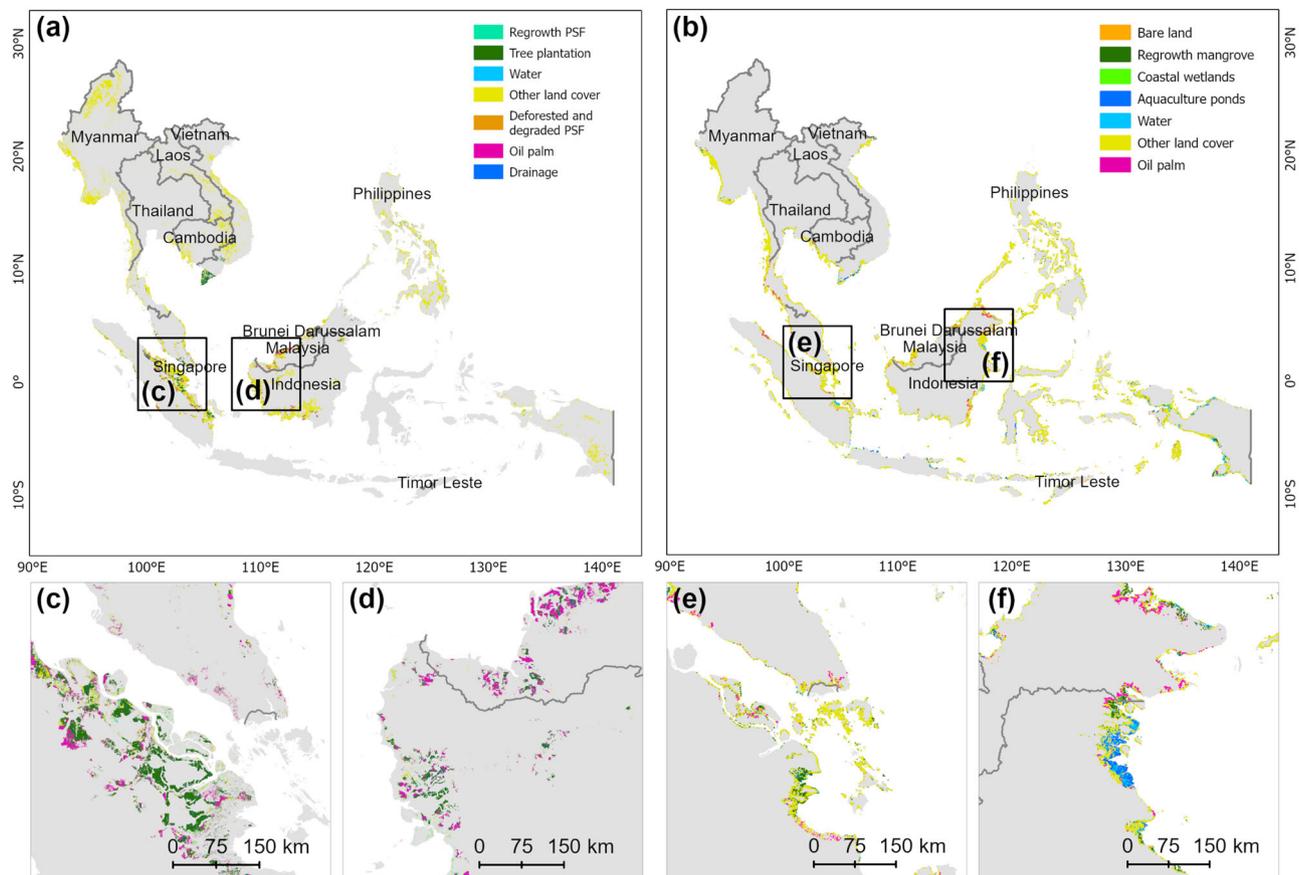


Fig. 1 | Distribution of land uses replacing peat swamp forests (PSFs) and mangroves across Southeast Asia by 2022. **a** Distribution of new land use types on deforested PSFs. **b** Distribution of new land use types on deforested mangroves. Two map insets provide better visualization of land uses in former PSFs in **c** Peninsular Malaysia and eastern Sumatra, and **d** western Borneo. Additionally,

map insets show land uses that have replaced mangroves in **e** Peninsular Malaysia and eastern Sumatra, and **f** eastern Borneo. For improved visualization and clarity, some land-use types have been enlarged tenfold. Source data are provided as a Source Data file.

