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Earth's Future

RESEARCH ARTICLE

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Key Points:

- Wetland restoration increases methane emissions, but enhances carbon sequestration and avoids emissions from drained soils
- Globally, restored wetlands reduce net greenhouse gas emissions compared with protecting existing wetlands alone
- Overall temperature effects are modest: carbon gains outweigh methane increases, producing a small net cooling by 2100

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

R. L. Wagner and M. V. Martin,
r.wagner@sheffield.ac.uk;
m.valmartin@sheffield.ac.uk

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Greenhouse Gas and Climate Effects of Global Wetland Restoration Under Future Warming

R. L. Wagner¹ , J. Weber² , P. O. Hopcroft³ , E. Fluet-Chouinard⁴ , D. J. Beerling¹ , and M. Val Martin¹ 

¹Leverhulme Centre for Climate Change Mitigation, School of Biosciences, University of Sheffield, Sheffield, UK,

²Department of Meteorology, University of Reading, Reading, UK, ³Earth System Science Division, Pacific Northwest National Laboratory, Richland, WA, USA, ⁴School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

Abstract Wetland restoration is a promising nature-based climate solution because it enhances carbon sequestration and avoids carbon dioxide (CO₂) emissions from drained soils. However, wetlands also emit methane (CH₄), which can offset these benefits. The combined impacts of wetland protection and restoration and climate-driven changes on global wetland GHG budgets remain poorly quantified. Here, we estimate CO₂ and CH₄ fluxes from drained and restored wetlands, and their climate impacts, using historically reconstructed wetland area, outputs from eight CMIP6 Earth System Models and the FaIR reduced-complexity climate model. We compare protection of present-day wetlands with restoration of historically drained wetlands by 2050, under two contrasting warming pathways. By 2100, global wetland CH₄ emissions increase by 11%–57% across scenarios, with the largest rise under high warming and restoration. Restoration strengthens carbon sequestration and avoids ongoing emissions from drained soils, improving the net ecosystem carbon balance by 0.4–0.6 Gt C yr^{−1}, equivalent to a mitigation potential of 1.6–2.3 Gt CO₂ yr^{−1}. Accounting for CH₄ warming, restoration reduces net GHG fluxes by up to 0.5 Gt CO₂-eq yr^{−1} relative to protection alone. Carbon gains dominate in the Northern Hemisphere, whereas enhanced CH₄ partially offset benefits in tropical and Southern Hemisphere regions. Climate simulations indicate that increased CO₂ uptake and avoided drainage emissions offset higher CH₄ emissions, producing a small net cooling (−0.03 to −0.007°C). Overall, large-scale wetland restoration provides clear carbon and GHG benefits, though the global temperature impact is modest, highlighting the importance of CO₂-CH₄ trade-offs.

Plain Language Summary Wetlands play an important role in the global carbon cycle and are an important ecosystem for biodiversity. When wetlands are drained, large amounts of carbon can be released to the atmosphere as carbon dioxide (CO₂). Restoring wetlands can stop these emissions and re-establish the carbon store. However, wetlands also naturally release methane (CH₄), a powerful greenhouse gas, which creates uncertainty about the overall climate benefit of wetland restoration. In this study, we used climate models to estimate how protecting existing wetlands and restoring previously drained wetlands could affect global greenhouse gas emissions. We found that restoration increases methane emissions, but it also increases carbon storage and prevents emissions from drained soils. As a result, large-scale wetland restoration would reduce global greenhouse gas emissions and produce a small cooling effect on global temperature. These findings show that wetland restoration can contribute to climate mitigation, although its global temperature impact is relatively modest.

1. Introduction

Climate change is an urgent and growing threat to both humans and the environment. In 2015, the Paris Climate Agreement established a global target to limit global warming to well below 2°C and preferably to 1.5°C, above pre-industrial levels. However in 2024, global average temperatures exceeded the 1.5°C threshold (Copernicus Climate Change Service, 2025), highlighting the urgent need for climate action. According to the IPCC 6th Assessment Report (IPCC, 2023), achieving net zero targets will require drastic reductions in greenhouse gas (GHG) emissions alongside large-scale implementation of carbon dioxide (CO₂) removal (CDR) strategies.

Nature-based climate solutions are increasingly recognised as essential to these mitigation efforts, offering opportunities to store carbon while improving biodiversity and delivering ecosystem services (Cohen-Shacham et al., 2016). Among them, wetland restoration and protection have emerged as promising land-based strategies

(Griscom et al., 2017). Although wetlands cover only approximately 6% of the Earth's land surface, they store an estimated 30% of the world's soil carbon (Stewart et al., 2024) and their restoration can enhance carbon sequestration alongside improved biodiversity, water filtration and flood protection (Robertson et al., 2025). Wetlands are critical natural CO₂ sinks. Between 2000 and 2020, global wetlands have been estimated to sequester about 1004 Tg C yr⁻¹, with 70% occurring in tropical wetlands (J. Li et al., 2025). However, declines in tropical and southern wetland carbon sequestration have offset gains in northern regions, resulting in a roughly stable global sink over the past two decades (J. Li et al., 2025) and highlighting the vulnerability of wetland carbon sequestration under climate stress.

Despite their importance, wetlands are among the most threatened ecosystems globally. Since 1700, an estimated 3.4 million km² (Mkm²) of wetlands have been lost, primarily for conversion to croplands (Fluet-Chouinard et al., 2023a). Additional pressures such as groundwater extraction, fire and infrastructure development continue to degrade remaining wetlands (Van Asselen et al., 2013). Drainage of wetlands exposes soil organic carbon to oxidation, leading to GHG emissions. Drained peatlands are estimated to release about 2 Gt CO₂ per year (Bonn et al., 2016), as the carbon pool becomes exposed above the water table and starts to decompose. Therefore, restoring wetlands offers a dual benefit as it halts ongoing emissions from drained soils and re-establishes CO₂ sequestration capacity and other ecological functions.

However, wetlands are also the largest natural source of methane (CH₄), a potent GHG with a global warming potential (GWP) 27 times greater than CO₂ over a 100 year period, and up to 80 times greater over a 20-year period (IPCC, 2023). Wetlands contributed approximately 159 Tg yr⁻¹ of CH₄ in 2010–2019, over half of natural and nearly a quarter of total (natural and anthropogenic) CH₄ emissions (Saunio et al., 2024). CH₄ is produced in wetlands via microbial methanogenesis in water-saturated, oxygen-poor soils, which is a process highly sensitive to temperature and hydrological conditions (Whalen, 2005). Since the pre-industrial period, the increase in atmospheric CH₄ concentrations from both natural and anthropogenic sources has driven a surface warming two thirds of that caused by CO₂ concentration increases over the same period (IPCC, 2023). Alongside its direct warming potential, CH₄ oxidation plays an important role in atmospheric chemistry (Holmes, 2018) by contributing to the formation of tropospheric ozone (West & Fiore, 2005), an air pollutant that affects both air quality and climate. Over recent decades, wetlands have been found to be a direct contributor to the rapid growth in atmospheric CH₄ levels (Ciais et al., 2026; Nisbet et al., 2023), and their contribution could increase further under projected future warming.

Future climate warming is expected to amplify wetland CH₄ emissions (Zhang et al., 2025), potentially offsetting the climate benefits of enhanced CO₂ uptake. Recent model and data-driven studies have projected increases in global wetland CH₄ emissions of 13%–50% by 2100, with end-of-century values ranging from 166 to 222 Tg CH₄ yr⁻¹ depending on the warming scenario (Chen et al., 2024; Folberth et al., 2025; Koffi et al., 2020; Shindell et al., 2013; Zhang et al., 2017). These increases are larger in high-latitude and equatorial regions, driven by warming, productivity gains and expanded inundation (Chen et al., 2024; Zhang et al., 2017).

The net climate effect of wetland restoration has also been explored (Günther et al., 2020; Schuster et al., 2024; Zou et al., 2022), with most studies concluding that avoided CO₂ emissions from re-wetting drained wetlands outweigh CH₄ emissions, resulting in a net climate benefit. For example, Zou et al. (2022) estimated that continued wetland degradation could result in cumulative emissions equivalent to approximately 408 Gt CO₂ by 2100, whereas rewetting could substantially reduce these emissions by restoring CO₂ uptake. Similarly, Günther et al. (2020) demonstrated that peatland restoration halts CO₂ emissions from drained soils and reduces overall radiative forcing, whilst Schuster et al. (2024) showed that wetland restoration can convert degraded wetlands from net carbon sources into carbon sinks, particularly in Northern Hemisphere peatlands. However, previous studies have assessed either climate-driven CH₄ increases or restoration effects in isolation, without evaluating the combined impacts on global wetland GHG budgets. Given the urgent need for scalable nature-based climate solutions, a robust understanding of the CH₄–CO₂ trade-off under future warming and land-use pathways is critical for evaluating the risks and mitigation potential of wetland restoration.

In this study, we assess the combined impacts of large-scale wetland protection and restoration under two contrasting climate futures (SSP1-2.6 and SSP3-7.0) on net wetland GHG emissions. We develop two global wetland scenarios based on a historical reconstruction of wetland area, where restoration represents the recovery of historically drained wetlands to their natural condition. Using an ensemble of eight CMIP6 Earth System Models

and process-based emission schemes, we calculate CH₄ emissions and CO₂ sequestration of wetlands and account for avoided CO₂ emissions from drained wetland restoration. We then quantify the net carbon and GHG implications using the net ecosystem balance (NECB), net GHG fluxes (in CO₂-equivalents) and the FaIR reduced-complexity climate model. This multi-species analysis provides a global assessment of the climate trade-offs associated with wetland protection and restoration under contrasting land-use and warming pathways.

