Tropical wetlands: solutions for or drivers of climate change?

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Carbon Governance in Southeast Asia

Social Science Research Thematic Grant (SSRTG) MOE2021-SSRTG-021
(2022-2027)

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Three premises:

1) Increased atmospheric concentrations of GHG driving global climate change

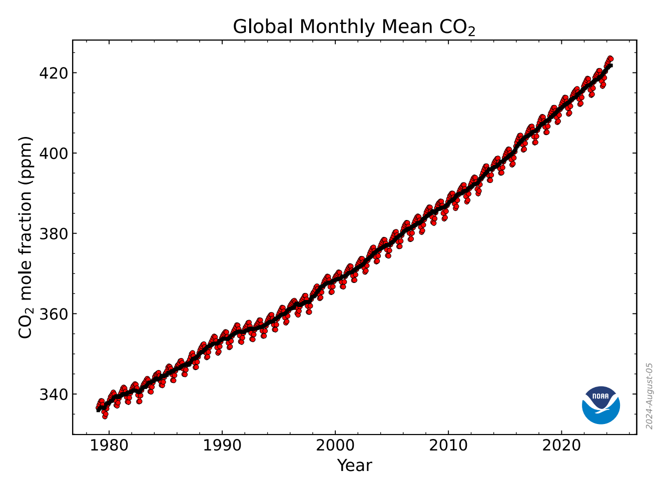
Methane (CH_4) important contributor; tropical wetlands are a major source

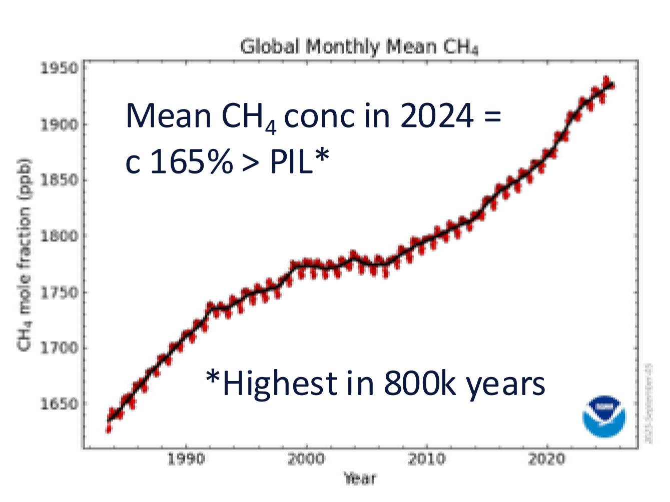
2) Wetlands are carbon "sinks"

C store = largely below the surface. High potential as "nature-based" means of climate change mitigation

3) Enhancement/Restoration/Protection of carbon-sink properties of wetlands can be funded through carbon credit schemes

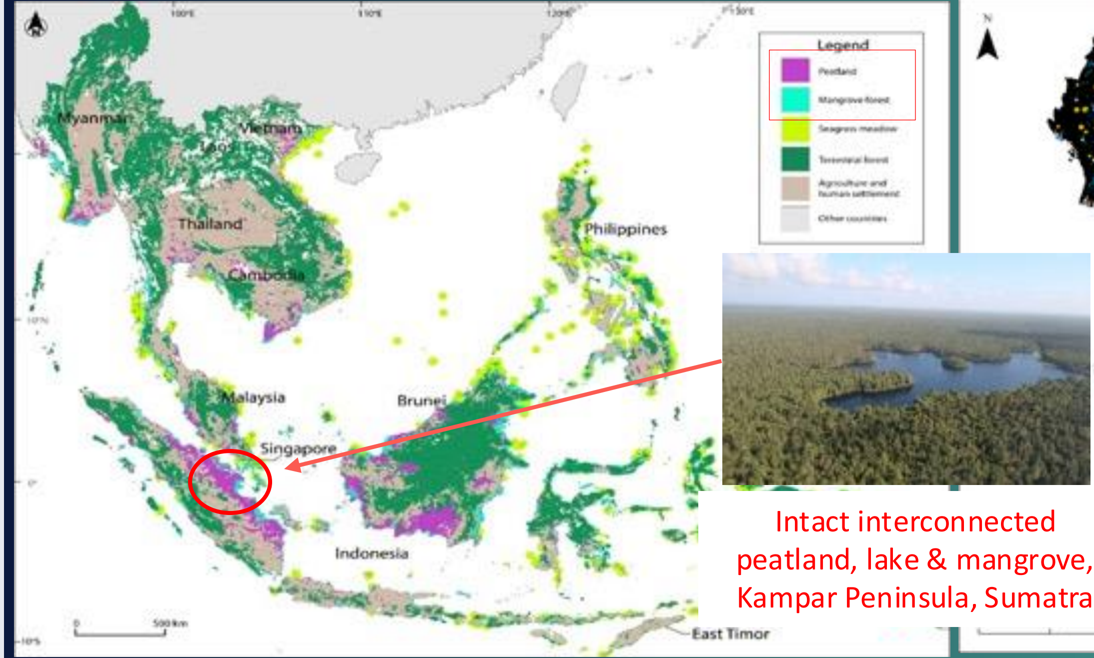
Avoided destruction/additional sequestration



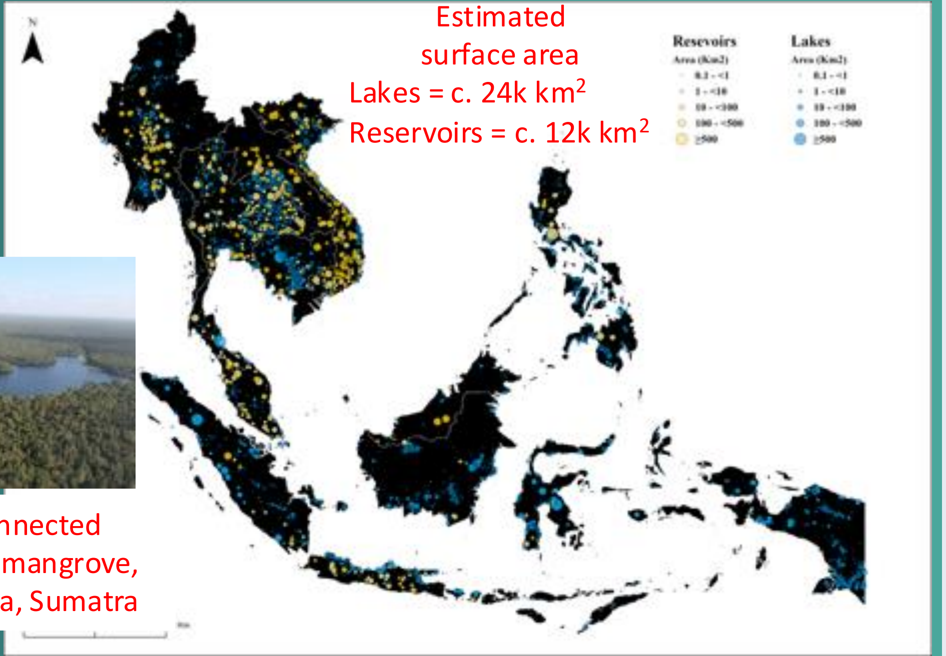


Saunois et al. (2025)

Southeast Asia has high potential for **enhanced** carbon sequestration in **nature-based carbon sinks**, including **wetlands** (peatlands, lakes, reservoirs, mangroves)



Intact interconnected peatland, lake & mangrove, Kampar Peninsula, Sumatra



Locations of main types of nature-based carbon sinks found in Southeast Asia (from Miller & Taylor 2024)

Sinks also provide **ecosystem services** in addition to carbon sequestration ("**co-benefits**")

Wetlands have unique attributes as nature-based carbon sinks ....