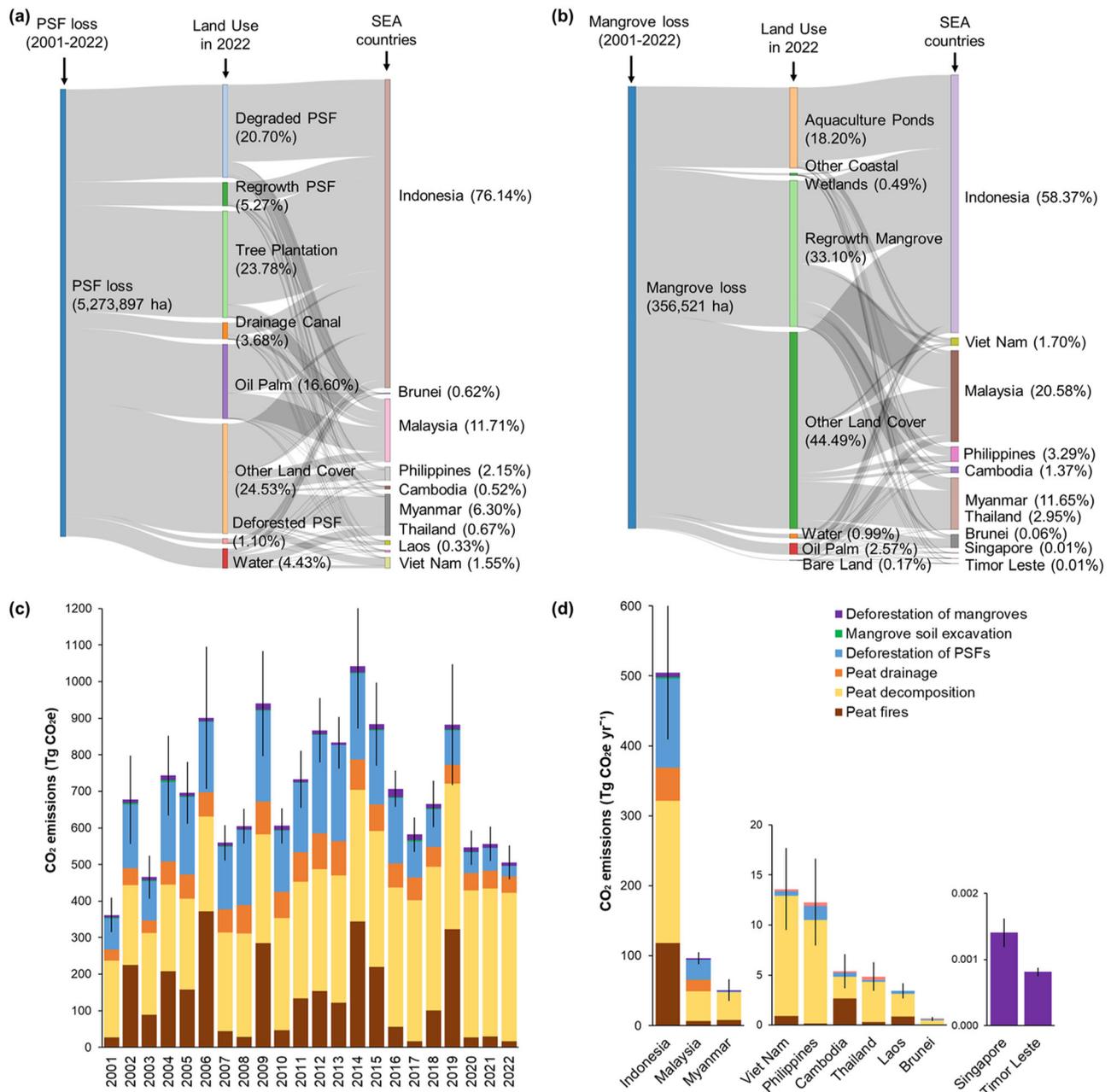


Fig. 2 | Land-use change and associated estimated CO₂ and CH₄ emissions for peat swamp forests (PSFs) and mangroves in Southeast Asian countries.

a, b The proportion of land-use (in hectares) replacing PSFs and mangroves in Southeast Asia between 2001 and 2022. **c, d** Annual calculated CO₂ emissions according to source (i.e., deforestation of mangroves, mangrove soil excavation,

deforestation of PSFs, peat drainage, peat decomposition, and fires in peat) and country between 2001 and 2022. Error bars for **(b)** indicate 95% confidence interval uncertainty estimated by combining activity data and emission factors (see ‘Methods’ for information on uncertainty analysis). Source data are provided as a Source Data file.

converted to other land uses prior to 2001 were also identified and the associated annual CO₂e emissions from peat decomposition were estimated. Unlike earlier assessments (refs. 11,13,20–22), we provide a detailed breakdown of estimated emissions by source, including biomass carbon loss from deforestation, peat decomposition, peat drainage and burning, and mangrove soil excavation or drainage. Additionally, we assess the mitigation potential of revegetation and rewetting in converted and drained PSFs and mangroves. Estimates of the mitigation potential of conserving and restoring PSFs and mangroves and their relative comparison with annual average of national and regional land-use emissions across Southeast Asia countries are provided. These estimates are timely as they come ahead of the next round of submissions of the NDCs in 2025 and the

Global Stocktake in 2028 to The United Nations Framework Convention on Climate Change (UNFCCC), in which a substantial proportion of promised reduced emissions are intended to come from the land-use change sector (Figs. S1 and S2).

Results and discussion

Trends of land-use change following deforestation

From 2001 to 2022, ~41% (239,723 ha year⁻¹) of PSFs and 7.4% (16,635 ha year⁻¹) of mangroves in Southeast Asia were lost relative to their extents in 2000 (Figs. 2, S3, and S4). By 2017, the annual rate of loss of PSFs had declined to 108,458 ha year⁻¹, while that of mangroves remained high at 18,400 ha year⁻¹, exceeding the 2001–2022 average (Figs. S3 and S4). The reduction in the rate of loss of PSF was associated

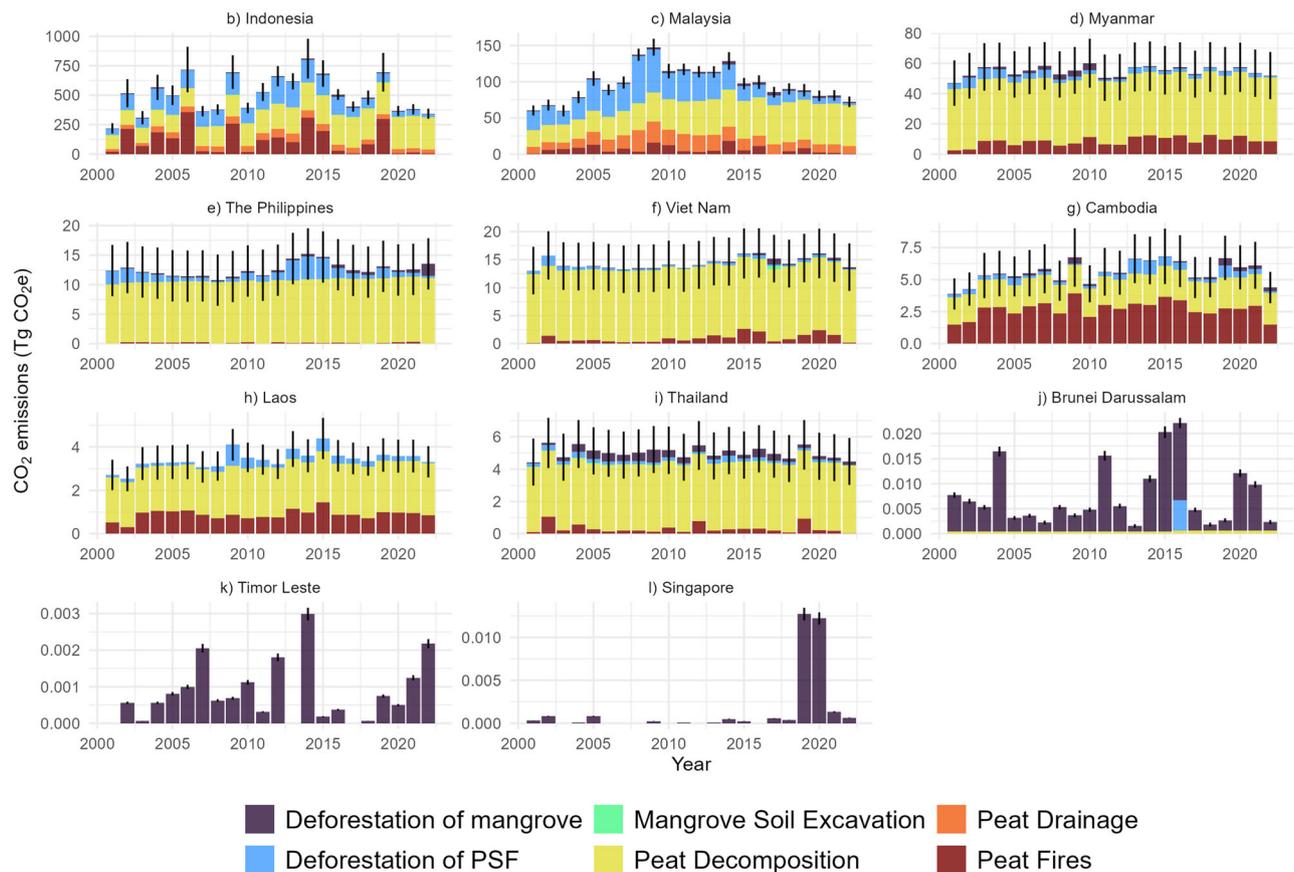


Fig. 3 | Annual variations in estimated CO₂ and CH₄ emissions from six different sources in Southeast Asia countries between 2001 and 2022. To improve visualization and readability, the y-axes have been scaled according to the estimated level of annual CO₂ emissions. Error bars indicate 95% confidence interval

uncertainty estimated by combining activity data and emission factors (see “Methods” for detailed uncertainty analysis description). Source data are provided as a Source Data file.