2. Development of Future Wetland Scenarios

Accurate land-use scenarios of wetland expansion are essential to assess the climate impacts of restoration and protection strategies. However, most Earth System Models (ESMs) do not explicitly represent wetlands as a distinct plant functional type, although some models include peatland representation (Qiu et al., 2018). In most ESMs, wetlands are represented hydrologically by assigning a “wet” fraction to each grid cell, so their extent is determined by inundation rather than plant functional type or historical conditions. This limits their ability to explore the effects of anthropogenic drainage, restoration, or protection on GHG emissions and CO₂ storage. Moreover, prognostic simulations of wetland extent in ESMs remain highly uncertain, particularly over historical timescales (Melton et al., 2013), which further limits our ability to assess wetland restoration dynamically in ESMs.

To address this limitation and explore the impacts of wetland management on GHG emissions, we developed two global scenarios of future wetland area, “Protection” and “Restoration,” based on the historical wetland reconstruction of Fluet-Chouinard et al. (2023a). This data set provides estimates of decadal maximum wetland area between 1700 and 2020 and combining simulated wetland extents with historical land-use data to quantify cumulative wetland loss due to drainage and conversion over time. We used the gridded reconstruction based on the Wetland Area and Dynamics for Methane Modelling (WAD2M) data set (Zhang et al., 2021) as the present-day wetland map baseline. WAD2M estimates wetland extent by combining satellite observations of surface water with land cover data.

We derived a historical time series of monthly wetland extent from 1900 to 2020 by interpolating the decadal maximum area estimates and scaling them relative to the WAD2M climatology. WAD2M provided a monthly climatology to represent seasonal inundation dynamics, while the decadal loss estimates were used to apply proportional reductions in wetland extent for earlier decades. Our approach produced a gridded monthly wetland extent back to 1900 that incorporates both historical anthropogenic drainage and seasonal hydrological variability, making it suitable for modeling CH₄ fluxes and CO₂ sequestration potential. Using monthly, rather than maximum inundation data identifies areas that are hydrologically suitable for restoration, which is important under future warming conditions.

Figure 1 presents the spatial and temporal characteristics of these scenarios. The Protection scenario assumes that 2019–2020 wetland area is maintained through to 2100 (4.5 Mkm² total area), with no additional drainage or expansion, representing a policy trajectory in which all remaining wetlands are preserved, but no large-scale restoration efforts are undertaken.

In the Restoration scenario, global wetland extent increases gradually from 2019 levels to pre-drained 1900 extent (average of 1900–1910) by 2050 (5.3 Mkm² total area). This corresponds to the restoration of approximately 0.8 Mkm² of drained wetlands globally, implemented at a rate of ~26,000 km² yr⁻¹. Restoration occurs linearly and uniformly across all areas that were identified as wetlands in 1900, with no regional variation in the timing of restoration. After 2050, restored wetlands are preserved until 2100. We did not consider wetlands drained prior to 1900 as restorable, to ensure the scenario represents a feasible restoration strategy based on historical land-use. In addition, we did not account for current land uses and assumed restoration of all 1900 drained areas.

To assess potential future conflict between land demand and wetland restoration, we overlaid cropland distributions in SSP1-2.6 and SSP3-7.0 with our mapped restoration area. We estimate that approximately 5% (SSP1-2.6) and 4% (SSP3-7.0) of the proposed restoration area overlaps with croplands by 2100, indicating limited direct competition with croplands at the global scale.

The global wetland cover in 2019 (Protection scenario, Figure 1b) is concentrated in tropical regions, such as the Amazon, Congo Basin and Southeast Asia, as well as high latitudes like Northern Canada and Siberia. In the Restoration scenario (Figure 1c), newly restored wetlands are primarily located in temperate and subtropical

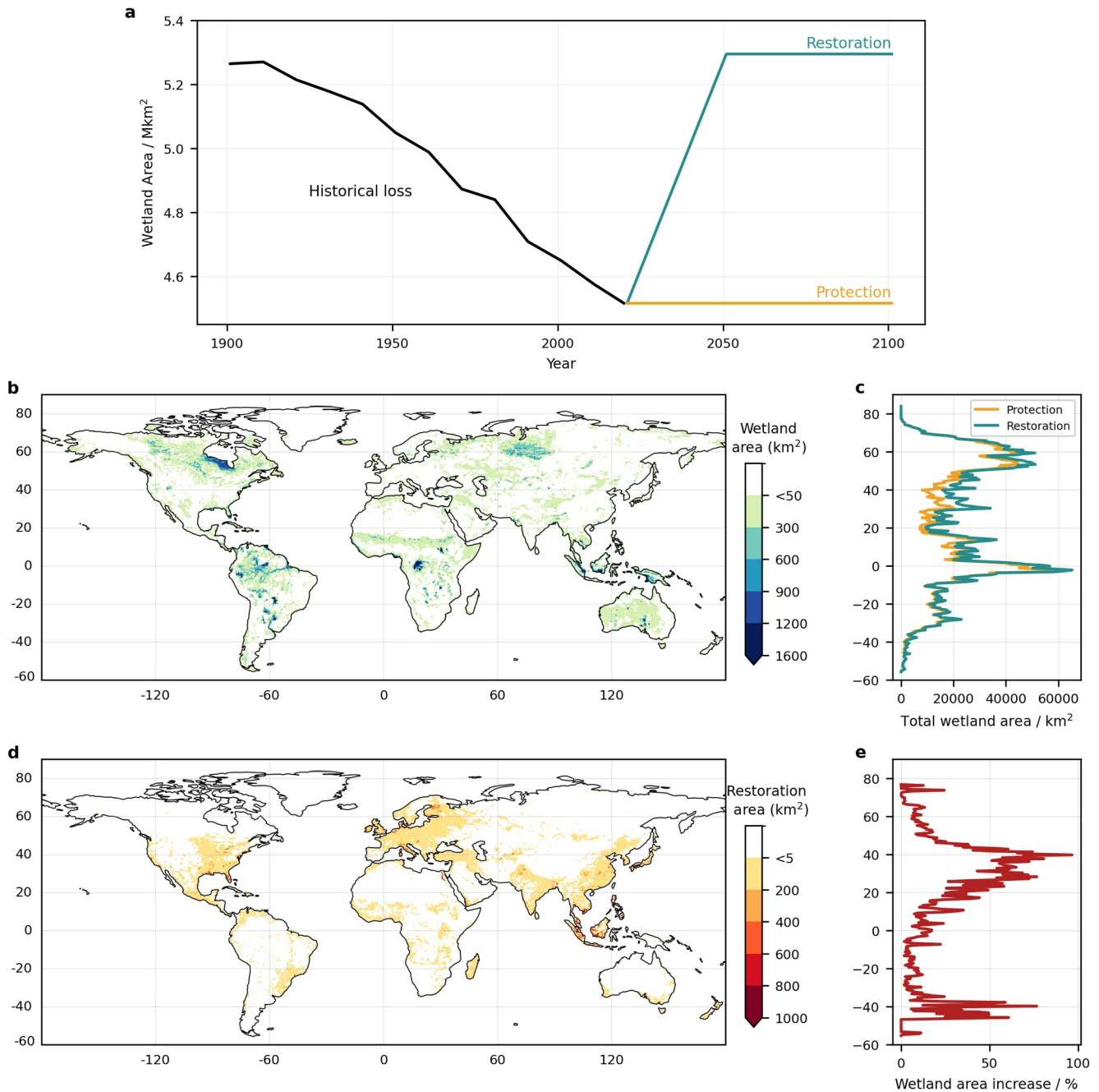


Figure 1. Global wetland area under the Protection and Restoration scenarios with (a) time series of yearly average total global wetland extent from 1900 to 2100 for both scenarios (Mkm²), (b) wetland area in 2019, representing the Protection scenario (km²), (c) latitudinal distribution of wetland area under both scenarios (km²), (d) spatial distribution of proposed wetland restoration area (km²) and (e) latitudinal increase of wetland area under the Restoration scenario relative to the Protection scenario in 2050 (%). Grid resolutions for the wetland maps are 0.5 × 0.5 from Fluet-Chouinard et al. (2023a).

latitudes, especially North America (18%), Europe (24%) and Southeast Asia (20%), reflecting the legacy of historical drainage for agriculture and other land uses. Across latitudinal bands (Figure 1e), most of the restoration relative to present-day occurs between 20°N and 50°N, accounting for nearly 50% of the total restoration area. A substantial restoration percentage increase is also observed around 40°S in temperate South America, Australia and New Zealand.

Table 1
Scenarios of Future Wetland Area and Climate Conditions Used in GHG Flux Estimations

Scenario	Wetland area change	Climate conditions
2C-Protection	Protect 2019 area	SSP1-2.6: Low warming (up to 2°C) and air pollution reduction
2C-Restoration	Restore to 1900 area by 2050, then protect	
4C-Protection	Protect 2019 area	SSP3-7.0: High warming (up to 4°C) and limited air pollution control
4C-Restoration	Restore to 1900 area by 2050, then protect	

The restoration target of 0.8 Mkm² represents the difference between reconstructed wetland extent in 1900–1910 (Restoration) and present-day wetland extent in 2019–2020 (Protection) using the historical monthly wetland data set described above. Our approach yields an estimate of wetland extent that is relevant for sustained CH₄ fluxes and CO₂ sequestration, and aligns well with reported restoration targets. For example, global assessments identify approximately 0.4–0.8 Mkm² of potentially restorable coastal wetlands and peatlands (Griscom et al., 2017), while Günther et al. (2020) estimate a peatland restorable area of 0.5 Mkm². The Ramsar Convention recommends restoring 30% of drained or degraded wetlands, equivalent to 0.77 Mkm² based on an estimated 2.5 Mkm² lost since 1970 (Robertson et al., 2025) and 20 UN member countries have already pledged 0.44 Mkm² toward wetland restoration (Stokes & Fonseca, 2025).