Atmospheric emissions of CO_2 & CH_4

~1.1 Pg C yr^{-1}

Fluvial C (dCO_2, DOC, DIC, P-C)

~1.0 Pg C yr^{-1},

C flux

C stock

Atmospheric CO_2

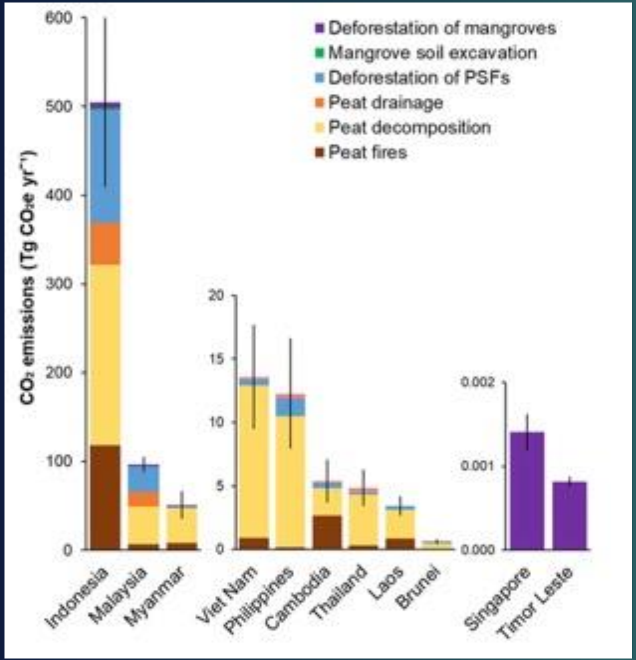
Fluvial C (dCO_2, DOC, DIC, P-C)

Sedimentary C (OM, IM)

0.2–1.6 Pg C yr^{-1}

Wetlands:
biogeochemical factories
C stocks >>>>>> C flux
Lateral connections
C stocks = *irrecoverable* C
High uncertainty in levels

Degraded wetlands in Southeast Asia ~ currently a **source** of GHG emissions…



Ave annual CO_2 emissions from degraded peatland and mangroves in SE Asia 2001-2022 (Sasimato et al. (2025) *Nature Comm*)

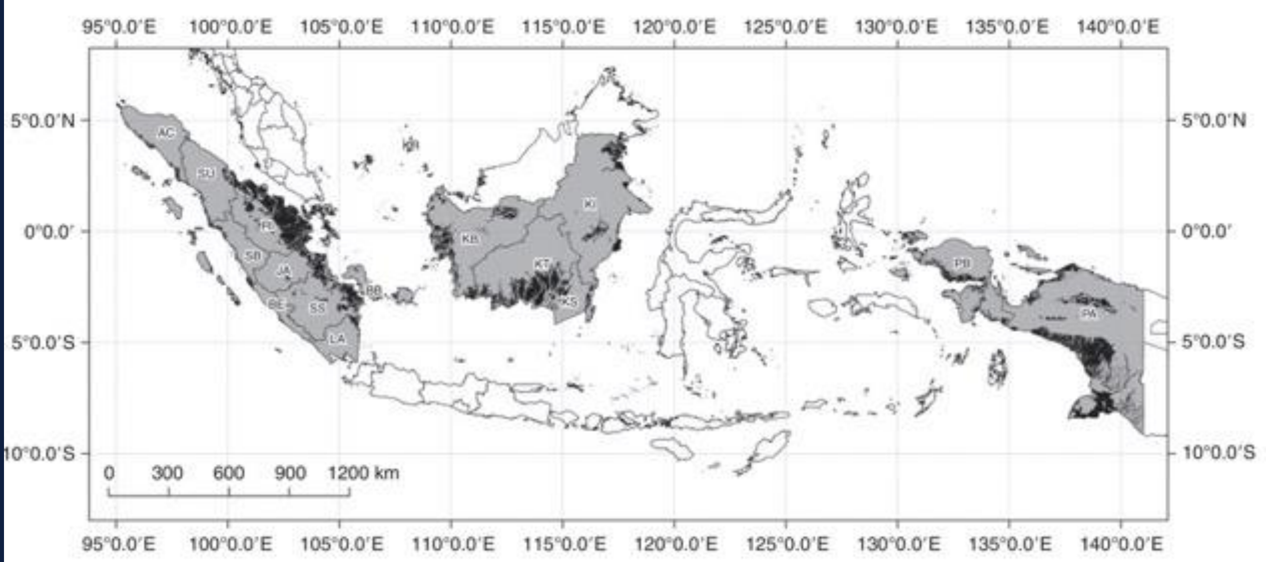
Drained and burnt peatland, Sumatra, Indonesia

SE Asia (5% global land area) accounts for **30% of global landuse emissions**

Indonesia – particularly rich in peat-based carbon stores

Much of carbon = "irrecoverable"

~60,000 km^2 peatland in Indonesia is degraded – >80x area of Singapore!



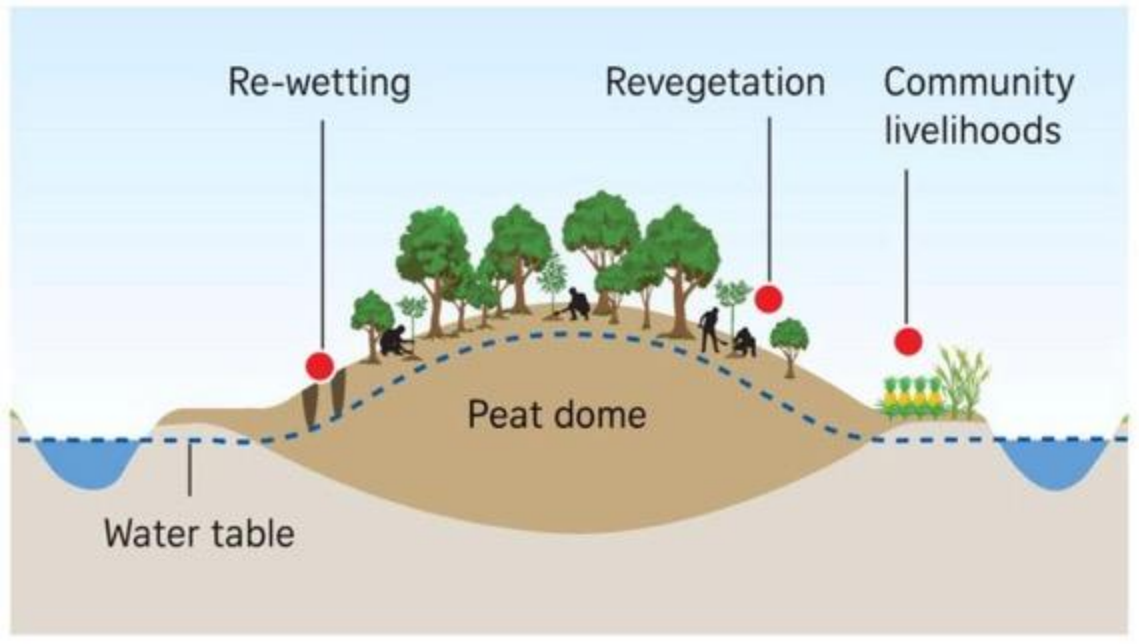
Peatland (black shading) in Indonesia (Tan et al., (2021) *Int. J. Wildland Fire*)