with a decrease in the annual area affected by biomass burning (185,834 ha year⁻¹) compared to previous years (375,117 ha year⁻¹ on average from 2001 to 2015) (Fig. S5). The extent of peatland burnt each year between 2001 and 2022 was highly variable (Fig. S5), ranging from 37,263 ha in 2017 to 853,474 ha in 2006 (annual average $314,891 \pm 263,938$ ha year⁻¹). This variability is best explained by sub-decadal drivers of rainfall variations in the region, notably the climatically dry phases of the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD)³⁰, which predispose drained peatlands in Southeast Asia to burning.

Estimated loss of PSFs by 2022 for the whole Southeast Asia region is -12.1 Mha or 1 Mha larger than reported by Miettinen et al.¹⁰, who estimated that 11.1 Mha of PSFs in Peninsular Malaysia, Sumatra, and Borneo had been lost by 2015. To standardize the timeline for fair comparison with this earlier assessment, we estimated that -11.2 Mha of PSF had been lost by 2015, highlighting the extent of expansion of new land uses on PSF continued after 2015, albeit it at a lower rate (0.13 Mha year⁻¹) (Fig. S3). Conversion to tree plantations was among most common land-use change impacting PSFs in the region from 2001 to 2022 after other land use and degraded PSF classes, resulting in a loss of almost 2.27 Mha. By comparison, oil palm plantations replaced around 1.36 Mha of PSFs over the same period (Fig. S3). Tree and oil palm plantations and their associated drainage canals (0.30 Mha) accounted for -74% (3.93 Mha or 0.17 Mha year⁻¹) of the total deforested PSF area between 2001 and 2022, with Indonesia and Malaysia the most severely impacted. Around 2.01 and 0.86 Mha of tree and oil palm plantations, respectively, replaced PSFs in Indonesia, compared with 0.25 and 0.49 Mha in Malaysia.

Losses of mangroves in Southeast Asia between 2001 and 2022 were -0.36 Mha (7.4%) (Fig. S4) and were mainly driven by economic demand for commodities associated with aquaculture and wood products, accounting for 62% of total loss areas between 2001 and 2022. During the analysis period, -0.064 Mha of mangroves were converted into aquaculture ponds in Southeast Asia. Further, around 33% of mangroves cleared between 2001 and 2022 had recovered their original vegetation cover by 2022 (Fig. S4).

Carbon emissions by sources

Deforestation and land-use change impacting PSFs and mangroves in Southeast Asia generated an estimated 691.8 ± 97.2 teragram (Tg) of CO₂e (CO₂ and CH₄) emissions annually between 2001 and 2022 (Figs. 2 and 3), with -98% (684.3 ± 97.4 Tg CO₂e year⁻¹) from PSFs and 2% from mangroves (13.53 ± 2.34 Tg CO₂e year⁻¹). Emissions from PSF comprise those from peat decomposition (ca 46%), biomass loss following deforestation (23%), peat burning (20%), and peat loss and on-site emissions following construction of artificial peat drainage canals (9%) (Fig. 2). Our estimated average annual regional emissions are higher compared to refs. 24,13,20,31, whose estimate range from 208 to 560 Tg CO₂e year⁻¹, although these estimates only considered Sumatra, Peninsular Malaysia, and Borneo and excluded peat fires (Table S1). However, when uncertainty is incorporated, our estimates are within the range of those recently provided by the UNEP Global Peatland Assessment²³. Further, our estimates are 100% greater than those provided in ref. 19 for PSFs and mangroves in Southeast Asia over the same period (2001–2022). These differences are likely due to a lack of consideration in ref. 19 of emissions from fires, the

construction of aquaculture ponds and drainage canal network, and aquatic sources. However, similar trends in national emissions are evident (Table S1), except for the case of Myanmar where determination of the extent and nature of peatland disturbance has been difficult (see ‘Methods’ for further explanation of data limitation).

Relatively high (above average) annual CO₂e emissions were mostly associated with periods of prolonged drought when the dry phases of ENSO and IOD coincided (e.g., 2006, 2009, 2015, and 2019). In contrast, low annual CO₂e emissions were observed during climatically relatively wet years (e.g., 2007–2008, 2010, 2020–2022), which may provide biophysical support for rewetting of drained peatlands and mangroves (Figs. 3 and S6). This pattern suggests that interdecadal climate variability has an important influence on annual emissions in the region, particularly those linked to major peat-burning events³². Major biomass fires and their associated emissions were not restricted to periods of ENSO-related, prolonged droughts, however, e.g., during the 2013–2014 fire season (Fig. 3)³³. Furthermore, annual CO₂e emissions from peat decomposition and drainage increased steadily between 2001 and 2022 (Fig. 3) with expansions in the extent of converted PSFs and the associated surface area of drainage canals (Figs. S3 and S7). By contrast, annual CO₂e emissions from biomass loss linked to deforestation decreased over the same period following reduced rates of PSF deforestation, particularly after 2019 (Fig. 3).

