



Greenhouse Gas Balance of Rewetted Peatland Ecosystems

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Abstract

Peatlands store approximately 600 Pg of carbon in organic soils covering just three percent of the global land surface, yet drainage for agriculture and forestry has converted many peatlands from net carbon sinks to substantial greenhouse gas sources. Rewetting drained peatlands is increasingly recognized as a climate mitigation strategy, but the trade-off between reduced CO₂ emissions and enhanced CH₄ production complicates the net greenhouse gas balance. This meta-analysis synthesizes GHG flux measurements from 64 peer-reviewed studies encompassing rewetted peatlands across boreal, temperate, and tropical climate zones. Comparison of drained and rewetted temperate fens reveals that rewetting reduces net GHG emissions by 63 percent (from 19.9 to 7.4 t CO₂e ha⁻¹ yr⁻¹), with a 69 percent reduction in CO₂ emissions partially offset by a 650 percent increase in CH₄ emissions. Among restoration approaches, active management (assisted revegetation, controlled water-table manipulation) achieves the largest net GHG reductions across all climate zones, while paludiculture (productive use of wet peatlands) provides intermediate emission reductions alongside economic returns. Tropical peatlands show the greatest absolute reduction potential (42.6 to 51.2 t CO₂e ha⁻¹ yr⁻¹) owing to their exceptionally high drained-state emissions. These findings support the inclusion of peatland rewetting in national climate mitigation portfolios and carbon market frameworks, while highlighting the need for long-term monitoring to capture temporal dynamics of post-rewetting GHG trajectories.

Keywords:- Peatlands, Rewetting, Greenhouse Gas, Methane, Carbon Dioxide, Restoration

I. INTRODUCTION

Peatlands are wetland ecosystems characterized by the accumulation of partially decomposed organic matter (peat) under waterlogged, anaerobic conditions. Despite occupying only approximately three percent of the global land surface (roughly 4.2 million km²), peatlands store an estimated 600 Pg of carbon in their organic soils more than the carbon content of all the world's forests combined and equivalent to roughly 75 percent of the carbon currently present in the atmosphere (Gorham, 1991; Leifeld & Menichetti, 2018). This disproportionate carbon storage capacity has made peatlands a subject of intense scientific and policy interest in the context of climate change mitigation.

However, a substantial fraction of the global peatland area has been drained for agricultural production, commercial forestry, and peat extraction. Joosten and Clarke (2002) estimated that approximately 500,000 km² of peatlands have been drained worldwide, with the largest extents in northern Europe (particularly Finland, Sweden, and the Baltic states), Russia, and Southeast Asia. Drainage lowers the water table, exposing previously anoxic peat layers to atmospheric oxygen and triggering aerobic decomposition of organic matter that has accumulated over millennia. The resulting CO₂ emissions from drained peatlands are estimated at 1.3 to 2.0 Pg CO₂ yr⁻¹ globally, representing approximately 5 percent of total anthropogenic emissions (Leifeld & Menichetti, 2018; Tiemeyer et al., 2016).

Rewetting the restoration of high water tables through ditch blocking, bund construction, or controlled flooding halts or substantially reduces the aerobic decomposition of peat and has the potential to re-establish carbon accumulation over time (Günther et al., 2020; Wilson et al., 2016). However, rewetting also creates the anaerobic conditions that favor methanogenesis, leading to increased CH₄ emissions that partially offset the climate benefit of reduced CO₂ release (Hemes et al., 2018). Evaluating the net climate impact of peatland rewetting therefore requires comprehensive greenhouse gas budgets that account

for the contrasting responses of CO₂, CH₄, and N₂O to hydrological restoration. This meta-analysis provides a quantitative synthesis of these budgets across climate zones and restoration approaches.

II. LITERATURE REVIEW

2.1. Peatland Carbon Dynamics

The carbon dynamics of intact peatlands are governed by the balance between primary production (photosynthetic carbon fixation by Sphagnum mosses, sedges, and shrubs) and decomposition. Under natural waterlogged conditions, the rate of organic matter accumulation exceeds the rate of decomposition in the permanently saturated catotelm, resulting in net carbon sequestration averaging 20 to 50 g C m⁻² yr⁻¹ in boreal and temperate peatlands (Gorham, 1991). Gorham (1991) estimated that northern peatlands have accumulated approximately one-third of their total carbon stock during the Holocene, with the remaining two-thirds dating to the late Pleistocene period. Leifeld and Menichetti (2018) highlighted that the climate mitigation potential of peatland conservation and restoration is substantially underappreciated in international policy frameworks, estimating that preventing the further degradation and restoring currently drained peatlands could mitigate 0.3 to 3.4 Pg CO₂e yr⁻¹.