Peatlands in Southeast Asia = ca 70% total of tropical peatlands;

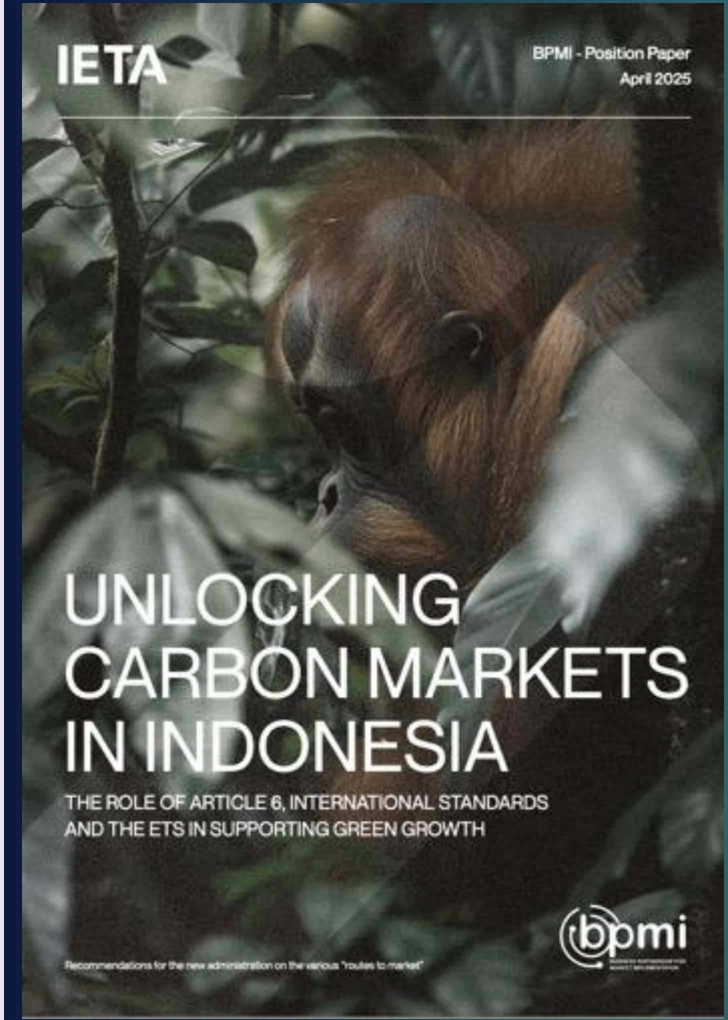
Degraded peatlands responsible for **>50%** of SE Asia's land use emissions

Scope for enhanced carbon sequestration through **restoration and protection?**

Indonesia's Peatland Restoration Agency (2016-2025) had a mandate to restore @ 26,000 km^2 of degraded peatland (extended to mangroves & reduced to 12,000 km^2 in 2021)



Peatland restoration based on "Hydrological unit" and largely involved raising the groundwater level (GWL = -30 to -40cm seen as *optimum*), replanting & economic revitalization ("3 Rs" ~ Rewetting, Revegetation & Revitalisation) . **Total estimated cost of USD 2 to 7 billion!**



Peatlands in Indonesia frequently cited as a basis of future carbon-credit supplies – and thus of international finance

Peatland-based carbon credits – not just environmental assets, but also seen as strategic economic instruments for “green growth” and fiscal revenue.

Pay for restoration and future protection …

e.g. International Emissions Trading Association (IETA) **2025** report …..

Singapore, Indonesia, Malaysia, Thailand launched carbon exchanges … Philippines & Vietnam to follow …

But…

But…

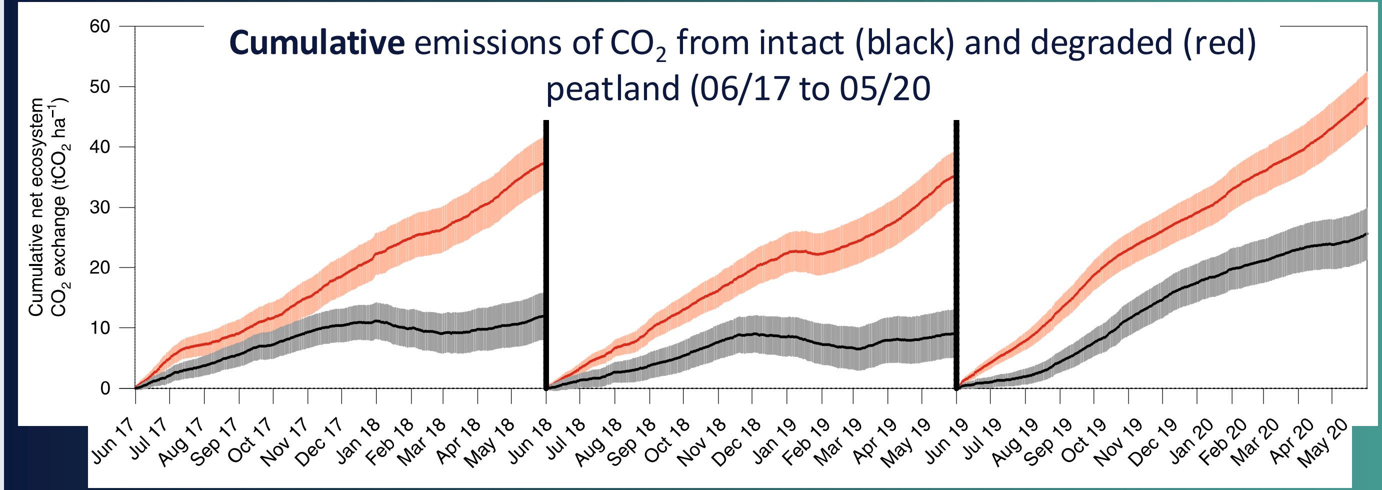
1) **Estimates** - Credits mainly generated by estimates of "avoided emissions" – estimates strongly influenced by IPCC globally averaged Tier 1 EFs ~ not process-based & do not account for spatial and temporal variations in Ground Water Level (GWL), photosynthesis etc

2) **Project based** – fails to account for Geography (including interconnectivity)

3) **Additionality** - Indonesian peat law (PP 71/2014; PP 57/2016) already meant to outlaw deep drainage and mandates restoration