Indonesia was the main contributor to regional CO₂e emissions from deforestation and conversion of PSFs and mangroves (73% or 504.7 ± 95.4 Tg CO₂e year⁻¹), followed by Malaysia (14% or 96.4 ± 8.5 Tg CO₂e year⁻¹) (Figs. 2 and 3), with the two countries accounting for 87% and 72% of the total areas of PSFs and mangroves in Southeast Asia, respectively. Our estimated annual emissions for Indonesia are substantially higher than reported in the country’s Second Forest Reference Level (FRL)³⁴ (209 Tg CO₂e year⁻¹), possibly because of: (1) differences in the period of assessment (Indonesia’s FRL reported emissions over a shorter period between 2006/2007 and 2019/2020 compared to our analysis period between 2001 and 2022), (2) the exclusion of emissions from land use converted prior to commencement of period of interest, and (3) unaccounted soil carbon stock losses linked to the construction of drainage canals, aquaculture ponds and subsequent increased export of dissolved organic carbon. Our estimates for Indonesia are -160 Tg CO₂e year⁻¹ lower than those provided by the UNEP Global Peatland Assessment²³, while they are similar to those for Malaysia. The disagreement in estimated CO₂e emissions is due to differences in the area of peatland (Table S2) and the exclusion of emissions from peat fires in the UNEP Global Peatland Assessment. For example, the extent of peatland in Indonesia according to the UNEP Global Peatland Assessment²³ was reported 20.9 Mha (and 39.8 Mha retrieved from pixel calculation of the original tiff data, see Table S2) or 6.2 Mha larger than our study, while their year(s) of activity data were unspecified. The area of peatland in Indonesia used in our analysis (14.8 Mha which is based on ref. 16) is comparable with the latest national peatland distribution assessment (13.4 Mha)³⁵. Further, our analysis suggests that annual CO₂e emissions from the other nine countries in the region were substantially larger than previous estimates²⁴ (Table S1). This inconsistency is likely due to limited information on peatland distribution and definition in these countries^{23,36}, which leads to high inconsistency and uncertainty between available datasets^{16,37}, and overlapped distribution of both peatland and mangrove (Table S3 and ref. 38). Our findings suggest that improving the accuracy of GHG emission estimates from land-use changes on peatlands will require improved accuracy of emission factors and information on peatland distribution and extent (activity data)³⁸.

Deforestation and land-use change affecting PSFs accounted for the vast majority of annual total CO₂e emissions (Figs. 2 and 3) owing to mangroves being less extensive, storing less carbon per unit area

(400–2000 ton C ha⁻¹) than peatlands (1500–5000 ton C ha⁻¹), and experiencing lower rates of deforestation over the last two decades^{39–41}. The results suggest that peatland conservation may have larger immediate carbon benefits compared with mangroves. However, more people are likely to benefit directly from the ecosystem services provided by intact mangroves than peatlands⁴², including for climate change adaptation and food security. Additionally, mangroves are threatened by multiple stressors in addition to land-use change, particularly accelerated sea level rise⁴³, and tropical cyclones⁴⁴. Impacts of sea level rise and other climate change stressors on mangrove and coastal peatland soil carbon stocks are currently uncertain and likely to vary spatially^{45–48}. While the preservation of soil carbon stocks is enhanced under prolonged periods of waterlogged conditions⁴⁹, other factors such as changes in water quality and erosion⁵⁰ and the effects of nutrient enrichment⁵¹ could alter the balance between carbon accumulation and loss and thus emissions.

Mitigation potentials by regrowth and restoration scenario

Secondary regrowth or recovered PSFs and mangroves on previously deforested areas between 2001 and 2022 were estimated to cover, respectively, 0.49 Mha and 0.12 Mha (see Figs. 4a and S8, and ‘Methods’). Biomass regeneration sequestered an additional 15.9 ± 2.0 Tg CO₂e year⁻¹ of mitigation potentials (Fig. 4b). This estimate is based on annual biomass carbon stock enhancement rates of 11.9 ± 3.0 Mg CO₂e ha⁻¹ year⁻¹⁵² and 14.6 ± 9.2 Mg CO₂e ha⁻¹ year⁻¹⁵³ for PSF and mangrove, respectively. We observed that the secondary regrowth of PSF, as identified using the tropical moist forests (TMFs) dataset⁵⁴, was not detected in areas of recent deforestation (2017–2022). Consequently, carbon biomass sequestration for new regrowth during this period could not be quantified. Estimates of enhanced carbon stocks via biomass regrowth would only offset 2.3% of annual CO₂e emissions from deforestation and land-use change of PSF and mangroves in Southeast Asia, suggesting that avoiding clearance of PSF offers greater mitigation potential compared to regrowth in the short-term, because of the extended time taken by regenerating forest to reach maturity, and thus achieve maximum carbon accumulation^{53,55} (Fig. 4b). Nevertheless, actual carbon uptake from regrowth and restoration likely exceeds our estimate because the majority of carbon stocks in wetlands are soil-based rather than above-biomass. However, we noted limited availability of data on soil carbon sequestration from regrowth and restoration of PSF as well as little evidence of soil carbon stocks build up following mangrove restoration, particularly after 5 years of planting⁵⁶. We suggest that future research aimed at improving carbon uptake accounting from PSFs and mangrove restoration should be focused on assessing soil carbon fluxes particularly their soil organic matter burial rates.

We estimated that implementation of restoration after 2022 involving revegetation of -2.64 Mha degraded and deforested PSF (Fig. 4c), rewetting of -5.34 Mha tree and oil palm plantations on drained peatlands, and recovery of mangroves on -0.07 Mha bare land and aquaculture ponds has a potential climate change mitigation of -94.4 ± 7.4 Tg CO₂e year⁻¹ (Fig. 4d and Table 1). Of this total, rewetting of drained plantations on peatland accounts for about 66%, with emission reductions from the revegetation of degraded and deforested PSFs and mangroves the remaining 33% and 1%, respectively. Rewetting drained and managed peatlands is the most effective means of achieving emissions reductions in the short term instead of revegetation, given the lag between reforestation and maximum carbon accumulation (Fig. 4b). While demand for plantation-based commodities remains, potential leakage can perhaps best be minimized through a combination of switching to taxa that are better able to withstand high water tables (e.g., paludiculture crops)⁵⁷, increased productivity in unaffected areas and reduced wastage. Further research is needed to determine the optimal depth of the water table for maintaining low GHG emissions without jeopardizing the