3. Estimation of Wetland Greenhouse Gas Fluxes and Associated Climate Effects

3.1. Wetland CH₄ and CO₂ Fluxes

To quantify the GHG fluxes associated with wetland protection and restoration scenarios, we estimated CH₄ emissions and CO₂ sequestration from natural and restored wetlands. Fluxes were calculated from 1900 to 2100 using outputs from eight CMIP6 ESMs under two contrasting Shared Socioeconomic Pathways (SSPs). We used SSP1-2.6, a sustainable development pathway with low emissions and warming limited to ~2°C by 2100, and SSP3-7.0, a fossil fuel-dependent pathway leading to high emissions and warming of ~4°C by 2100 (Riahi et al., 2017). This results in four scenario combinations of: 2C-Protection, 2C-Restoration, 4C-Protection and 4C-Restoration (Table 1).

Our approach required monthly soil temperature, heterotrophic (microbial) and autotrophic (plant) respiration and gross primary productivity (GPP) from CMIP6 outputs. Soil temperature and heterotrophic respiration were used as inputs to a CH₄ emission scheme, while GPP and respiration were used to estimate CO₂ sequestration. Eight CMIP6 model outputs were used for the calculation of CH₄ and CO₂ fluxes, and were selected based on their availability of the required variables and their similarity in their horizontal resolution and complexity (Table 2). We used CMIP6 data for both historical (1900–2014) and future (2015–2100) periods. For consistency across the ensemble, all variables were re-gridded to the UKESM grid resolution (1.25 × 1.875) prior to the analysis and wetland area scenarios were also re-gridded from their original resolution of 0.5 × 0.5 to 1.25 × 1.875.

Table 2
CMIP6 Earth System Models Used to Calculate Wetland GHG Fluxes

CMIP6 model	Land surface model	Resolution
ACCESS-ESM1-5 (Ziehn et al., 2020)	CABLE (Kowalczyk et al., 2016)	1.875 × 1.25
BCC-CSM2-MR (Wu et al., 2019)	BCC-AVIM (W. Li et al., 2019)	0.9 × 1.25
CESM2 (Danabasoglu et al., 2020)	CLM5 (Lawrence et al., 2019)	0.9 × 1.25
CNRM-ESM2-1 (Séférian et al., 2019)	ISBA-CTRIP (Decharme et al., 2019)	1.875 × 1.875
EC-Earth3-Veg-LR (Döscher et al., 2022)	LPJ-GUESS (Smith et al., 2014)	1.125 × 1.125
GFDL-ESM4 (Dunne et al., 2020)	LM4 (Shevliakova et al., 2024)	1 × 1.25
IPSL-CM6A-LR (Boucher et al., 2020)	ORCHIDEE (Krinner et al., 2005)	1.25 × 1.25
UKESM1-1-LL (Sellar et al., 2019)	JULES (Clark et al., 2011)	1.25 × 1.875

In our approach for calculating CH₄ emissions and carbon sequestration, restored wetlands are assumed to return immediately to natural wetland conditions. While this may overlook short-term transitional dynamics, restored wetland sites have been shown to transition from net CO₂ sources to sinks within ~4 years (He et al., 2024). Emissions from restored wetlands remain uncertain, particularly for non-peat systems due to limited observations (Bianchi et al., 2021). Some studies report higher CH₄ emissions from wetlands after rewetting that stabilize over time to levels comparable to natural wetlands (He et al., 2024; Mitsch et al., 2012), while others found that CH₄ fluxes were similar across restored and natural wetlands (Schuster et al., 2024). Many studies also show that CH₄ and CO₂ fluxes are primarily controlled by water table depth, which can override other ecosystem and management-related controls (Evans et al., 2021; Zou et al., 2022). These findings indicate that, despite variability and potential short-term CH₄ spikes, fluxes from restored wetlands with re-established hydrology and vegetation can be comparable to natural wetlands, supporting the use of this approximation for long term and large scale assessments.

Wetland CH₄ emissions were estimated using an emission scheme used in the Sheffield Dynamic Global Vegetation Model (SDGVM) (Hopcroft et al., 2011), which is based on the widely used empirical scheme of Cao et al. (1996), adapted for large-scale applications. CH₄ production in each grid cell was calculated as:

$$CH_4 \text{ Production} = R_H \cdot P_0 \cdot Q_{10}^{(T-T_{ref})/10} \cdot f_w \cdot CH_4 : C \quad (1)$$

where R_H is the heterotrophic soil respiration in the top 1m of soil (kg C m⁻² s⁻¹), P_0 is a scaling constant representing the base methanogenesis rate from heterotrophic respiration (0.47, (Cao et al., 1996)), Q_{10} is the temperature sensitivity factor (1.5), T is the soil temperature in the top 1m of soil, T_{ref} is the reference temperature (30°C), f_w is the wetland fractional area and $CH_4:C$ is a fixed ratio converting carbon loss to CH₄ emissions.

Although this scheme does not explicitly resolve multiple CH₄ pools, it has been widely used in global wetland CH₄ modeling and shows good agreement with both observations and more complex biogeochemical models (Ringeval et al., 2013; Saunio et al., 2024; Wania et al., 2013; Zhang et al., 2025). For consistency with the observed global totals, simulated CH₄ emissions were scaled to the 2010–2019 global mean total of 159 Tg yr⁻¹, from the Global Methane Budget (Saunio et al., 2024), following a standard top-down scaling approach used in other recent studies (Comyn-Platt et al., 2018; Gedney et al., 2019).

Wetland carbon sequestration was estimated using net ecosystem exchange (NEE), defined as the difference between GPP and total ecosystem respiration (R_e), and scaled by the wetland fractional area (f_w) in each grid cell:

$$C_{\text{sequestration}}(NEE) = (R_e - GPP) \cdot f_w \quad (2)$$

where R_e is defined as the sum of autotrophic and heterotrophic respiration (kg C m⁻² s⁻¹). NEE is a widely used proxy for carbon sequestration, as it represents the net carbon exchange between the ecosystem and the atmosphere (J. Li et al., 2025; Schuster et al., 2024; Zou et al., 2022; Lu et al., 2017). A negative NEE indicates net carbon uptake by the ecosystem, whereas a positive NEE indicates net carbon emission to the atmosphere.

Wetland carbon uptake was approximated by scaling grid-cell NEE by wetland fractional area, to derive a first-order estimate of wetland CO₂ uptake on a global scale. This approach is consistent with the CH₄ emissions calculation, as both are derived from the same CMIP6 soil carbon and respiration outputs. It also enables comparison with global-scale estimates of carbon fluxes and field-based measurements, such as eddy covariance observations.

As GPP and R_e are obtained from CMIP6 simulations, they reflect the dominant vegetation types and soil processes represented within each grid cell rather than explicit resolved wetland ecosystems. More complex wetland carbon models simulate detailed carbon pools, decomposition processes and lateral carbon exports, but they require extensive paramaterisation and data inputs that are often unavailable at global scales (L. Li et al., 2024).

3.2. Drained Wetland CO₂ Emissions

In addition to natural and restored wetlands, we estimated CO₂ emissions from historically drained wetlands to capture avoided emissions under restoration scenarios. Drained areas were defined as locations present in the

Restoration scenario, but absent in the Protection scenario (0.8 Mkm², Section 2). In the Protection scenario, CO₂ emissions from drained areas are held constant through to 2100, whereas in the Restoration scenario, these emissions are progressively avoided as wetlands are restored. Because the monthly wetland data set reflects both seasonal inundation and drainage, we take the average of the Protection and Restoration areas to remove the influence of seasonal variability when estimating drained areas.

CO₂ emissions from drained wetlands were calculated using emission factors from the IPCC Wetland Supplement (Hiraishi et al., 2014), applied using zonal averages across land-use categories for each major climate region: boreal (>60°), tropical (23.5° N/S) and temperate (23.5–60° N/S) (Table S1 in Supporting Information S1). These emission factors were applied to the estimated drained area in each zone to compute the total CO₂ emissions from drained wetlands over time. The IPCC emission factors were primarily derived for drained organic soils (peatlands), which can sustain long-term CO₂ emissions following drainage. While mineral soil wetlands may exhibit smaller or shorter-lived CO₂ emissions, recent studies have reported significant CO₂ losses from drained mineral soils (Whitfield et al., 2025). Applying these emission factors across all drained wetlands may therefore lead to some overestimation of total drained emissions. However, given the limited availability of emission factors for drained mineral soil wetlands, this approach provides a practical estimate of avoided emissions associated with our restoration scenarios.

We acknowledge that this approach differs from the CH₄ emission and CO₂ uptake calculations (Section 3.1), because of current data and model constraints. Drained CO₂ emissions are not explicitly represented in most CMIP6 land surface models and therefore cannot be directly estimated from the model ensemble used in this study. We used emission factors from the IPCC Wetland Supplement, which have been widely used in previous large-scale assessments (Günther et al., 2020; Sasmito et al., 2025) and provide a first-order estimate of drainage-related emissions.

More detailed land-use-specific emissions factors are available in the IPCC Wetland Supplement (Hiraishi et al., 2014), but applying them would require details about the current land use composition of drained areas. As the wetland area data were interpolated from the decadal maximum reconstruction of Fluet-Chouinard et al. (2023a), scaling land use information may misrepresent the land use fractions. For consistency with the CH₄ and carbon flux calculations, we used the monthly wetland area with the simplified latitudinal zoning approach.