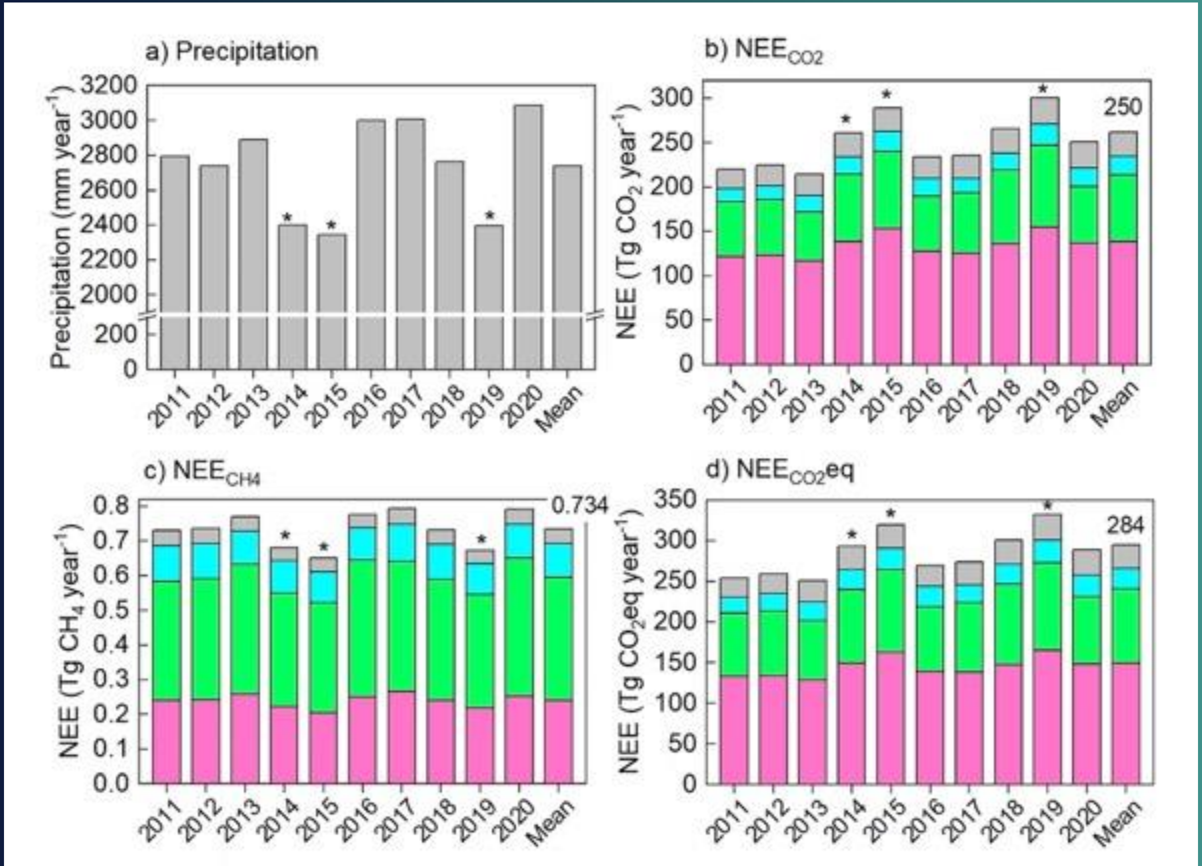
4) **Carbon stores or sinks**? Accumulating evidence that tropical wetlands, including peatlands, can be sources of carbon emissions

Evidence suggests **both degraded and restored peatlands** in Indonesia are **net emitters of CO_2 and CH_4 to the atmosphere**



From Deshmukh et al. (2021) *Nature Geoscience*

Tower for carbon flux measurements, APRIL planation, Kerinci, Riau Province, Sumatra



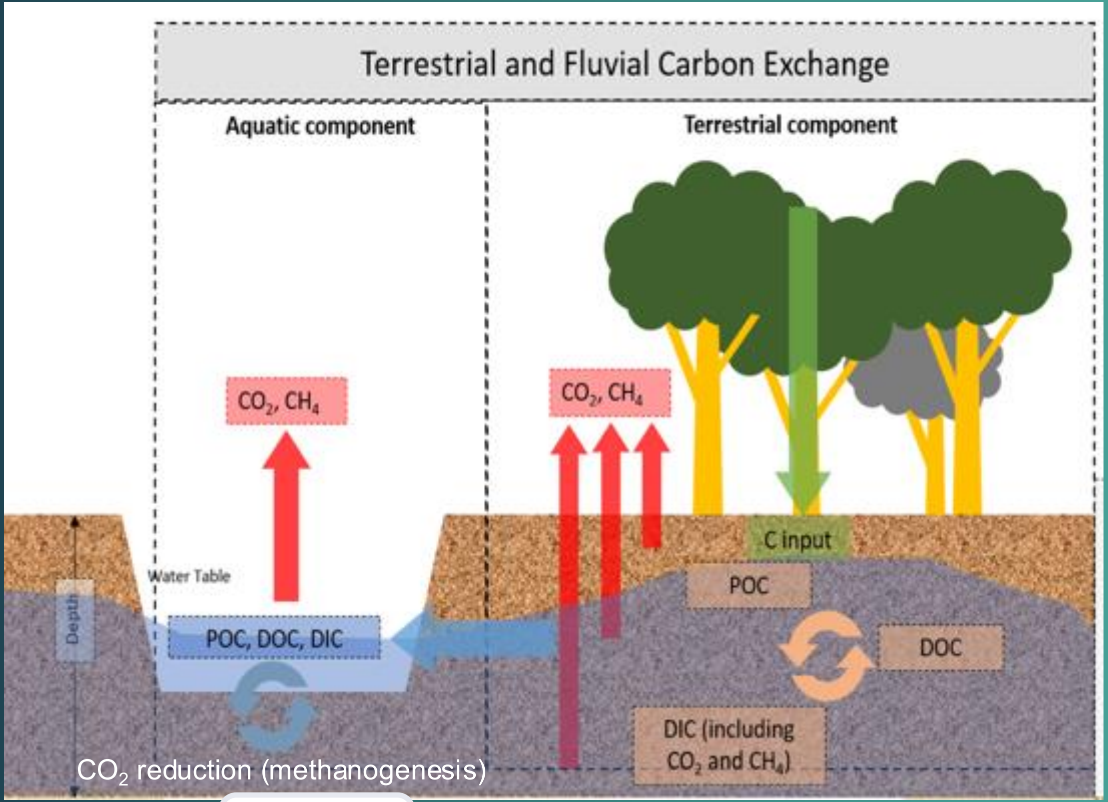
Region-wide estimates of Net Ecosystem Exchange (NEE) for peatland in SE Asia – from Hirano et al (2025) *AGU Advances*

* = El Nino (drought) years

But these data do not include aquatic exports, emissions linked to fire, age of carbon emissions etc

INTPREP research aimed for precision in identifying & quantifying C sources & influence of water table depth on C emissions from tropical peat

Impact of GWL variations and of blocking drainage on carbon export (DOC) & emissions (CO_2 & CH_4)?