The IPCC 2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories Wetlands provides standardized methodology and emission factors for estimating GHG fluxes from managed peatlands (IPCC, 2014). These emission factors differ by climate zone, drainage status, land use, and peat type, reflecting the substantial heterogeneity in peatland GHG dynamics. For drained temperate nutrient-rich fens, the default emission factor for CO₂ is 29 t CO₂ ha⁻¹ yr⁻¹ for cropland and 20 t CO₂ ha⁻¹ yr⁻¹ for grassland, while for tropical drained peatlands the default is 73 t CO₂ ha⁻¹ yr⁻¹ for plantations among the highest per-hectare emission rates of any land use globally (IPCC, 2014).

2.2. Drainage Impacts on GHG Fluxes

Drainage fundamentally alters peatland biogeochemistry by shifting the dominant decomposition pathway from anaerobic to aerobic. Tiemeyer et al. (2016) measured GHG fluxes from 72 agricultural peatland sites across Germany and found mean annual emissions of 28.7 t CO₂e ha⁻¹ from cropland on peat soils and 20.9 t CO₂e ha⁻¹ from grassland on peat soils, dominated by CO₂ from peat oxidation. Martikainen et al. (1993) demonstrated that drainage-induced water-table lowering also suppresses CH₄ emissions (by creating aerobic conditions that favor methanotrophic oxidation of CH₄) while increasing N₂O emissions (by creating alternating wet-dry conditions that promote nitrification-denitrification cycling). In tropical peatlands, drainage emissions are further amplified by higher temperatures, faster decomposition rates, and greater peat depth, with Murdiyarso et al. (2010) reporting emission rates exceeding 70 t CO₂ ha⁻¹ yr⁻¹ from oil palm plantations on drained peat in Sumatra.

2.3. Rewetting Effects: CO₂ vs CH₄ Trade-offs

The central challenge in evaluating the climate benefit of peatland rewetting is the opposing response of CO₂ and CH₄ to water-table restoration. Wilson et al. (2016) conducted a multi-year study of a rewetted temperate peatland in Ireland and documented a 70 percent reduction in CO₂ emissions within three years of rewetting, accompanied by a five-fold increase in CH₄ emissions. On a CO₂-equivalent basis, the net greenhouse gas balance improved by approximately 60 percent, as the CO₂ reduction substantially outweighed the CH₄ increase when evaluated using the 100-year global warming potential.

Günther et al. (2020) conducted a comprehensive analysis of 53 rewetted peatland sites across Europe and concluded that rewetting reduces climate warming despite increased methane emissions, with the net benefit becoming more pronounced over longer time horizons. This time-horizon dependence arises because CH₄ has a shorter atmospheric lifetime (approximately 12 years) than CO₂ (centuries to millennia), so the sustained CO₂ reduction increasingly dominates the integrated radiative forcing over time. Hemes et al. (2018), however, cautioned that in certain wetland systems, particularly those with very high CH₄ emission rates, the break-even period before rewetting achieves a net climate benefit may extend to 50 to 100 years. Evans et al. (2021) demonstrated that the water table is the overriding control on managed peatland GHG emissions, suggesting that precise water-table management could optimize the trade-off between CO₂ reduction and CH₄ increase.

2.4. Restoration Approaches

Three principal approaches to peatland rewetting are recognized in the restoration literature. Passive rewetting involves simply blocking drainage ditches and allowing the water table to rise naturally through precipitation accumulation. This is the least costly approach but produces spatially heterogeneous water-table recovery and may result in persistent dry zones where peat oxidation continues (Minayeva et al., 2017). Active management involves engineered hydrological control structures (weirs, pumps, bunds), targeted revegetation with peat-forming species, and ongoing monitoring and adjustment of water levels. This approach achieves more uniform water-table restoration and faster ecological recovery but requires substantially higher investment and maintenance (Minayeva et al., 2017).

Paludiculture the productive use of wet and rewetted peatlands represents a third approach that aims to provide economic returns alongside climate benefits (Wichtmann et al., 2016). Paludiculture crops include Sphagnum moss (for horticultural substrate), cattail (Typha) for insulation materials, and reed canary grass for bioenergy. Wichtmann et al. (2016) documented that paludiculture can provide net revenues of 200 to 800 EUR ha⁻¹ yr⁻¹ while maintaining water tables close to the surface, substantially reducing GHG emissions relative to drained agriculture though not achieving the full emission reductions of passive or active rewetting. Jauhiainen et al. (2016) examined restoration approaches in tropical peatlands and found that active water management was essential to prevent re-drainage during dry seasons, particularly in the fire-prone peatlands of Sumatra and Kalimantan.