Nitrous oxide (N₂O), although a potent GHG with a GWP approximately 273 times greater than that of CO₂ over a 100 year period, was not considered in this study. According to the IPCC Wetland Supplement, undisturbed wetlands are typically very weak sources of N₂O (Hiraishi et al., 2014). Estimating N₂O emissions would require nitrogen cycle outputs from CMIP6 models, which are not consistently available for all models used in this study. Additionally, nitrogen cycle processes remain poorly constrained by observations and uncertain across models (Davies-Barnard et al., 2020; Tang et al., 2025). Drained wetlands can emit small amounts of N₂O, but they are an order of magnitude smaller than CO₂ fluxes (kg rather than tonnes) (Zou et al., 2022). Given this relatively small contribution to the overall GHG budget and the lack of spatial nitrogen management data, N₂O was excluded from the current global-scale assessment.

3.3. Net Climate Effect of Wetland Emissions

To quantify changes in wetland carbon storage and assess the climate implications of future wetland scenarios, we calculated the net ecosystem carbon balance (NECB) and the net GHG flux. Both metrics combine wetland CH₄ emissions, wetland carbon sequestration and drained wetland CO₂ emissions.

NECB represents the net change in the carbon store of an ecosystem and therefore indicates whether wetlands act as a net carbon sink or source- NECB, in Gt C yr⁻¹, was calculated as:

$$NECB = CH_4 \frac{12}{16} + C_{seq} + CO_2 \text{ drained} \frac{12}{44} \quad (3)$$

The net GHG flux, expressed in CO₂-equivalents, provides a more direct metric of the potential climate impact of an ecosystem as it accounts for the warming effects of different GHGs. CH₄ emissions were converted to CO₂-eq using the 100-year GWP of 27 for non-fossil CH₄ (Intergovernmental Panel on Climate Change (IPCC), 2023).

This metric has widely been used in previous studies (Zou et al., 2022) and is adopted in international climate policy as a standard metric. Whilst alternative conversion metrics, such as the sustained-flux GWP (SGWP) have been proposed (Neubauer & Megonigal, 2015), the 100-year GWP provides a consistent and policy-relevant basis for comparison across studies (Ma et al., 2024). The net GHG flux, in Gt CO₂-eq yr⁻¹, was calculated as:

$$\text{Net GHG} = \text{CH}_4 \times 27 + \text{CO}_2_{\text{seq}} + \text{CO}_2_{\text{drained}} \quad (4)$$

To further assess how wetland emissions influence atmospheric greenhouse gas concentrations and temperature, we used the Finite Amplitude Impulse Response (FaIR) v2.2.4 reduced-complexity climate model (Leach et al., 2021). FaIR simulates global-mean concentrations and temperature responses to prescribed emissions and is designed to approximate the simulation of more complex ESMs using a computationally efficient approach.

We ran FaIR in monthly mode using pre-calculated climate response calibrations from an ensemble of 66 CMIP6 models. Simulations were driven with SSP emissions, under SSP1-2.6 and SSP3-7.0, representing our 2C and 4C warming scenarios. FaIR simulations were initialized from 1750 using historical emissions. From 2015 onward, emissions followed the SSP scenarios and from 2020 onward they included the combined wetland and climate scenarios.

To assess the climate impact of wetland restoration, we computed differences between Restoration and Protection scenarios under each SSP (2C-Restoration minus 2C-Protection and 4C-Restoration minus 4C-Protection). CH₄ emissions and net CO₂ fluxes (defined as wetland carbon sequestration combined with avoided CO₂ emissions from drained soils) were added to baseline SSP emissions. We evaluated the climate response to CH₄ alone and to the combined CH₄ and CO₂ fluxes. Only the additional emissions from restoration were included, allowing the FaIR simulations to isolate the incremental climate effect of wetland restoration relative to the baseline SSP pathways.

4. Evaluation of GHG Estimates Against Observations

To evaluate the framework used for estimating GHG fluxes from wetlands, we compared CH₄ emissions and carbon sequestration (NEE) against independent data sets and literature values (Figure 2). Figure S1 in Supporting Information S1 shows the locations of the six wetland regions used for CH₄ validation, following Zhang et al. (2025) and the distribution of site-level NEE observations from meta-analysis studies and FLUXNET measurements at wetland sites. Table S2 in Supporting Information S1 lists all data sets and references used in the evaluation.

For CH₄ emissions, modeled values were compared regionally against both an ensemble of 16 process-based wetland models from Zhang et al. (2025) and top-down atmospheric inversion estimates from regional studies (Table S2 in Supporting Information S1). We focused on the six major wetland regions: the Amazon, Hudson Bay Lowland (HBL), West Siberian Lowland (WSL), Alaska, Pantanal and Sudd (Figure S1 in Supporting Information S1). We computed average CH₄ emissions over 2000–2020 using historical (2000–2014) and SSP1-2.6 (2015–2020) simulations.

Total estimated CH₄ emissions across these regions are consistent with both the process-based model ensemble and inversion-derived values (Figure 2a). In the Amazon, our simulated flux is lower than the Zhang et al. (2025) multi-model mean, but close to the inversion estimate from Tunnicliffe et al. (2020), underscoring the persisting uncertainties in tropical wetland CH₄ fluxes (Murguia-Flores et al., 2023).

For carbon sequestration, modeled NEE was compared to annual flux data from 24 wetland sites in the FLUXNET data set (Pastorello et al., 2020) covering 2000–2015, and values reported in meta-analyses by Zou et al. (2022) and J. Li et al. (2025). For each site, NEE values were extracted by averaging the four closest model grid cells (by latitude and longitude). Climate zones were defined similarly to those used in the drained CO₂ emission analysis (Section 3.2). NEE values were grouped and compared globally and by climate zone to account for the differences in spatial scale between site-level flux measurements and CMIP6 model grid cells.

Initial evaluation against site-based observations (Figure 2b) shows that modeled NEE is broadly consistent with the range of values reported in the literature. However, our values show a smaller spread relative to observations, likely due to temporal aggregation of model results over 15 years (2000–2015) and differences in spatial

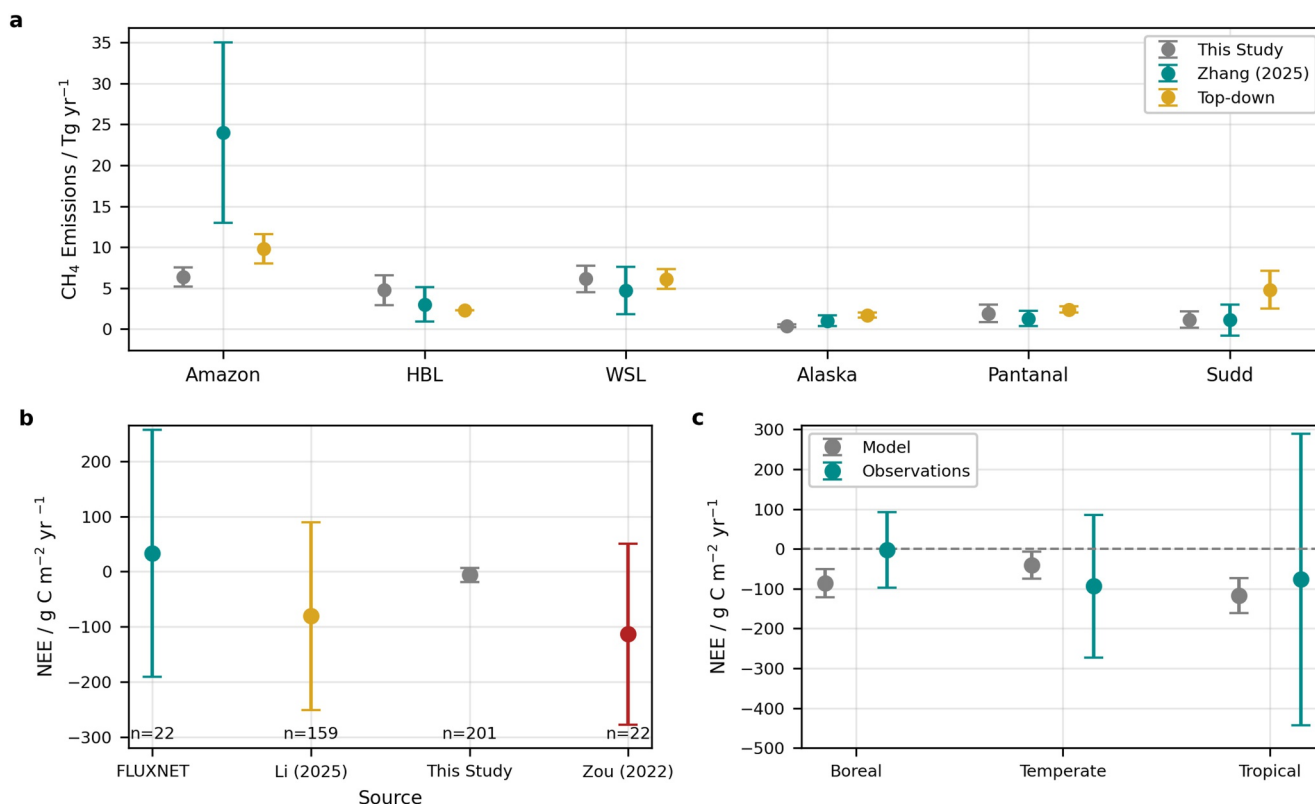


Figure 2. Comparison of estimated wetland GHG emissions against observations. (a) Total wetland CH_4 emissions across six key wetland hotspots, compared with the multi-model ensemble from Zhang et al. (2025) and top-down studies (Table S2 in Supporting Information S1). Points represent mean values and bars indicate one standard deviation. (b) Estimated NEE compared with FLUXNET data and meta-analysis studies (J. Li et al., 2025; Zou et al., 2022). Points represent the average value and the error bars represent the standard deviation. Sample sizes are shown below each point. (c) Expanded comparison of the distribution of modeled and observed NEE (FLUXNET and meta-analysis) across climate zones. Points represent the average value and the error bars represent the standard deviation.

resolution, as our model estimates represent $\sim 100 \times 100$ km grid-cell averages, whereas field observations reflect local-scale conditions. Additionally, observational literature values vary in their measurement period, ranging from seasonal, growing season or multi-year measurements. These observations may capture short term variability or extreme conditions, leading to a wider range of reported NEE values that may be smoothed out in our multi-year averages of modeled NEE.