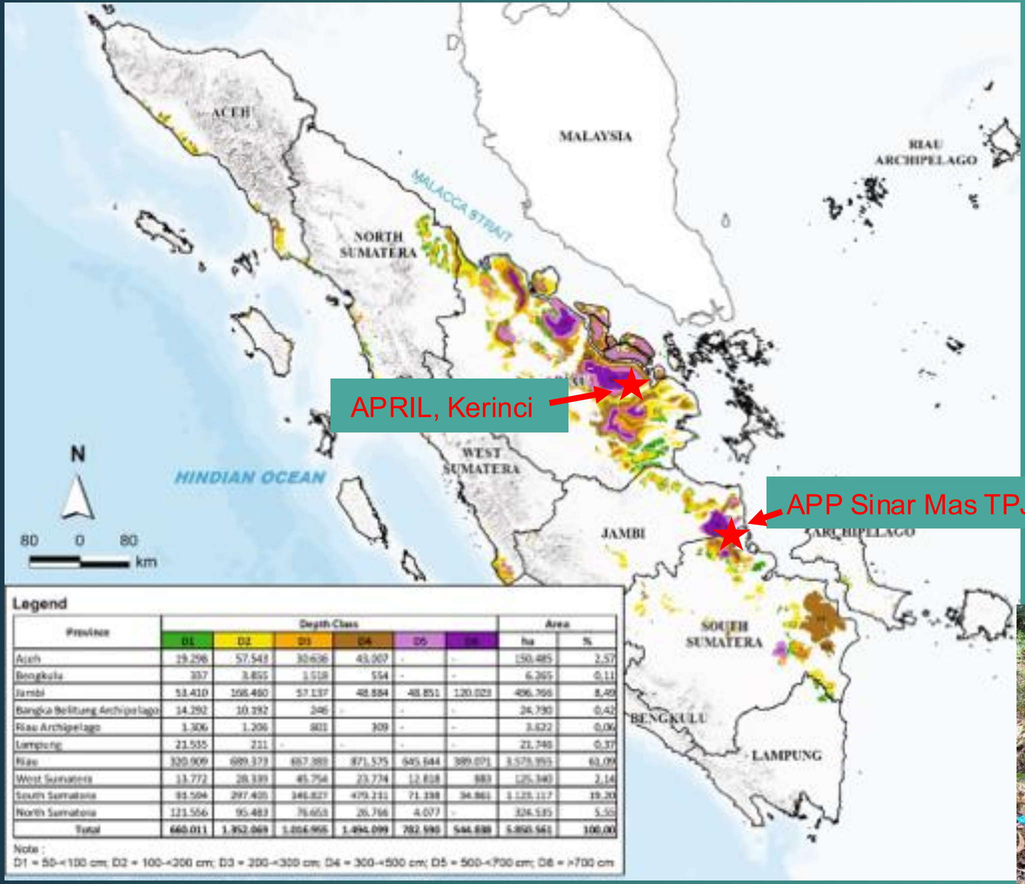


Vegetation

Peat

Porewater

Canals

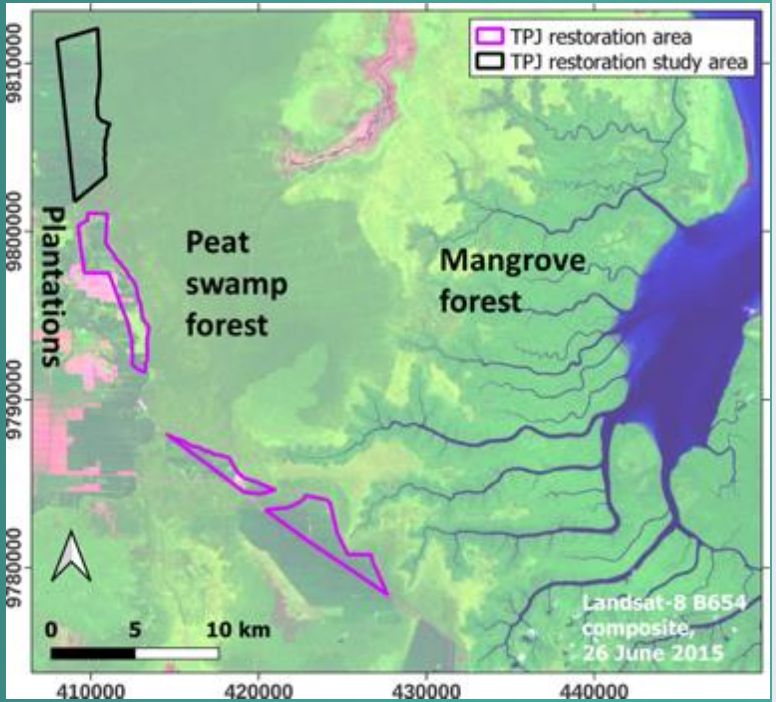


Province	Depth Class						Area	
	D1	D2	D3	D4	D5	D6	ha	%
Aceh	19.298	57.543	30.636	43.007	-	-	150.485	2,57
Bengkulu	337	3.855	1.518	554	-	-	6.265	0,11
Jambi	53.410	168.460	57.137	48.884	48.851	120.023	496.766	8,49
Bangka Belitung Archipelago	14.292	10.192	246	-	-	-	24.730	0,42
Riau Archipelago	1.306	1.206	801	309	-	-	3.622	0,06
Lampung	21.535	211	-	-	-	-	21.746	0,37
Riau	320.909	689.373	657.389	871.575	645.644	389.071	3.573.955	61,09
West Sumatera	13.772	28.339	45.754	23.774	12.818	883	125.340	2,14
South Sumatera	93.594	297.405	146.827	479.211	71.198	34.861	1.123.117	19,20
North Sumatera	121.556	95.483	76.653	26.766	4.077	-	324.535	5,55
Total	660.011	1.352.069	1.016.955	1.494.099	782.590	544.838	5.850.561	100,00

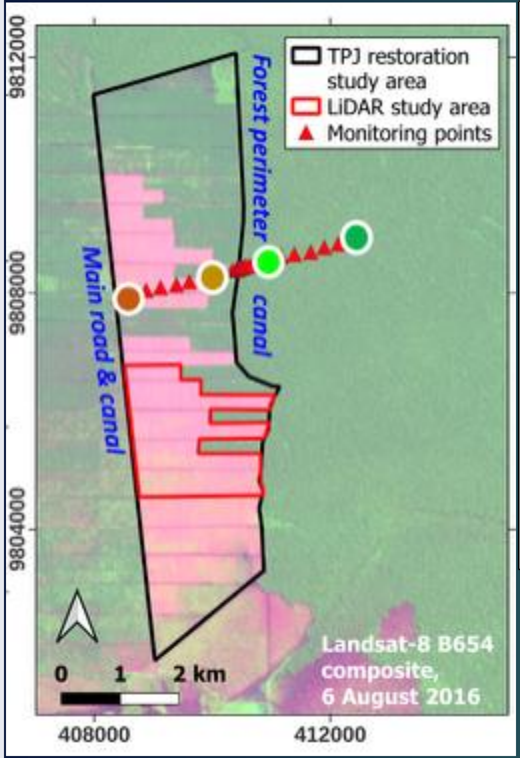
Note :
D1 = 50-<100 cm; D2 = 100-<200 cm; D3 = 200-<300 cm; D4 = 300-<500 cm; D5 = 500-<700 cm; D6 = >700 cm