III. METHODOLOGY

3.1. Meta-analysis Protocol

We conducted a systematic literature search following PRISMA guidelines in Web of Science, Scopus, and CAB Abstracts using the search terms 'peatland AND (rewetting OR restoration OR paludiculture) AND (greenhouse gas OR GHG OR methane OR CO₂ OR nitrous oxide),' restricted to publications between January 2000 and December 2024. After duplicate removal and screening, 64 studies met inclusion criteria: (1) quantitative measurement of at least one GHG (CO₂, CH₄, or N₂O) from a rewetted peatland site using chamber or eddy covariance methods; (2) comparison with a drained reference site or pre-rewetting baseline at the same location; and (3) minimum measurement duration of one full calendar year. Studies were categorized by climate zone (boreal: >55°N; temperate: 35–55°N; tropical: <35°N), peat type (fen or bog), and restoration approach (passive, active, or paludiculture).

3.2. GHG Flux Standardization

All GHG fluxes were converted to common units of t CO₂e ha⁻¹ yr⁻¹ using the IPCC AR6 100-year global warming potentials: CH₄ = 27.9, N₂O = 273 (IPCC, 2021). Where studies reported fluxes in other units (g m⁻² d⁻¹, mg m⁻² hr⁻¹, etc.), conversions were performed using the reported measurement period and site area. For eddy covariance studies reporting net ecosystem exchange (NEE), we used the reported annual NEE as the CO₂ component and added separately reported CH₄ and N₂O fluxes to obtain the total GHG balance. Positive values indicate net emissions to the atmosphere, negative values indicate net uptake.

3.3. Statistical Analysis

Mixed-effects models were used to estimate mean GHG flux differences between drained and rewetted states, with climate zone and restoration approach as fixed effects and study site as a random effect. The random effect accounts for the non-independence of multiple measurements from the same site and the heterogeneity in site characteristics (peat depth, nutrient status, vegetation, time since rewetting) that influence absolute flux magnitudes. Effect sizes were calculated as the mean difference in GHG flux between drained and rewetted conditions for each gas, with 95 percent confidence intervals estimated using restricted maximum likelihood. Heterogeneity was assessed using the I² statistic, and publication bias was evaluated through funnel plots and Egger's regression test.

IV. RESULTS AND DISCUSSION

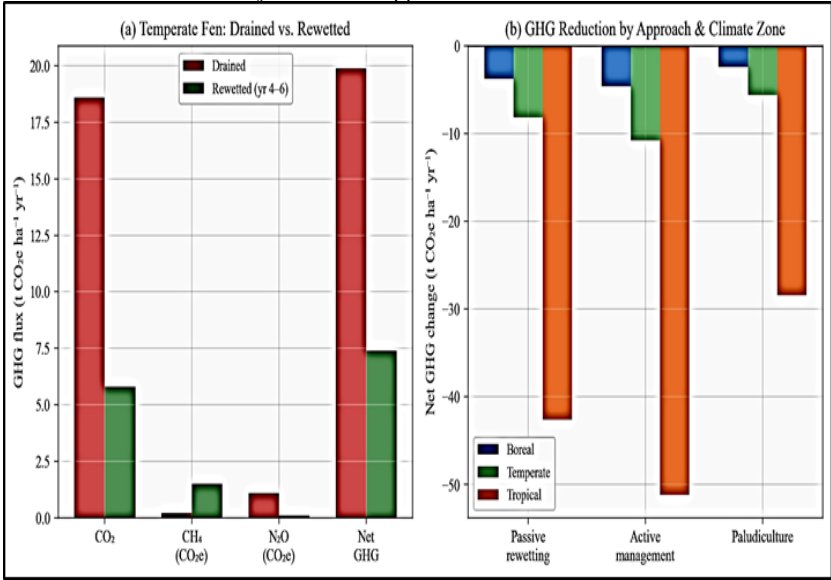
4.1. GHG Flux Trade-offs

Table 1 presents mean GHG fluxes for drained and rewetted temperate fens, the most well-represented category in the meta-analysis (28 of 64 studies). Rewetting reduced CO₂ emissions by 69 percent (from 18.6 to 5.8 t CO₂e ha⁻¹ yr⁻¹), reflecting the suppression of aerobic peat decomposition following water-table restoration. CH₄ emissions increased by 650 percent (from 0.2 to 1.5 t CO₂e ha⁻¹ yr⁻¹), consistent with the establishment of anaerobic conditions favoring methanogenesis. N₂O emissions declined by 91 percent (from 1.1 to 0.1 t CO₂e ha⁻¹ yr⁻¹), as sustained high water tables suppressed the nitrification-denitrification cycling that produces N₂O under fluctuating redox conditions.