To further evaluate spatial representativeness, the analysis was expanded to include grid cells with wetland fractional cover greater than 30%, representing more wetland-dominated regions (Figure 2c). This comparison shows good agreement with literature values across climate regions, with tropical wetlands exhibiting the largest NEE values in both modeled and observational estimates.

Overall, both evaluations indicate that the model reproduces the broad magnitude and spatial patterns of wetland NEE. Remaining differences between modeled and observed values are expected given scale mismatches between point-based flux measurements and gridded model outputs (Jung et al., 2020), as well as natural heterogeneity in wetland ecosystems and limited observations, particularly in the tropics (Sjögersten et al., 2014). These results support the use of our approach for estimating first-order wetland carbon sequestration patterns at large spatial scales.

5. Projected Wetland Greenhouse Gas Balance

In this section, we assess projected wetland CH_4 emissions, carbon sequestration and CO_2 emissions from historically drained wetlands under the four scenarios, combining two land-use trajectories (Protection and Restoration) and two climate pathways (2C and 4C). We then examine how these changes influence the overall wetland GHG balance over the 21st century.

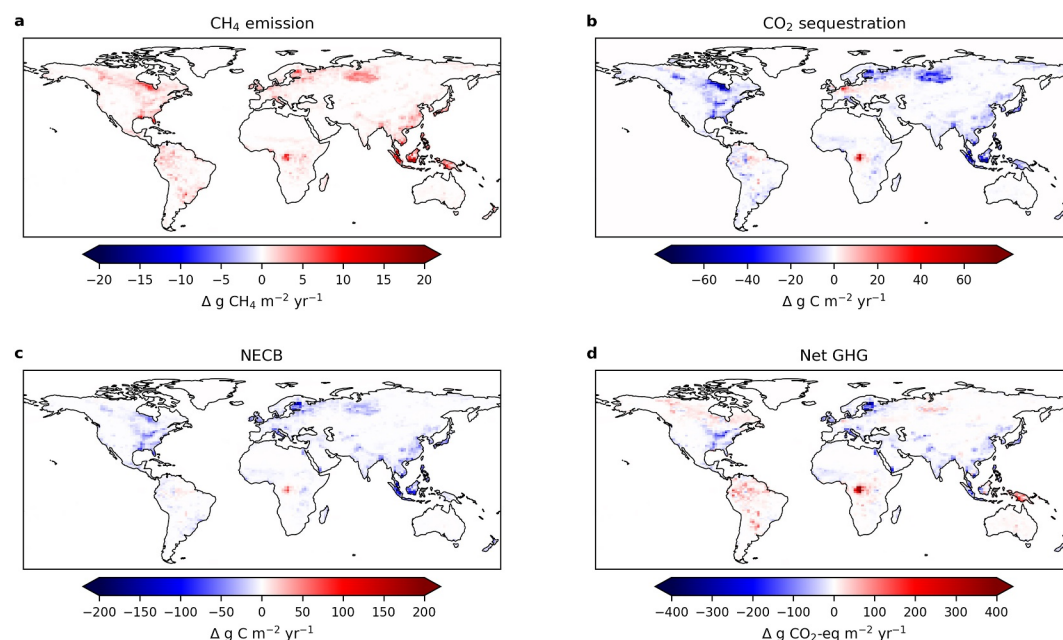


Figure 3. Spatial distribution of projected change in wetland fluxes under the 4C-Restoration scenario for (a) CH₄ emission ($\text{g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$), (b) CO₂ sequestration ($\text{g C m}^{-2} \text{ yr}^{-1}$), (c) NECB ($\text{g C m}^{-2} \text{ yr}^{-1}$) and (d) Net GHG flux ($\text{g CO}_2\text{-eq m}^{-2} \text{ yr}^{-1}$). Changes are calculated as the differences between 2090–2100 and 2010–2020 decadal averages.

As an example, Figure 3 presents the spatial distribution of projected changes at the end of the century for CH₄ emissions, CO₂ sequestration and the resulting NECB and net GHG flux under the 4C-Restoration scenario. This scenario combines high warming with large-scale wetland restoration and illustrates where the largest changes occur globally. Spatial results for the other scenarios are shown in Figures S2–S6 in Supporting Information S1 and are discussed in the following subsections.

5.1. Future CH₄ Emissions

Wetland CH₄ emissions are projected to increase across all scenarios, driven by climate warming and, in our Restoration scenarios, by wetland area expansion (Figure 4a). In our estimates, present-day global wetland CH₄ emissions are approximately $160 \text{ Tg CH}_4 \text{ yr}^{-1}$ (2010–2019), consistent with the Global Methane budget (Saunio et al., 2024).

By 2100, all scenarios show increases in CH₄ emissions, with larger increases under restoration pathways due to expansion of wetland area. The largest increase occurs under 4C-Restoration, with emissions increasing by $+90 \text{ Tg CH}_4 \text{ yr}^{-1}$ (57% increase relative to 2019 emissions), reaching $\sim 250 \text{ Tg CH}_4 \text{ yr}^{-1}$ by 2100. The 4C-Protection scenario shows a lower increase ($+53 \text{ Tg CH}_4 \text{ yr}^{-1}$, 33%), but this is slightly higher than 2C-Restoration ($+48 \text{ Tg CH}_4 \text{ yr}^{-1}$, 30%), highlighting the strong influence of climate warming alone. The smallest increase is found in the 2C-Protection scenario ($+18 \text{ Tg CH}_4 \text{ yr}^{-1}$, 11%).

At regional scales (Figure 4b, Table S3 in Supporting Information S1), the 4C-Restoration scenario also results in the largest increase in CH₄ emissions across all continents, despite geographic differences in warming rates and restored wetland area. In Europe and Asia, restoration dominates the change. For example, in Europe, 2C-Restoration ($+5 \text{ Tg CH}_4 \text{ yr}^{-1}$, 102%) exceeds 4C-Protection ($+3 \text{ Tg CH}_4 \text{ yr}^{-1}$, 66%). Conversely, in America, Africa and Oceania, the effect of warming outweighs wetland expansion, with projected emissions under 4C-Protection exceeding those under 2C-Restoration.

Europe shows the largest relative sensitivity overall, with CH₄ emissions increasing by 176% by 2100 under 4C-Restoration compared to 66% under 4C-Protection. Asia and North America also show substantial increases under 4C-Restoration (115% and 94%, respectively). Spatially, CH₄ fluxes are intensified in major wetland regions (Figure S2 in Supporting Information S1), especially across Southeast Asia where emissions increase across all