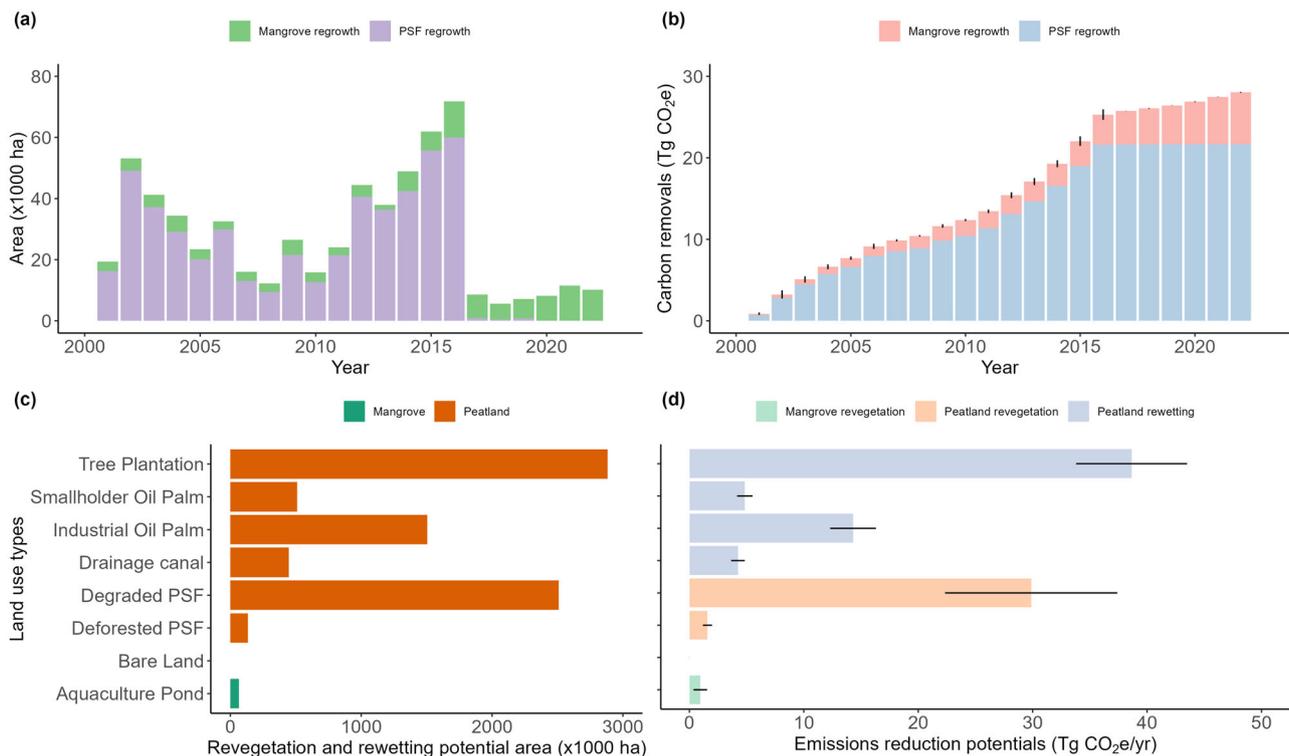


Fig. 4 | Estimated area and CO₂e mitigation potentials resulting from the regrowth of peat swamp forests (PSFs) and mangroves between 2001 and 2022, and the revegetation and rewetting of selected land-use types occupying former areas of PSF and mangroves in Southeast Asia. a Annual area of identified regrowth of PSFs and mangroves between 2001 and 2022. **b** Annual CO₂e removals generated by regrowth of PSFs and mangroves between 2001 and 2022. **c** Revegetation and rewetting potential for selected land-use types in

what were PSFs and mangroves as of 2022. **d** Estimated potential reductions in CO₂e emissions for selected land-use types and restoration scenarios (i.e., mangrove revegetation and peatland rewetting and revegetation). Further information on the detailed CO₂e removal factors and assumptions for calculating potential reductions in CO₂e emissions can be found in the Methods. Error bars indicate 95% confidence intervals. Source data are provided as a Source Data file.

production of plantation commodities⁵⁸. Overall, the implementation of restoration often faces complex biophysical, economic, and governance barriers^{31,57,59–62} and may lead to enhanced emissions elsewhere⁶³. Results presented here suggest that the fulfillment of emission reduction targets for the land sector in Southeast Asia will be strongly dependent on the conservation in a more-or-less intact state of PSFs and mangroves.

Potential contribution to emissions reduction targets

As a proportion of national-level land-use change emissions, the climate change mitigation potential through avoided deforestation and conversion of PSFs and mangroves is far more significant for some countries in the region than others (Table 1). Avoiding deforestation and conversion of PSFs and mangroves to other land uses is equal to 88%, 64%, 60%, and 39% of the national land-use emissions of, respectively, Malaysia, Indonesia, Brunei Darussalam and Myanmar. The climate change mitigation potential is less for the other countries in the region—The Philippines (26%), Cambodia (18%), Vietnam (13%), Thailand (10%), Laos (9%), Singapore (2%), and Timor Leste (0.04%). Indonesia alone is responsible for the largest (73%) annual CO₂e emissions from PSFs and mangroves and therefore the greatest potential for reducing emissions from land-use change in the region (1422 Tg CO₂e year⁻¹, or 35%). In its NDCs, Indonesia plans to reduce its emissions from Forestry and Other Land-use (FOLU) by 2030 up to 729 Tg CO₂e, depending on the level of external support²⁹. Our estimated annual emissions from PSFs and mangroves in Indonesia are -504.7 ± 95.4 Tg CO₂e, and thus similar to the country's target of emission reductions from FOLU without external financial support (500 Tg CO₂e). The conservation of PSFs and mangroves alone could

thus potentially meet the country's unconditional reduction target for FOLU emissions²⁸. This potential could be increased further by 15% (76.7 ± 7.3 Tg CO₂e) through the restoration of PSFs and mangroves that have been degraded or converted to other land uses (Table 1).

Conserving and restoring PSFs and mangroves in Southeast Asia, despite their relatively limited extent (5.4% and 0.2% of land in the region and globally, respectively), could potentially contribute -770 ± 97 Tg CO₂e year⁻¹ of reduced emissions to climate change mitigation. These numbers include the opportunity for restoration of currently degraded PSFs and mangroves in Southeast Asia that could contribute -94 ± 7 Tg CO₂e annually. If realized, such efforts could reduce GHG emissions from FOLU by 54% in Southeast Asia region, and 16% globally (Fig. 5). Peatland and mangrove conservation and restoration thus should be considered an important part of meeting NDC targets, despite their limited area. The Association of Southeast Asian Nations (ASEAN) Peatland Management Strategy 2023–2030 specifically promotes the sustainable management of peatlands and aligns with the national-level conservation and restoration targets as agreed under the Convention of Biodiversity (COP 15) ref. 36. Effective implementation of these targets may still not be sufficient for Southeast Asia countries to compensate for their land-based emissions (Table 1), however. Far more ambitious national-level conservation and restoration targets than those already agreed may be required in order for Southeast Asian countries to meet their obligations under the Paris Agreement.

Our findings highlight the importance of conserving and restoring carbon-rich peatland and mangrove ecosystems as a natural climate change solution for countries with substantial coverage and losses of

Table 1 | Average loss of peat swamp forest (PSFs) and mangroves in Southeast Asia and their associated carbon emissions and mitigation potentials relative to national land-use change (LUC) emissions