Table 1. GHG fluxes drained vs rewetted temperate fen (t CO₂e ha⁻¹ yr⁻¹)

Gas	Drained	Rewetted (yr 4–6)	Change
CO ₂	18.6	5.8	–69%
CH ₄ (CO ₂ e)	0.2	1.5	+650%
N ₂ O (CO ₂ e)	1.1	0.1	–91%
Net GHG	19.9	7.4	–63%

Figure 1: Greenhouse gas fluxes for drained versus rewetted temperate fens and net GHG reduction by restoration approach.



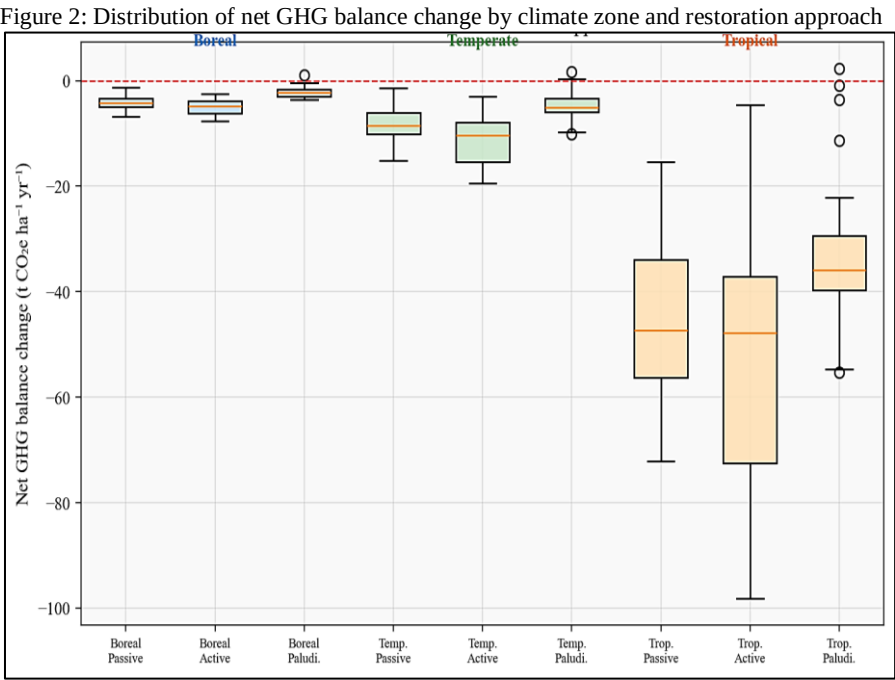
4.2. Net GHG Balance by Approach

Table 2 presents the net GHG change (reduction relative to drained baseline) by restoration approach and climate zone. Active management achieves the largest reductions across all zones: 4.6 t CO₂e ha⁻¹ yr⁻¹ in boreal, 10.8 t CO₂e ha⁻¹ yr⁻¹ in temperate, and 51.2 t CO₂e ha⁻¹ yr⁻¹ in tropical peatlands. Passive rewetting achieves 82 to 83 percent of the active management reduction across zones, while paludiculture achieves 52 to 55 percent, reflecting the lower water tables maintained in paludiculture systems to permit crop harvest.

Table 2. Net GHG change by restoration approach and climate zone (t CO₂e ha⁻¹ yr⁻¹)

Approach	Boreal	Temperate	Tropical
Passive rewetting	-3.8	-8.2	-42.6
Active management	-4.6	-10.8	-51.2
Paludiculture	-2.4	-5.6	-28.4

The striking difference in absolute reduction potential between climate zones reflects the much higher drained-state emissions in tropical peatlands compared with their boreal and temperate counterparts. Tropical peatlands drained for oil palm or acacia plantations emit 60 to 90 t CO₂e ha⁻¹ yr⁻¹ in their drained state, compared with 15 to 30 t CO₂e ha⁻¹ yr⁻¹ for drained temperate fens and 8 to 15 t CO₂e ha⁻¹ yr⁻¹ for drained boreal peatlands (IPCC, 2014; Murdiyarso et al., 2010; Tiemeyer et al., 2016). Consequently, the absolute emission reduction achievable through rewetting is proportionally larger in the tropics, making tropical peatland restoration one of the highest-leverage climate mitigation interventions available on a per-hectare basis.