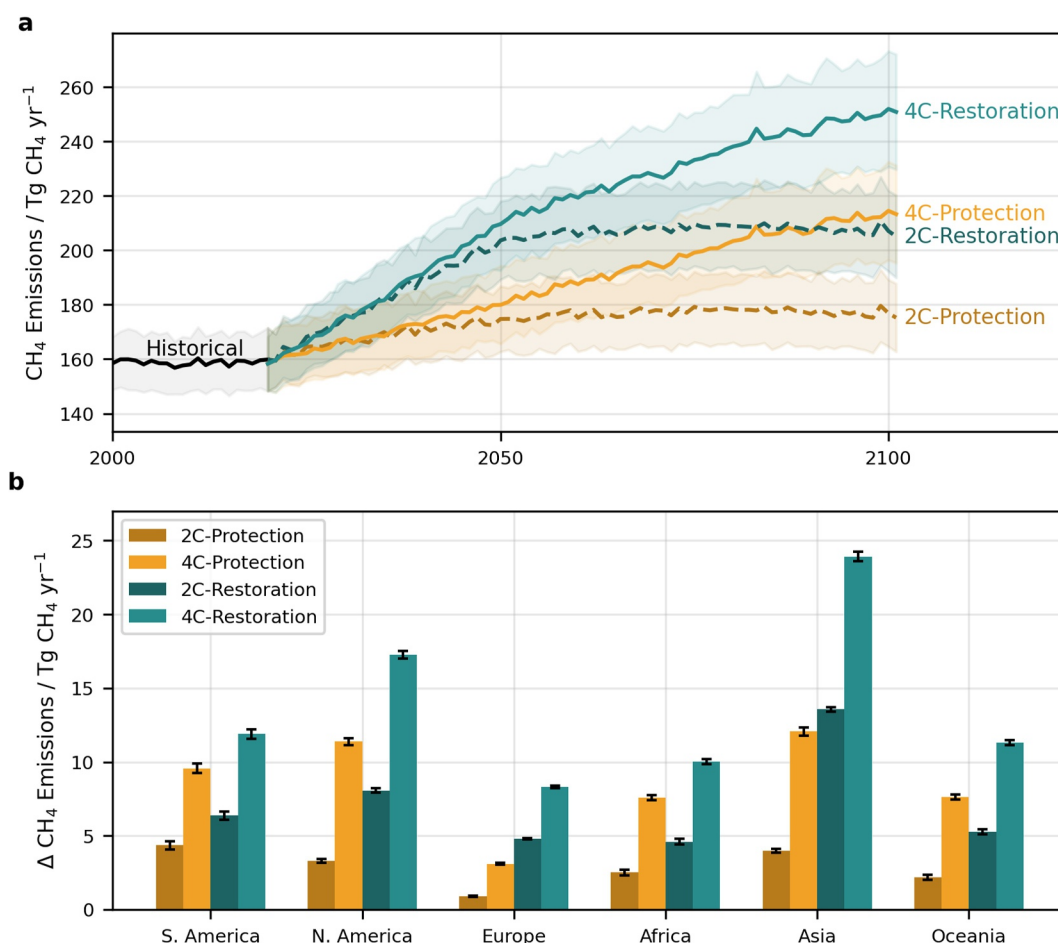


Figure 4. Projected CH₄ emissions from wetlands under future scenarios combining land-use (Protection and Restoration) and climate pathways (2C and 4C). (a) Total global wetland CH₄ emissions from 1900 to 2100 for historical and future scenarios (Tg CH₄ yr⁻¹). Solid lines show multi-model means and the shaded areas represent the standard error of the mean. (b) Regional changes in CH₄ emissions by continent (Tg CH₄ yr⁻¹), calculated as the difference between the 2090–2100 and 2010–2020 decadal averages. Error bars show the propagated standard error for the mean of the regional decadal change.

scenarios, amplified by both restoration and warming. The dominant drivers differ regionally. In Europe (and to a lesser extent Asia), restoration exerts a stronger influence than warming alone. In contrast, in North America and tropical regions (South America and Africa), warming plays a larger role in amplifying CH₄ emissions. This pattern is consistent with the large wetland area expansion in Europe and Asia (58% and 23% respectively), compared to 4%–14% in North America, South America and Africa.

Similar estimates of future wetland CH₄ emissions have been reported in previous studies. For example, our Protection scenario estimates of +18 Tg CH₄ yr⁻¹ for 2C and 53 Tg CH₄ yr⁻¹ for 4C are comparable to those from Chen et al. (2024), which reported +19.2 Tg CH₄ yr⁻¹ for SSP1-2.6 and +39 Tg CH₄ yr⁻¹ for SSP3-7.0 using a machine learning approach with a static wetland map. Folberth et al. (2025), using UKESM with interactive wetland emissions, reported +23 Tg CH₄ yr⁻¹ increase under SSP1-2.6. Other CMIP5-based studies reported increases, ranging from +14 Tg CH₄ yr⁻¹ (RCP 2.6) to +160 Tg CH₄ yr⁻¹ (RCP 8.5; Koffi et al., 2020; Shindell et al., 2013; Zhang et al., 2017).

5.2. Future CO₂ Sequestration and Drained CO₂ Emissions

Present-day wetlands act as a substantial global carbon sink and this sink changes under future climate and restoration scenarios (Figure 5). We estimate that present-day wetlands are a net sink of carbon of about 600 Tg C yr⁻¹ (~2.2 Gt CO₂ yr⁻¹ for 2010–2020) (Figure 5a), representing about 20% of total present-day anthropogenic

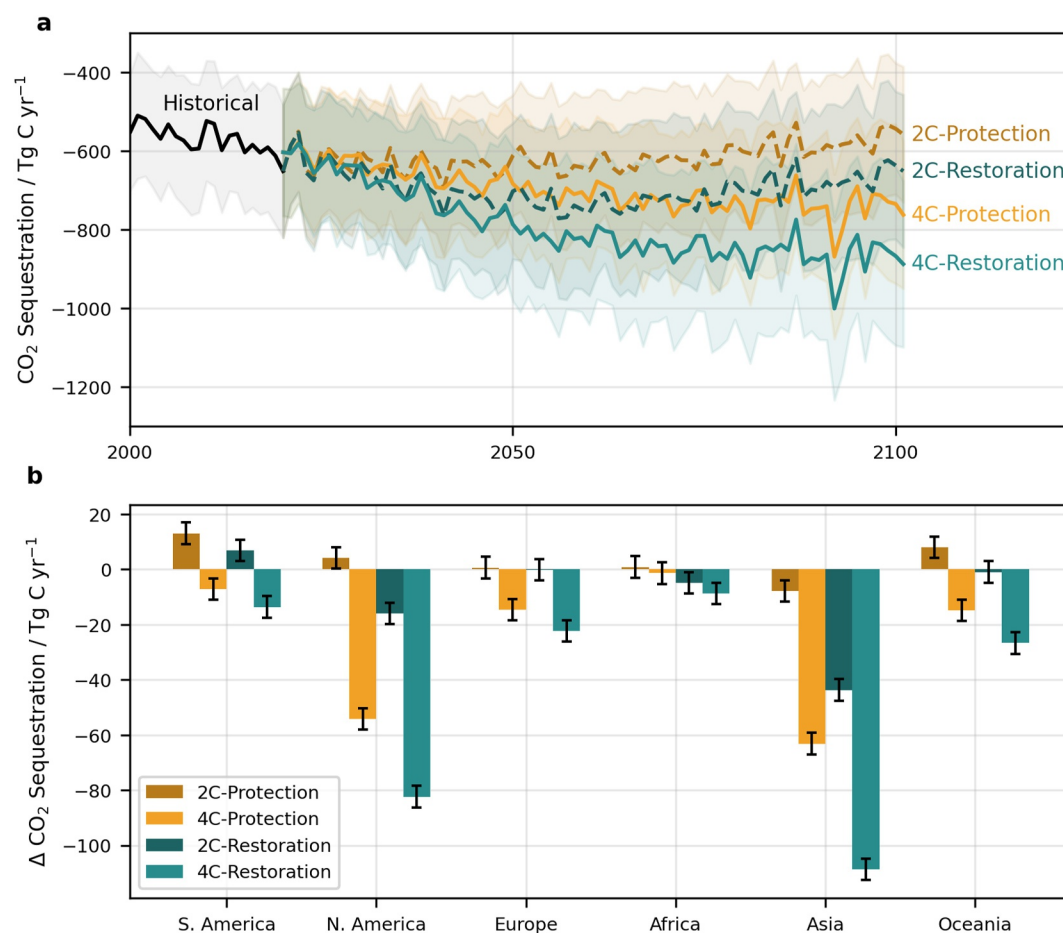


Figure 5. Projected CO₂ sequestration from wetlands under future scenarios combining land-use (Protection and Restoration) and climate pathways (2C and 4C). (a) Total global wetland CO₂ sequestration from 1900 to 2100 for historical and future scenarios (Tg C yr⁻¹). Solid lines show multi-model means and the shaded areas represent the standard error of the mean. (b) Regional changes in CO₂ sequestration by continent (Tg C yr⁻¹), calculated as the difference from 2090 to 2100 and 2010 to 2019 decadal averages. Error bars show the propagated standard error for the mean of the regional decadal change. Note that CO₂ sequestration values are negative, indicating net carbon uptake from the atmosphere by wetlands.

CO₂ emissions (Friedlingstein et al., 2025). This global sink is projected to continue under future scenarios, although its magnitude varies with both climate and land-use pathway.

By 2100, projected carbon sequestration ranges from 570 to 880 Tg C yr⁻¹, with the strongest uptake under 4C-Restoration (−287 Tg C yr⁻¹, +49% relative to present-day), followed by 4C-Protection (−161 Tg C yr⁻¹, +27%) and 2C-Restoration (−75 Tg C yr⁻¹, +13%). In contrast, 2C-Protection shows a slight weakening in carbon sequestration (+20 Tg C yr⁻¹, −3%) by 2100, although wetlands still remain a net sink of carbon. These results suggest that restoration can enhance carbon uptake, especially under stronger warming. The larger uptake under the 4C scenarios highlights the additional influence of climate-driven effects, such as CO₂ fertilisation, which may reinforce carbon sequestration beyond the effect of restoration alone and may also reflect relatively weak moisture limitation in the CMIP6 models.

At regional scale (Figure 5b and Table S4 in Supporting Information S1), the 4C-Restoration scenario drives the greatest strengthening of carbon sequestration, especially in Europe (136%), Asia (106%) and North America (77%). Under 4C-Protection, uptake in the same regions also show notable increases- 51% in North America, 89% in Europe and 62% in Asia. Under 2°C warming, protection alone leads to a weakening of CO₂ sequestration across most regions, apart from Asia. Restoration under 2C has more modest effects, for example, Europe shows only a +5% difference between 2C-Restoration and 2C-Protection, compared to +47% under 4C. The smaller