Country	PSFs loss ha year ⁻¹ , 2001–2022	Mangrove loss	Carbon emissions Tg CO ₂ e year ⁻¹ , 2001–2022	Carbon removals by natural regrowth ^a	Emissions reduc- tion potential by restoration	Total mitigation potentials	LUC emissions	Total mitiga- tion potentials proportion to LUC emissions %
Indonesia	190,617	9459	504.7 ± 95.4	-13.52 ± 2.00	76.74 ± 7.30	567.9 ± 95.7	888 ± 50	64
Malaysia	42,593	3336	96.4 ± 8.5	-1.33 ± 0.13	15.40 ± 1.25	110.5 ± 8.6	126 ± 10	88
Myanmar	2450	1887	50.6 ± 15.3	-0.59 ± 0.10	0.62 ± 0.14	50.6 ± 15.3	130 ± 4	39
Philippines	2102	534	13.3 ± 4.0	-0.05 ± 0.00	0.25 ± 0.02	13.8 ± 4.1	50 ± 5	13
Viet Nam	605	275	12.3 ± 4.3	-0.24 ± 0.03	0.89 ± 0.14	12.9 ± 4.3	106 ± 8	26
Cambodia	561	223	5.4 ± 1.7	-0.07 ± 0.04	0.14 ± 0.02	5.5 ± 1.7	30 ± 2	18
Thailand	252	479	4.8 ± 1.4	-0.086 ± 0.003	0.20 ± 0.02	5.0 ± 1.4	50 ± 9	10
Laos	422	-	3.4 ± 0.7	-0.014 ± 0.003	0.08 ± 0.02	3.5 ± 0.7	38 ± 2	9
Brunei Dar- ussalam	122	10	0.6170 ± 0.2153	-0.025 ± 0.003	0.14 ± 0.003	0.7 ± 0.2	1.2 ± 0.1	60
Singapore	-	3	0.0014 ± 0.0002	-0 ± 0	0.0006 ± 0.0004	0.0021 ± 0.0005	0.1 ± 0.01	2
Timor Leste	-	1	0.0008 ± 0.0001	-0 ± 0	0.0004 ± 0.0002	0.0012 ± 0.0002	2.7 ± 0.2	0.04
SEA	239,723	16,387	691.8 ± 97.2	-16.32 ± 2.01	94.4 ± 7.4	770.3 ± 97.5	1422 ± 54	54

Total mitigation potentials are the summary product of emissions, removals, and emissions reduction potentials of carbon according to an optimal restoration scenario. Land-use change emissions represent country- and regional-level annual emissions between 2001 and 2022 obtained from ref. 83.

^aNegative value indicates carbon removals generated by enhanced biomass carbon stocks following natural regrowth. CO₂e values are presented as mean ± 95% confidence interval.

these ecosystems (Table 1). Further, this study provides timely evidence of the scale and magnitude of actionable and pragmatic climate change mitigation strategies provided by conservation interventions aimed at both restoring and protecting PSFs and mangroves in Southeast Asia ahead of the next round of NDC submissions in 2025 (Fig. 5). PSF and mangroves in the region clearly have an important role to play in meeting net zero emissions by 2050 under the Paris Agreement. For countries other than Indonesia that have not specified their emission reduction targets for the land sector in their submitted NDC, the findings presented here have important implications for policy development and implementation, at national, regional, and global levels.

Methods

Activity data

We compiled and used multiple published spatial datasets for activity data (area of PSFs and mangroves deforested and converted to other land covers), using basemaps for peatland¹⁶ and mangroves⁶⁴. For deforestation of PSFs and land-use change, we overlaid the peatland basemap and datasets of annual tropical moist forest (TMF) change between 2001 and 2022 and main class land cover types in 2022 (e.g., deforested and degraded PSF, regrowth of PSF, tree plantation, water surface, and other land covers) provided by ref. 54. Deforestation of PSFs was thus defined in a similar way to the original dataset, which was tree canopy loss at 30 × 30 m resolution. Peatland land cover prior to 2001 was identified by overlaying the peatland base map with any peatland area deforested prior to 2001 as identified by ref. 54. Therefore, historical and annual areas of each land-use were tracked from the deforestation data—a common approach applied to identify historical land-use change⁶⁵. Subset examples of land use transition validation by using satellite imagery are provided in Fig. S9. Additional datasets were included and overlaid with deforested and converted PSFs, including a map of industrial and smallholder oil palm plantations⁶⁶, and drainage canal network map⁶⁷. Annual burned area data obtained from NASA MODIS MCD64A1 product⁶⁸ was overlaid with peatland extent to generate estimated peat burned area.

For mangroves, we assessed deforestation area by overlaying the mangrove area baseline in 2000⁶⁴, and annual tree cover loss between 2001 and 2022⁶⁹. Deforested mangrove distribution and area were

then identified when tree cover loss pixels overlapped with mangrove baseline data. Land-use changes in deforested mangroves over the assessment period were identified through a dataset of drivers of mangrove loss provided by ref. 70. Six main land covers are considered; bare land, mangrove, coastal wetlands, aquaculture pond, other land cover, and water body. However, this dataset does not cover Singapore, Brunei Darussalam, and Timor Leste. The extent of mangrove loss in these three countries was low. Combined losses of mangroves in Singapore, Brunei Darussalam, and Timor Leste account for less than 0.1% of total losses of mangroves in Southeast Asia between 2001 and 2022. The oil palm dataset⁶⁶ was combined with information on mangrove deforestation from the first analysis to identify and quantify the extent of mangroves converted to oil palm. We applied a similar approach for PSF to track historical annual land cover change in mangroves including mangrove regrowth by using known deforestation year data. All of the spatial data analyses were carried out using 30 × 30 m pixel-based calculations in Google Earth Engine. Except for the baseline vector maps of peatlands and mangroves, all other spatial data, including generated activity data, used in our analysis had a resolution of 30 m.

Carbon emission factors

Tier 1 emission factors from the 2013 IPCC Wetlands Supplement⁷¹ and 2019 Refinement to the 2006 IPCC Guidelines⁷² were applied to both PSFs and mangroves to calculate CO₂ and CH₄ emissions arising from deforestation, peat fires, drainage development and decomposition of peat, and from the construction and operation of fish/shrimp ponds. While Tier 1 emission factors are global, most of the compiled data specifically for peatlands are from the Southeast Asia region⁷¹. In those cases where valid Tier 1 emission factors were unavailable or not relevant, emission factors from earlier studies conducted in Southeast Asia were applied (see further detail on emission factors and assumptions that underpinned the analysis in Table S4). The current study focused on the following sources of GHG emissions: (1) loss of biomass carbon from deforestation involving both PSFs and mangroves under the assumption that hydrology and tidal connectivity remained intact, (2) peat decomposition from soil CO₂ and CH₄ effluxes and dissolved organic carbon, (3) CO₂ and CH₄ emissions generated by peatland fires, (4) excavated peat soil carbon stock loss