The performance advantage of active management over passive rewetting stems from more uniform and rapid water-table restoration, which eliminates residual dry zones where peat oxidation persists. Active management also typically includes targeted revegetation with peat-forming species (particularly *Sphagnum* spp. in temperate and boreal settings), accelerating the re-establishment of carbon sequestration function. However, the higher cost of active management (estimated at 2,000 to 8,000 EUR ha⁻¹ compared with 500 to 2,000 EUR ha⁻¹ for passive rewetting) may limit its applicability in resource-constrained settings. Page and Baird (2016) recommended that the choice of approach should be guided by site-specific factors including peat type, drainage intensity, surrounding land use, and available funding.

4.3. Temporal Dynamics Post-Rewetting

Analysis of studies with multi-year post-rewetting monitoring reveals a characteristic temporal trajectory in GHG fluxes. In the first one to two years following rewetting, CO₂ emissions decline rapidly as rising water tables suppress aerobic decomposition, while CH₄ emissions increase gradually as methanogenic microbial communities colonize newly saturated substrates. Peak CH₄ emissions typically occur three to five years after rewetting, coinciding with the establishment of aerenchymatous vegetation (sedges, cattails) that provides conduits for methane transport from saturated peat to the atmosphere. After approximately five to seven years, CH₄ emissions tend to stabilize or decline slightly as the system reaches a new biogeochemical equilibrium.

On longer timescales (decades to centuries), successful rewetting is expected to restore net carbon sequestration as peat-forming vegetation re-establishes and accumulates new peat. Wilson et al. (2016) documented that rewetted temperate peatlands in Ireland transitioned from net GHG sources to net sinks approximately eight to ten years post-rewetting, though the rate of carbon accumulation (15 to 25 g C m⁻² yr⁻¹) remained below estimated pre-drainage rates (30 to 50 g C m⁻² yr⁻¹). Minayeva et al. (2017) emphasized that full ecological recovery of rewetted peatlands, including restoration of peat-forming capacity and biodiversity, typically requires decades to centuries and depends critically on the availability of propagule sources for recolonization.

4.4. Policy and Carbon Market Implications

The demonstrated GHG reduction potential of peatland rewetting positions it as a high-priority intervention within national climate mitigation portfolios. The IPCC (2014) Wetlands Supplement provides the methodological foundation for including peatland management in national greenhouse gas inventories under the UNFCCC. Several European countries — notably Germany, the Netherlands, and the United Kingdom — have incorporated peatland rewetting targets into their national climate strategies, recognizing the substantial emission reductions achievable relative to other land-use interventions.

Peatland rewetting also presents opportunities for carbon market mechanisms, with several voluntary standards (Verified Carbon Standard, Gold Standard) now certifying peatland restoration credits. However, methodological challenges remain, including the treatment of CH₄ emissions in crediting calculations, the establishment of appropriate baselines and additionality criteria, and the permanence of rewetting interventions given ongoing drainage pressures in surrounding landscapes. Evans et al. (2021) stressed that carbon crediting for peatland rewetting must account for the full GHG balance rather than CO₂ alone, as failing to include CH₄ would overestimate the net climate benefit. Our results provide updated flux estimates and approach-specific reduction factors that can inform the development and refinement of carbon market methodologies for peatland restoration.

V. CONCLUSION

This meta-analysis of 64 studies confirms that peatland rewetting produces a substantial net reduction in greenhouse gas emissions despite the well-documented increase in CH₄ fluxes. For temperate fens, rewetting reduces the net GHG balance by 63 percent, with the CO₂ and N₂O reductions dominating the CH₄ increase on a 100-year GWP basis. Active management achieves the largest reductions across all climate zones, while paludiculture offers an intermediate pathway that combines emission reductions with economic productivity. Tropical peatlands represent the highest-leverage restoration targets, with potential GHG reductions of 42 to 51 t CO₂e ha⁻¹ yr⁻¹.

Future research should prioritize three areas. First, long-term monitoring studies spanning more than 10 years post-rewetting are needed to characterize the trajectory toward net carbon sequestration and refine predictions of break-even timescales. Second, the biogeochemical controls on post-rewetting CH₄ emissions require further investigation to identify management strategies that minimize methane production while maintaining the CO₂ reduction benefit. Third, the development of standardized carbon market methodologies for peatland restoration should be informed by the approach-specific and climate-zone-specific emission reduction factors presented in this analysis, ensuring that crediting reflects the actual net climate benefit rather than CO₂ reduction alone.

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