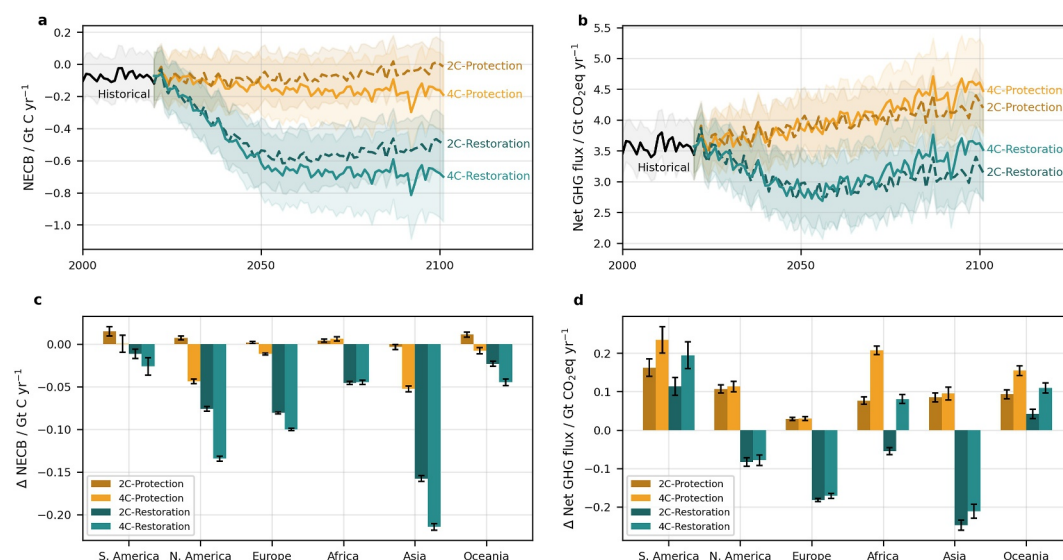


Figure 6. Climate impacts of wetland restoration and protection. Total global (a) NECB (Gt C yr^{-1}) and (b) net GHG flux ($\text{Gt CO}_2\text{-eq yr}^{-1}$) for historical, protection and restoration scenarios. Shaded areas represent the standard error of the mean. Change summed by continent for (c) NECB (Gt C yr^{-1}) and (d) net GHG flux ($\text{Gt CO}_2\text{-eq yr}^{-1}$)- calculated as the difference between 2090–2100 and 2010–2019 decadal averages. Error bars show the propagated standard error for the mean of the regional decadal change.

response under 2C likely reflects weaker temperature and CO_2 fertilisation effects, resulting in smaller increases in plant productivity and carbon inputs to wetland soils.

On a spatial scale, most wetlands remain net carbon sinks by 2100, although some weakening is evident in Europe, South America and Africa (Figure S3 and Table S4 in Supporting Information S1). This pattern aligns with J. Li et al. (2025) which reported gains across the Northern Hemisphere, offsetting tropical and southern declines. These results reinforce the need for protecting existing wetlands, particularly in areas where carbon sequestration may weaken in the future.

In addition to CO_2 uptake by wetlands, we also estimate CO_2 emissions from historically drained wetlands (Figure S4 in Supporting Information S1, Section 3.2), which are avoided under restoration. Globally these emissions are about $1.5 \text{ Gt CO}_2 \text{ yr}^{-1}$, consistent with previous estimates of $\sim 2 \text{ Gt CO}_2 \text{ yr}^{-1}$ (Bonn et al., 2016). These emissions are concentrated in regions with extensive historical drainage, including North America, Europe and Southeast Asia. Our regional estimates are also broadly consistent with previous studies. For example, European emissions ($286 \text{ Tg CO}_2 \text{ yr}^{-1}$) closely match the published estimate of $276 \text{ Tg CO}_2 \text{ yr}^{-1}$ for drained peatlands (van Giersbergen et al., 2025), while emissions in Southeast Asia ($382 \text{ Tg CO}_2 \text{ yr}^{-1}$) fall within the reported range of $355\text{--}855 \text{ Tg CO}_2 \text{ yr}^{-1}$ (Hooijer et al., 2010). Avoided emissions from drained wetlands therefore represent an important component of the climate mitigation potential of restoration.

5.3. Net Carbon Sink Potential and Net GHG Balance

To assess the overall carbon implications, we combined GHG fluxes into two metrics: NECB, which represents the net carbon sink or source in ecosystems (Gt C yr^{-1}) and net GHG flux, which accounts for the warming effects of CH_4 ($\text{Gt CO}_2\text{-eq yr}^{-1}$). Both metrics combine wetland CO_2 sequestration and CH_4 emissions and CO_2 emissions from historically drained soils (Section 3.3).

Wetlands are a net sink of carbon, with a present-day NECB of about $-0.1 \text{ Gt C yr}^{-1}$ (Figure 6a). This is smaller than the estimated CO_2 sequestration alone ($-0.6 \text{ Gt C yr}^{-1}$) because NECB also accounts for offsetting carbon losses from CO_2 emissions from drained wetlands and CH_4 emissions.

By 2100, NECB diverges depending on climate and land-use pathways. Under 4C-Restoration, the net carbon sink strengthens to $-0.7 \text{ Gt C yr}^{-1}$, followed by 2C-Restoration at $-0.5 \text{ Gt C yr}^{-1}$. The stronger sink under 4C

reflects higher CO₂ uptake from restored wetlands and avoided emissions from drained areas, although partially offset by larger CH₄ emissions. In contrast, 4C-Protection shows minor changes, stabilizing at $-0.2 \text{ Gt C yr}^{-1}$, while 2C-Protection weakens further, reaching near-zero or slightly positive NECB values by 2100. This suggests that under 2C warming without restoration, wetlands may lose their role as a net carbon sink in some regions likely due to the continuation of drained CO₂ emissions.

At regional scale, NECB responses to wetland restoration vary, with most continents showing a strengthened carbon sink by 2100 under restoration (-0.01 to $-0.21 \text{ Gt C yr}^{-1}$, Figure 6c and Table S5 in Supporting Information S1). However, some regions, such as North and South America under 2C-Protection ($+0.01 \text{ Gt C yr}^{-1}$) show marginal gains or even weakening of the sink. These patterns reflect continued carbon losses from key wetland hotspots like the HBL, South America and the Congo basin (Figure S5 in Supporting Information S1), highlighting regional disparities in the net carbon balance.

To account for differences in wetland extent across regions, Table S6 in Supporting Information S1 reports NECB directly as carbon flux ($\text{g C m}^{-2} \text{ yr}^{-1}$). Under 4C-Restoration, all continents show negative NECB fluxes, with the strongest carbon sinks in North America ($-24 \text{ g C m}^{-2} \text{ yr}^{-1}$). In contrast, under 2C-Protection Europe shows a positive NECB flux ($+3 \text{ g C m}^{-2} \text{ yr}^{-1}$), indicating net carbon losses. Across scenarios, NECB trends closely follow changes in carbon sequestration, indicating that CO₂ uptake is the dominant driver.

NECB provides one indication of the climate mitigation potential of wetland restoration, as it accounts for net changes in carbon storage. For our restoration scenarios (0.8 Mkm^2), we estimate a global mitigation potential of $1.6\text{--}2.3 \text{ Gt CO}_2 \text{ yr}^{-1}$ (equivalent to 0.4 and 0.6 Gt C yr^{-1} for 2C and 4C, respectively) by 2100. These estimates are consistent with previous assessments. For example, Griscom et al. (2017) report a comparable mitigation potential ($1.6 \text{ Gt CO}_2 \text{ yr}^{-1}$) for avoided peatland degradation and peatland restoration over a similar wetland area.

When assessed as net GHG flux (Figure 6b), which expresses the combined effects of CH₄ and CO₂, wetlands are a net source of GHGs at present, with global fluxes around $+3.6 \text{ Gt CO}_2\text{-eq yr}^{-1}$. This contrasts with the net carbon sink shown by NECB and highlights the warming effect of CH₄.

By 2100, net GHG fluxes remain positive globally under all scenarios. Restoration reduces emissions, with the largest reductions under 2C ($-0.5 \text{ Gt CO}_2\text{-eq yr}^{-1}$, 13%), followed by 4C ($-0.1 \text{ Gt CO}_2\text{-eq yr}^{-1}$, 3%). In contrast, the Protection scenarios result in increased GHG fluxes by 2100, with +16% ($+0.6 \text{ Gt CO}_2\text{-eq yr}^{-1}$) under 2C and +24% ($+0.9 \text{ Gt CO}_2\text{-eq yr}^{-1}$) under 4C, due to the continued influence of drained CO₂ emissions. Across both land scenarios, 4C pathways result in higher net GHG fluxes than their 2C counterparts (by $\sim 0.3 \text{ Gt CO}_2\text{-eq yr}^{-1}$ in 2100), reflecting enhanced CH₄ emissions under stronger warming.

On a regional scale (Figure 6d and Table S7 in Supporting Information S1), South America, Oceania and Africa show increases in net GHG flux across most scenarios. For example, net GHG flux increases in South America by $0.11\text{--}0.24 \text{ Gt CO}_2\text{-eq yr}^{-1}$ and in Oceania by $0.04\text{--}0.15 \text{ Gt CO}_2\text{-eq yr}^{-1}$. Africa also shows increases ($0.08\text{--}0.21 \text{ Gt CO}_2\text{-eq yr}^{-1}$) with the exception of 2C-Restoration ($-0.05 \text{ Gt CO}_2\text{-eq yr}^{-1}$). This pattern suggests that in tropical and Southern Hemisphere regions, rising CH₄ emissions outweigh gains in carbon sequestration, limiting mitigation potential. In contrast, restoration in Northern Hemisphere regions, such as North America, Europe and Asia, reverses the positive net GHG flux trends, shifting wetlands from sources to sinks by 2100 due to enhanced carbon uptake and reduced drained CO₂ emissions, which together offset increasing CH₄ emissions (Figure S6 in Supporting Information S1). These contrasts highlight regional differences in mitigation potential, although the spatial pattern may also be influenced by the use of drained soil emission factors defined for broad climate zones.

The latitudinal distributions of NECB and net GHG flux (Figure 7) further illustrate these spatial patterns. Restoration in the Northern Hemisphere leads to a clear strengthening of NECB and a reduction in net GHG flux, highlighting the importance of high-latitude and temperate wetlands for climate mitigation. In contrast, equatorial regions (near 0°) show consistent increases in net GHG flux, largely due to intensified CH₄ emissions. NECB in these regions still strengthens under restoration scenarios due to increased CO₂ sequestration and avoided drained CO₂ emissions, highlighting the differences between carbon-based and GHG-based metrics.