Two study sites on the island of Sumatra, Indonesia

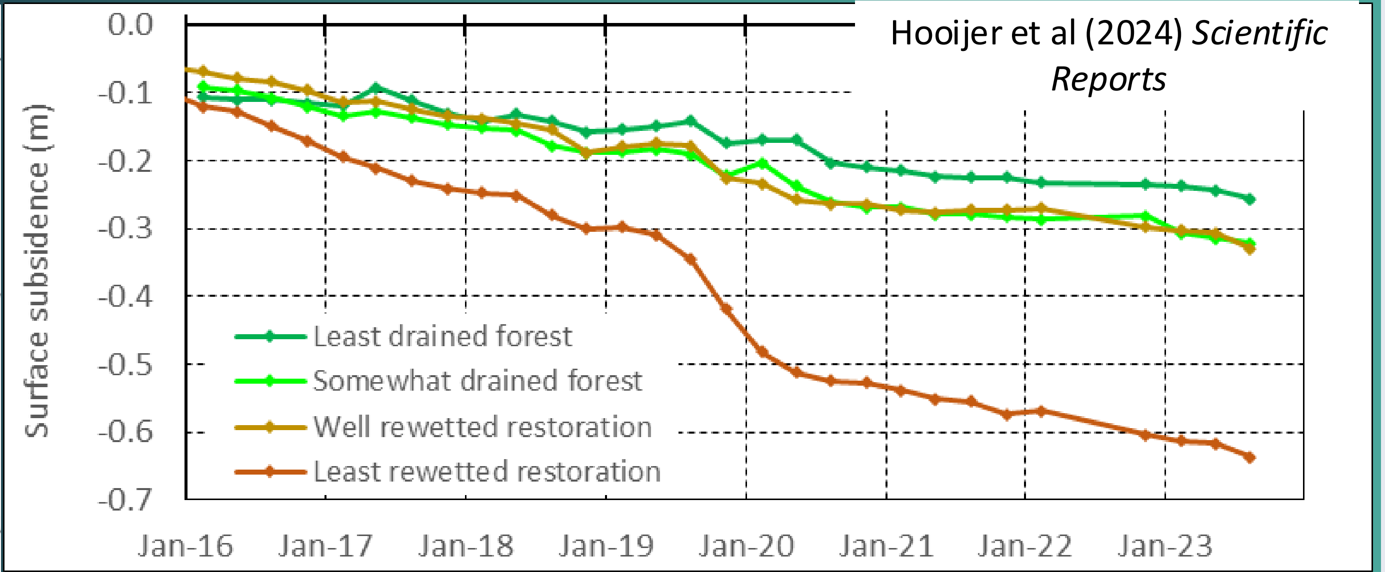
Research site in South Sumatra (TPJ) - Asia Pulp and Paper (APP) blocked drainage canals on area of recovering *Acacia* plantation, 2015 - INTPREP monitored surface subsidence, GWL and revegetation, and set up a mesocosm experiment



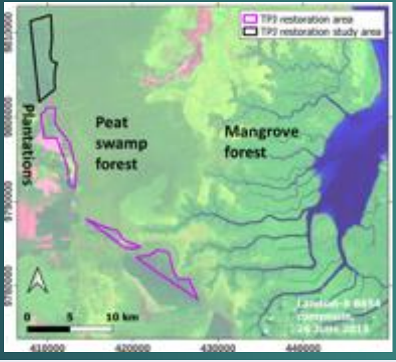
Around 8 yrs of peat subsidence (=shrinkage) data



Transect across retired, partially re-wetted plantation & adjoining forest



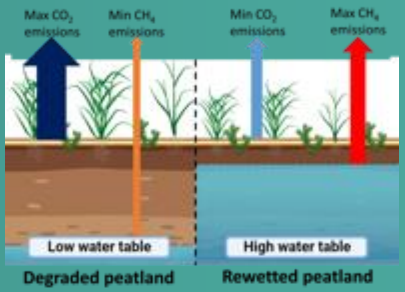
Hooijer et al (2024) *Scientific Reports*

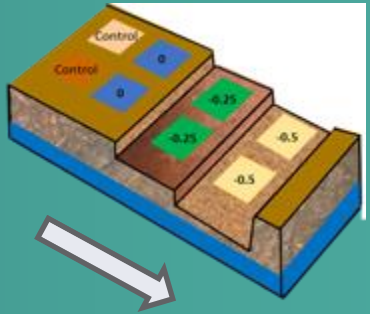


- Least rewetted restoration site
- Well rewetted restoration site
- Somewhat drained swamp forest
- Least drained swamp forest

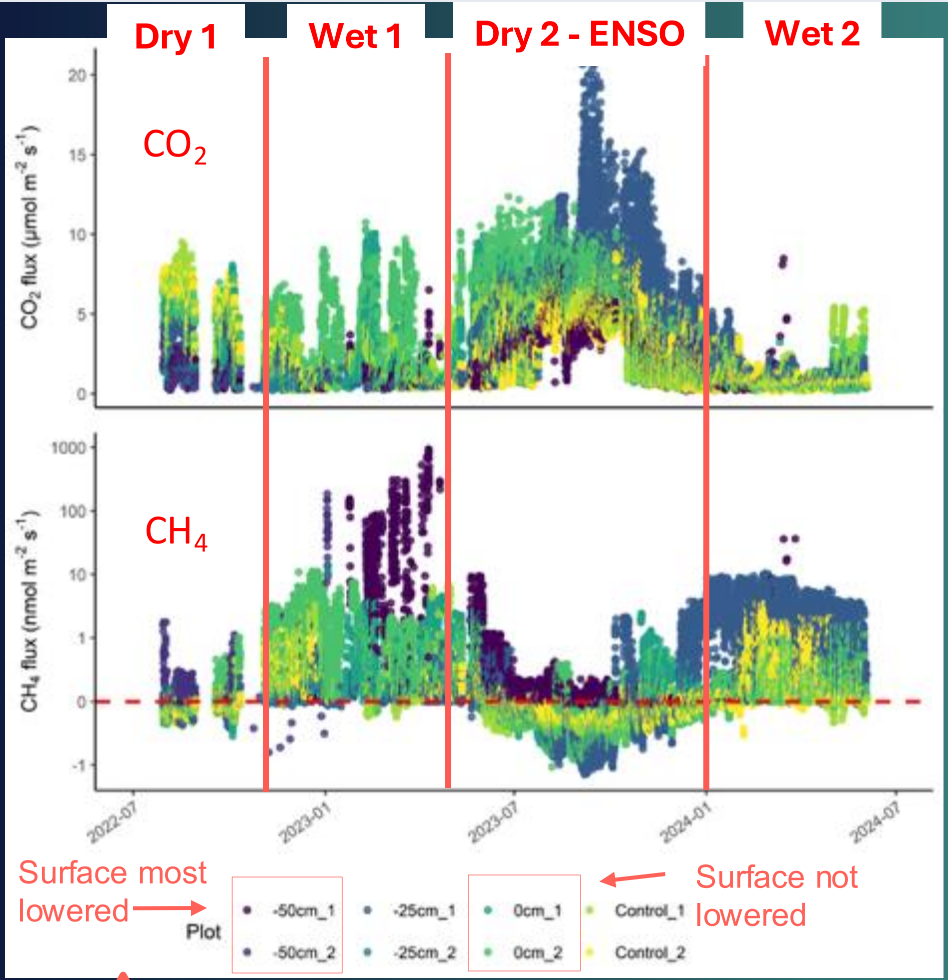
Subsidence can increase risks from rising sea level

Peatland Mesocosm Experiment – test effects GWL





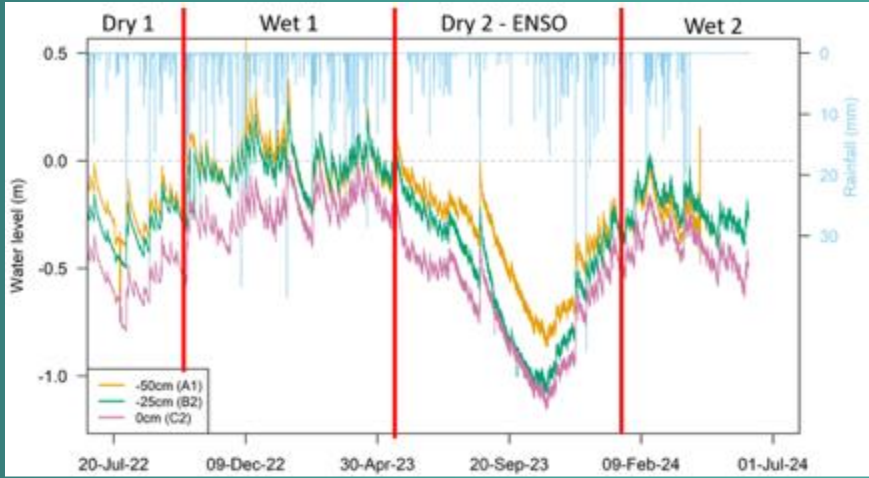
Control	Surface left intact, just cleared
0	Not lowered & top 0.25 m mixed
-0.25	Lowered 0.25m & top 0.25 m mixed
-0.5	Lowered 0.5m & top 0.25 m mixed