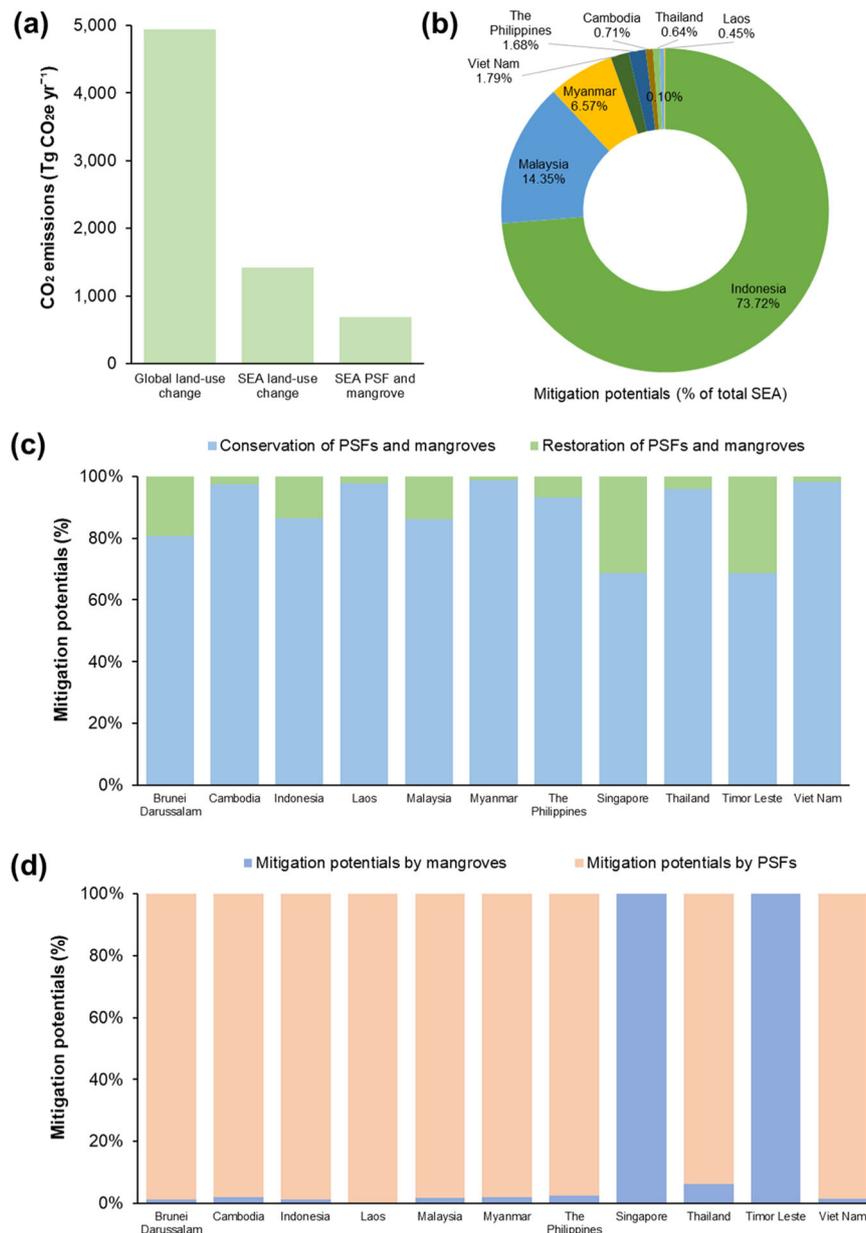


Fig. 5 | Relative contributions to climate change mitigation potential from restoration and conservation of peat swamp forest (PSFs) and mangroves in countries in Southeast Asia. a Carbon emissions from PSFs and mangroves relative to regional and global land-use emissions. **b** Country-by-country contribution to regional climate change mitigation potential from conservation of PSFs and mangroves. Note that percentages from Singapore, Brunei Darussalam, and Timor

Leste are not shown due to low values (0.095% combined). **c** Proportion of climate change mitigation potential from protection and restoration of PSFs and mangroves at country level in Southeast Asia. **d** Relative contribution to climate change mitigation potential from PSFs and mangroves on a country-by-country basis in Southeast Asia.

and on-site aquatic CO₂ and CH₄ effluxes from the drainage canal surface network, (5) on-site aquatic CH₄ effluxes from aquaculture ponds, and (6) losses of soil carbon stock during the conversion of mangroves to aquaculture ponds. Owing to a paucity of relevant literature, we did not include N₂O emissions, although these may be substantial from some land uses⁷³.

Determination of carbon removals and emissions reduction potential

For the estimation of carbon removals and emissions reduction potentials from forest regrowth, carbon stock enhancement was used for the forest regrowth and revegetation categories, as well as estimates of potential reduced emissions reduction following rewetting in

tree and oil palm plantations on peat (see Tables S4 and S5 for detailed carbon removals and assumptions regarding the peat water table and emissions reduction potentials used in this study). Carbon removal factors following regrowth and revegetation of PSFs and mangroves were adopted from global biomass carbon stock enhancement synthesis studies developed by refs. 52 and 53 (Table S4). Potential reductions of CO₂ and CH₄ emissions following optimal rewetting scenarios on converted PSF for tree plantation and oil palm were derived from the relationship between water table depth (WTD) and CO₂ and CH₄ emissions developed by ref. 58. We considered rewetting scenarios only feasible for tree and oil palm plantations due to insufficient water table data and emissions factor for rewetting degraded peatlands as well as high land management uncertainty of idle

degraded peatlands⁷⁴. The optimal rewetting scenario was determined by increasing WTD to 30 cm below the surface. According to global data synthesis (ref. 58), the lowest tradeoff between CO₂ and CH₄ emissions is when WTD is 30 cm below the peat surface. Emissions of CO₂ and CH₄ were calculated using, respectively linear and non-linear relationships. Raising WTD by 10 cm led to a reduction in CO₂ emissions of a maximum of 3 Mg CO₂ ha⁻¹ year⁻¹, while CH₄ emissions are nearly zero when WTD is kept below 30 cm from the surface.

Determination of carbon emissions and emission reductions

Estimates of annual CO₂e (CO₂ + CH₄) emissions generated by each of the six potential sources considered here were the product of activity data (annual deforestation and land-use change area) and emission and removal factors. Both carbon stock difference and carbon flux change approaches were used, depending on the mechanisms of carbon release (e.g., one-time vs. continuous carbon losses). For example, a carbon stock difference approach was applied to estimating CO₂e emissions from deforestation and soil carbon stock loss following peat drainage canal development, and the construction of aquaculture ponds. Moreover, soil CO₂ and CH₄ fluxes were used for calculating emissions from peat decomposition and aquatic carbon emissions. For the calculation of emissions, we applied CH₄ global warming potential at the 100-year timescale (GWP₁₀₀) of 28 as a basis for comparing the relative warming impact between CH₄ and CO₂ as suggested by the Fifth IPCC Assessment Report⁷⁵. We acknowledge that the conventional GWP₁₀₀, despite being broadly used, has theoretical limitations when applied to natural systems (i.e., single pulse emissions while ecosystem emissions are typically continuous) and that the 100-year time scale is purely arbitrary. Moreover, we recognize that other metrics such as the Sustained Global Warming Potential⁷⁶ and GWP* may be preferred when quantifying the radiative forcing of ecosystems over time⁷⁷. We thus consider our estimated emissions to be conservative because of our use of the GWP₁₀₀ index, which is in line with international GHG reporting standards under the UNFCCC⁷⁵. Estimated CO₂e emissions by sources and countries are presented in the dataset for this paper⁷⁸.