⚠ Log scale for CH_4

Taillardat et al (in prep)

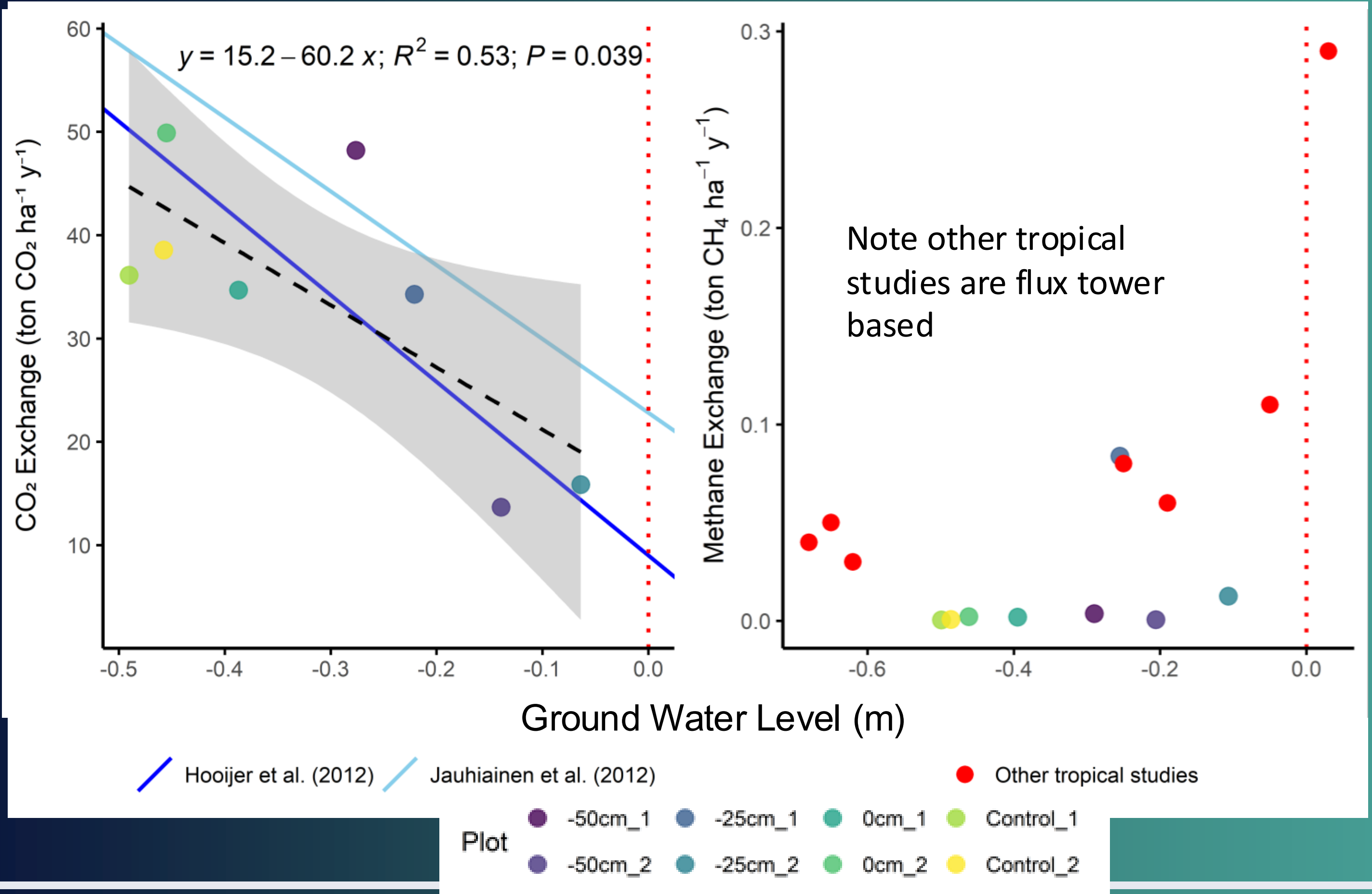
>140,000 individual CO_2 and CH_4 flux measurements (hourly data points) over 2 years.



Two clear wet and dry periods, including the **2023-2024 ENSO** (Dry 2).

Water Table Level oscillated from +0.4 m (Wet 1) to -1.25 m (ENSO – Dry 2).

Annual mean CO_2 and CH_4 exchange values v GWL (WTD)

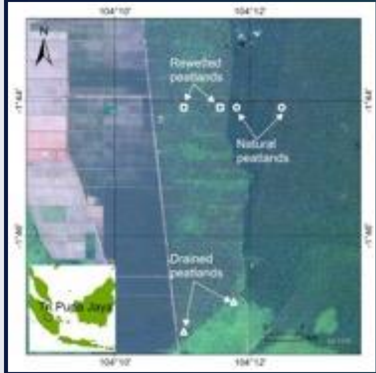


Can GWL predict annual greenhouse gas emissions from peat?

- Our study confirms the established **linear relationships between CO_2 exchange and GWL.**

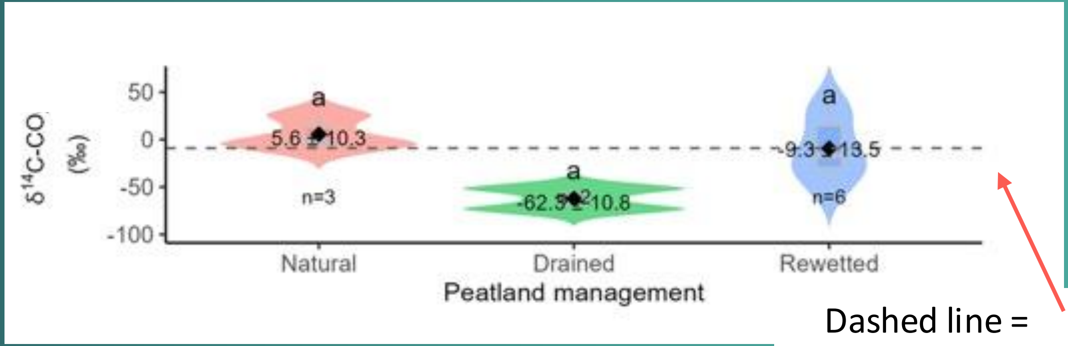
CH_4 - GWL relationship appears more complicated as our results do not match with previous values.

Determining the effects of plant roots, micro-variations in topography and rewetting on soil CO_2 (n = 1,245) and CH_4 (n = 767) effluxes and C age



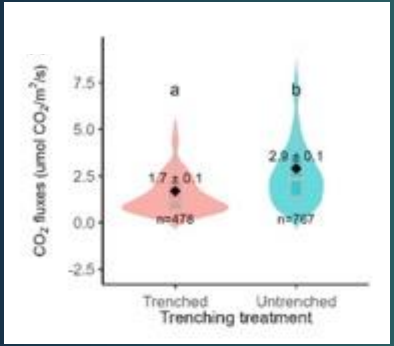
Trenched plot – isolates emissions from peat

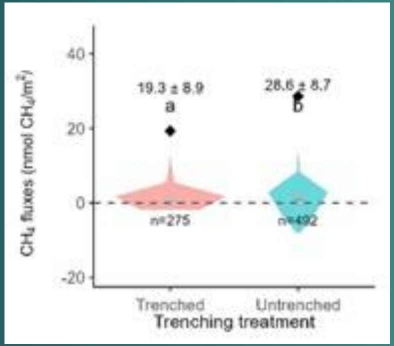
Drained peat emissions disproportionately old C (>500 yrs old) – CO_2 includes old C!



Dashed line = $\delta^{14}C$ of ambient air in PSF

Sasimato et al (in prep)





Trenching suppresses autotrophic inputs.

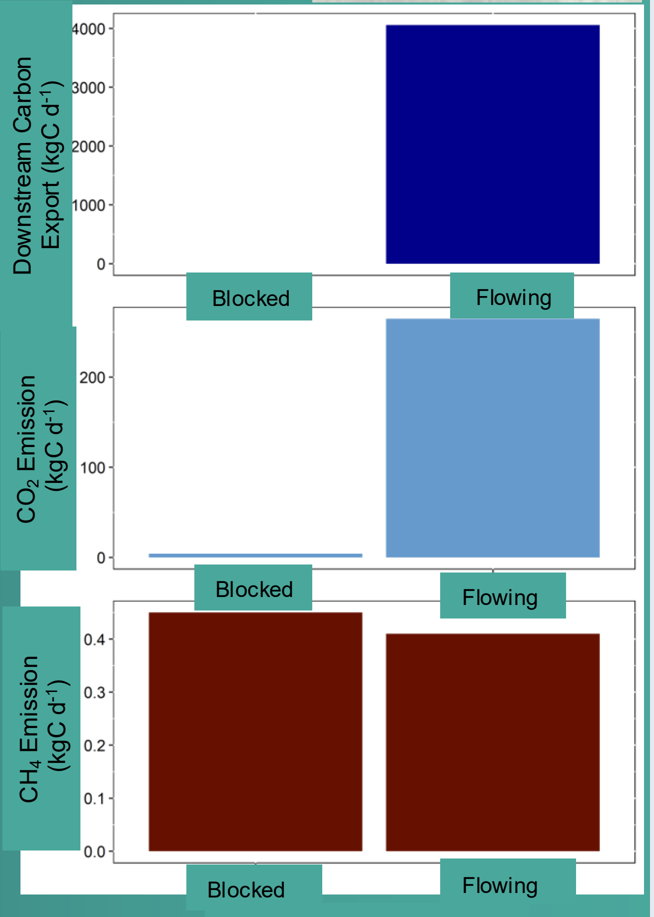
Results reveal importance of heterotrophic respiration (trenched plots) ~ decomposition and methanogenesis

CH_4 = more complex (root exudates imp)

Blocking effects quality and quantity of fluvial export & emissions of C

Blocked canal

Flowing canal



Average $F^{14}C$ age of CO_2 measured – **>500 yr BP**

Taillardat et al. (2025) *GRL*

Human cost of peatland restoration (climate change mitigation)

Yustina Octifanny, CGSEA PhD student

"The Katingan Peatland Restoration and Conservation Project … seeks to protect and restore 149,800 hectares of peatland ecosystems …. based on a solid business model."

PT. Rimba Makmur Utama Project Description (2016)

Ibu Remi, repsondent ~ Mentangiai, Kapuas, Central Kalimantan

Several major companies purchased **carbon credits** ~
Shell purchased more than US$ 9 million worth of credits …

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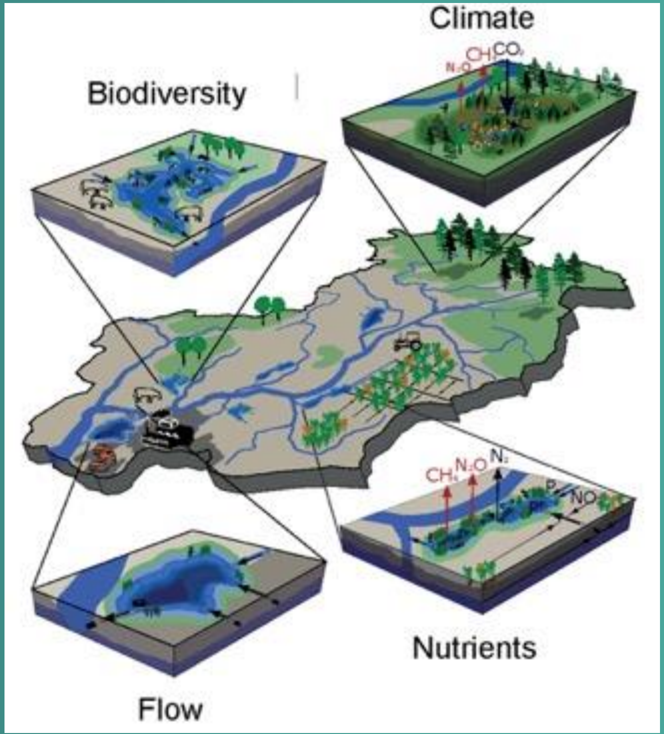
- Local communities forced to give up shifting cultivation
- Tree planting the only replacement livelihood - poorly paid (ca US$ 400 per year)
- Work largely done by women

Wetlands have **multiple functions** & **interconnected across scales**

To be **effective**, governance must reflect these realities – and ensure adaptive & equitable outcomes

Scale is critical – must accommodate multi-functionality and interconnectivity* e.g. by nesting

*includes telecoupling over large distances (wetlands as "*planetary commons*")



Landscape (e.g. "**wetlandscape**") scale of governance. Figure from Hambäck et al (2023) *SoTE*

- (Tropical) wetlands are critically important, nature-based carbon sinks, **storing immense stocks of irrecoverable carbon**
- They are dynamic social-ecological systems that provide ecosystem services beyond carbon (**notably food security**!)
- Whether wetlands contribute to/mitigate global climate change is in the balance, with **process-based understanding limited and high uncertainties** associated with current practices & knowledge levels – **especially regarding CH_4**!

Thank you!

NUS National University of Singapore | Department of Geography
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} Four main areas of research

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PhD scholarships available – application deadlines = 1 November and 15 May

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Geospatial Intelligence - new from August 2026

Minors
Aquatic Ecology, Geosciences, Geographical Information Systems, Urban Studies, Environmental Sustainability
Planned Second Majors:
Environmental Sciences for Sustainability; Urban Studies

New: *Accelerated ("3+1+1") programme* with East China Normal University

“Fieldwork is the jewel in the crown of geography”
Royal Geographical Society, UK

An ability to observe, measure, analyse and make sense of our surroundings and interactions is a key life skill!

The Department of Geography@NUS currently runs overseas field courses to:

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Thailand (GE3230A)
(west) Malaysia (ENV3102)
Cambodia (GE4221)
Kenya (GE4220)
Maldives (CCS5207)

Also, many courses involve Singapore-based field work

NUS Geography students enjoying a homestay in Cambodia