Biomass carbon loss following deforestation. Estimates of annual CO₂e emissions following deforestation were determined from the direct loss of aboveground biomass carbon stocks for both PSFs and mangroves. The aboveground biomass carbon stocks baseline for PSF was obtained from Southeast Asia data synthesis by ref. 79, while we applied Tier 1 IPCC values for mangroves⁷¹ (Table S4).

Peat decomposition. We considered both peat CO₂ and CH₄ effluxes and used Tier 1 emission factors for calculating annual levels of peat decomposition for different land uses (Table S4). Estimated annual peat decomposition was the product of CO₂ and CH₄ emissions on the area of converted PSF, and therefore the magnitude of annual peat decomposition increased over the analysis period. The extent of deforested and converted PSF prior to 2001 was determined and used to generate estimates of annual emissions from peat decomposition. We assumed that converted and drained peatlands, regardless of the time since conversion, are continuously generating CO₂ and CH₄ as a function of decomposition. This assumption limits the ability to include peat depletion time where shallow peat may disappear faster than deep peat over a certain period, and thus will likely contribute to an overestimation of GHG emissions.

Peat fire emissions. Emissions following peat fires were calculated by considering the mass of organic soil fuel, gasses (CO₂ and CH₄), and the relevant combustion factor (see Table S4 for detailed values) along with the area of peatland burnt that year determined from the NASA MODIS MCD64A1 burnt area monthly product⁶⁸. In this study, we used the latest combustion factor data developed by ref. 80, where it is

assumed that peat fires only generate 54% of combustion products. Consequently, the emissions from peat fires in this study may be lower than Tier 1 IPCC data where peat fires are assumed to generate 100% combustion products.

Peat drainage. For calculating CO₂ and CH₄ emissions from peat drainage, we considered three carbon loss pathways: (1) loss of peat soil carbon stock following excavation of peat for canal development, (2) dissolved organic carbon export, and (3) on-site CO₂ and CH₄ emissions from the drainage canal surface area. For loss of soil carbon stock linked to the construction of a drainage network, the uppermost 1 m of peat was assumed to have been excavated and all excavated peats were rapidly decomposed on exposure to the atmosphere.

Emissions from conversion of mangroves to aquaculture ponds. Conversion of mangroves to aquaculture is associated with enhanced emissions of carbon owing to substantial soil carbon loss following soil disturbance and removal during pond development⁸¹. In this study, we assumed that ~54% of total soil carbon stocks have been lost during the construction of aquaculture ponds⁵³. We adopted Tier 1 2013 IPCC Wetlands supplement for aggregated organic and mineral soil carbon stocks as we believe this value is conservative to cover large hydrogeomorphic variability of mangroves in Southeast Asia. Moreover, we included on-site CH₄ emissions from the aquaculture ponds through the use of a Tier 1 IPCC 2019 Refinement emission factor⁷².

Uncertainty analysis

We estimated the uncertainty of CO₂ and CH₄ emissions presented in Figs. 2 and 3 by combining the uncertainty of activity data with the relevant emission and removal factors. Spatial uncertainty of 11% was applied for land use change on PSFs (ref. 54), while no spatial uncertainty estimates are available for the burned area, drainage canal network, and land-use change on mangroves. Therefore, final emission uncertainty estimates for these activity data relied on the uncertainty of the emission factor. An error propagation method⁸² was applied to generate uncertainty estimates, and this method estimates the uncertainty at 95% confidence intervals.

Limitation of this study

Our regional and national-scale analysis of CO₂e emissions from PSFs and mangroves in Southeast Asia improved earlier assessments by providing higher spatial and temporal resolutions (Table S1). However, several limitations remain, mainly concerning the availability, reliability, and consistency of data. First, we recognize uncertainties and inconsistencies characterizing national-level peatland distribution and area statistics (Table S6), problems that were also highlighted by the UNEP Global Peatland Assessment²³. Our analysis relied upon ref. 16, in which the estimates of peatland area for Indonesia and Malaysia are relatively conservative when compared with those provided in refs. 37, 23,24 while comparing well with earlier assessments^{10,35}. We are aware that the high estimate of peatland area reported for Myanmar, Philippines, Vietnam, and Cambodia in the dataset of ref. 16 used in this study warrants future refinement through ground validation, as these mapped peatlands may correspond to areas with organic-rich soils of fluvial origin. We acknowledge that for these countries, estimates of peatland area in ref. 16 are between the higher estimates in ref. 37 and the lower ones in ref. 23 (Table S2). We thus believe that estimates provided in ref. 16 offer a middle ground in terms of peatland area data that are currently publicly available, noting that spatial datasets referred to in refs. 10,20,24,31 are not publicly accessible and thus could not be used in the present study. Second, we used the only available drainage canal network data derived from satellite image analysis by ref. 67. These data were not sufficiently and finely resolved to include the narrowest canals located in degraded peatlands. Further, the data cover only Sumatra, Peninsular Malaysia, and Borneo.

Thus aquatic emissions from peatlands in other parts of the region (e.g., Papua) are not considered in our study. Third, processing secondary datasets that differ in their format and spatial resolution may generate another layer of spatial uncertainty. Fourth, we have been unable to implement an independent ground-check of activity data. Moreover, there is an ongoing need to generate improved emission factors in order to reduce uncertainties in assessments of soil carbon stocks loss following the excavation of peatlands (for drainage canal network) and mangrove soils (for aquaculture pond development). It is crucial to improve these aspects in future assessments.

Data availability

Source data are provided with this paper. Results data on peatlands and mangrove land use change spatial data and their annual CO₂e emissions by country and sources generated in this study are available in figshare data repository⁷⁸ (<https://figshare.com/s/Scf6e5f33ddd42930a84>). Land use change spatial data generated by this study, respectively for peatlands and mangrove are accessible through the following Earth Engine assets: `projects/ee-sdsasmito/assets/SEA_Peatlands_Land_Use_2001_2022` and `projects/ee-sdsasmito/assets/SEA_Mangroves_Land_Use_Change_2001_2022`. An interactive map visualization of the original data resolution for new land uses that replaced peat swamp forests and mangroves are available through the following Google Earth Engine app: <https://ee-sdsasmito.projects.earthengine.app/view/sea-peatmangrove>. Source data are provided with this paper.

Code availability

Codes to generate land-use change-affected PSFs and mangroves are available to the following repository link: <https://doi.org/10.5281/zenodo.14536801>.

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Author contributions

The conceptualization of this work was by S.D.S., P.T., D.T., and M.L. The methodology was developed by S.D.S. and P.T. Investigations were

undertaken by S.D.S., P.T., D.T., and M.L. Literature data acquisition, data analysis, and visualization were done by S.D.S., P.T., and W.C.A. Funding was obtained by D.T. and M.L. The original draft was written by S.D.S., along with P.T., D.T., and M.L. W.C.A., H.K., N.N., L.F., D.A.F., S.E.P., C.E.L., and D.M. provided substantial contributions in reviewing and editing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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