Overall, NECB and net GHG flux provide complementary information on the carbon balance and potential climate implications of wetlands. NECB indicates that restored wetlands generally act as a net carbon sink by

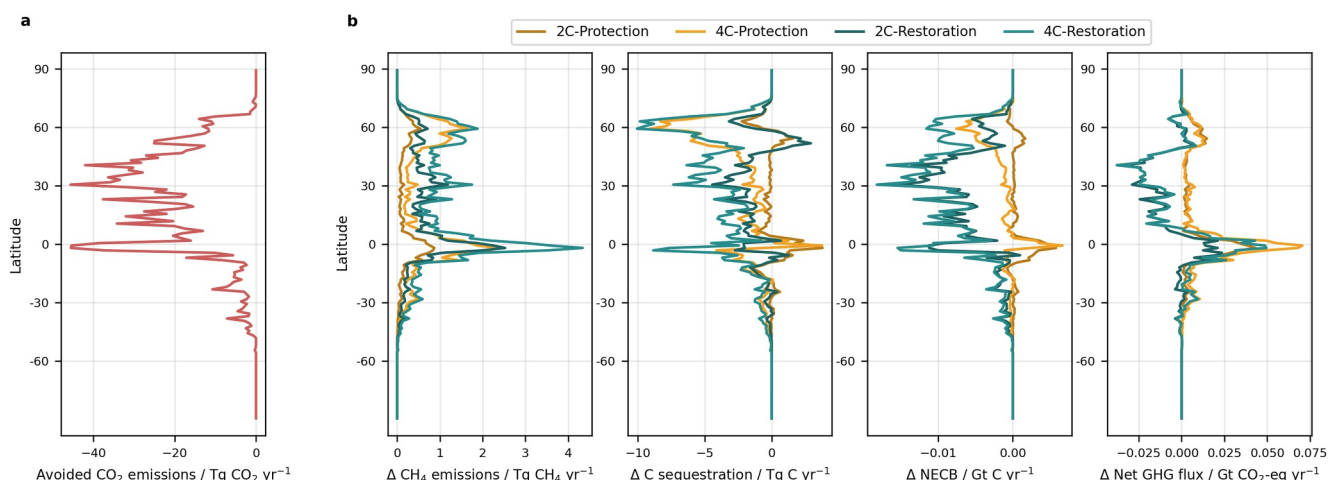


Figure 7. Latitudinal distribution of (a) avoided CO₂ emissions from restoration of drained emissions (Tg CO₂ yr⁻¹) and (b) changes in CH₄ emissions (Tg CH₄ yr⁻¹), CO₂ sequestration (Tg CO₂ yr⁻¹), NECB (Gt C yr⁻¹) and net GHG flux (Gt CO₂-eq yr⁻¹) across scenarios. Calculated as the difference between 2090–2100 and 2010–2019 decadal average.

2100, while net GHG flux highlights the extent to which CH₄ emissions can offset this benefit in GHG terms, given its high warming potential.

5.4. Climate Impacts of Wetland Restoration

To assess how wetland GHG fluxes influence climate, we used the FaIR reduced-complexity climate model to simulate changes in atmospheric CO₂ and CH₄ levels and global mean temperature under the SSP1-2.6 and SSP3-7.0 pathways, representing the 2C and 4C warming scenarios, respectively. The emissions used to drive FaIR and the resulting timeseries for each variable are shown in Figure S7 in Supporting Information S1 and further details are provided in Section 3.3.

FaIR simulations show that wetland restoration reduces atmospheric CO₂ levels under both warming scenarios, with reductions of 10 ppm (2C) and 13 ppm (4C) (Figure 8a). The slightly larger reduction under 4C is mainly driven by stronger CO₂ sequestration. Global mean CO₂ levels are projected to stabilize at ~445 ppm under SSP1-2.6 and to exceed ~865 ppm under SSP3-7.0 by 2100 (Meinshausen et al., 2020), making restoration-induced changes a modest (around 2%) perturbation relative to total projected anthropogenic levels.

In contrast, atmospheric CH₄ levels increase following wetland expansion, reaching +108 ppb (2C) and +180 ppb (4C) by 2100 (Figure 8b), which represents a 5%–10% rise relative to projected CH₄ levels by 2100 (1055 ppb

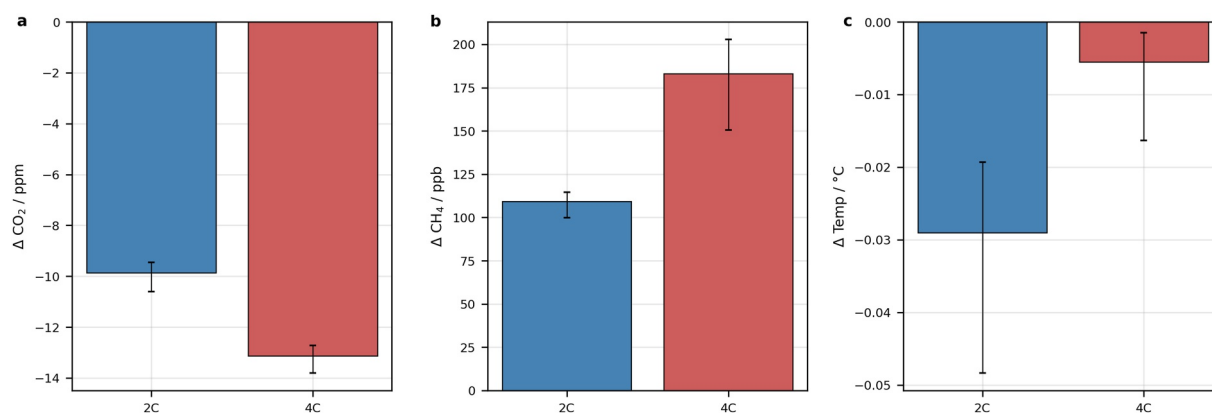


Figure 8. Climate impact of wetland restoration from FaIR simulations driven by CH₄ emissions and net CO₂ emissions (CO₂ sequestration and avoided drained CO₂ emissions). Bars represent the difference in (a) CO₂ atmospheric mixing ratios, (b) CH₄ atmospheric mixing ratios and (c) global mean temperature between restoration and protection scenarios under 2C and 4C warming futures. Values are averaged across 2090–2100. Error bars show the 5th and 95th percentile range across the ensemble.

under SSP1-2.6 (2C) and 3370 ppb under SSP3-7.0 (4C) (Meinshausen et al., 2020)). Considered alone, these CH₄ increases would produce an additional warming of 0.04–0.05°C by 2100 (Figure S7 in Supporting Information S1), consistent with previous estimates of wetland climate feedbacks under future warming (0.04–0.12°C across RCP2.6 to RCP8.5 (Zhang et al., 2017)).

When the full carbon balance of restoration is considered (including CO₂ sequestration, CH₄ emissions and avoided drainage emissions) the net temperature response becomes small and negative in both scenarios (Figure 8c). Under 2C (SSP1-2.6), restoration produces a net cooling of −0.03°C by 2100. Under 4C (SSP3-7.0), the cooling effect is smaller (−0.007°C), as larger CH₄ levels under higher warming reduce the magnitude of the CO₂-driven cooling.

Although both the net GHG flux and FaIR approaches indicate that wetland restoration provides an overall climate benefit, they provide complementary perspectives on the climate response. The net GHG flux expresses CH₄ emissions as CO₂-equivalent using fixed a 100-year GWP metric, whereas FaIR explicitly simulates the evolution of atmospheric greenhouse gas concentrations and temperature. Consequently, the warming effect of increased CH₄ emissions diminishes as atmospheric CH₄ approaches a new equilibrium because of its relatively short atmospheric lifetime, whereas the cooling associated with CO₂ removal persists over much longer timescales.

These global mean temperature responses are small relative to projected 21st century warming (~2–4°C). They indicate that large-scale wetland restoration does not impose a global temperature penalty from increased CH₄ emissions when carbon sequestration and avoided drainage emissions are accounted for. However, the resulting reduction in global temperature is modest, indicating a limited influence of wetland restoration on global mean temperatures in these scenarios. The net climate effect reflects the trade-off between CH₄ amplification and CO₂ uptake, which is itself sensitive to background warming.

6. Limitations and Uncertainties

Several limitations should be acknowledged. First, there are uncertainties in the estimation of wetland GHG fluxes. Our CH₄ and CO₂ flux estimates are based on simplified schemes, including an empirical CH₄ production scheme and NEE-based carbon uptake and therefore do not explicitly resolve transport processes or full carbon pool dynamics. Restoration was assumed to return wetlands directly to natural flux regimes, without representing recovery dynamics or hydrological changes that could influence GHG emissions.

In addition, NEE values derived using CMIP6 models reflect the dominant vegetation and soil processes represented within each grid cell, and therefore do not explicitly resolve wetland specific processes, particularly those related to water-table dynamics. Estimates of CO₂ sequestration associated with wetland restoration are therefore uncertain and may differ from those obtained using wetland carbon-cycle models. Despite this limitation, the resulting NEE values show broad agreement with field observations. However, there is a lack of global-scale wetland NEE data sets from models available for direct comparison, which restricts our evaluation.

We also applied emission factors derived for drained peatlands to all drained wetlands which may overestimate these emissions in mineral soil wetlands. Furthermore, this approach does not explicitly account for spatial variability in carbon stocks, drainage history, land use, or environmental controls on decomposition, and may therefore overestimate emissions from some mineral soil wetlands while underestimating others. However, globally consistent data sets describing these controls are currently unavailable, and emission-factor approaches from the IPCC Wetland Supplement remain the most widely applied method for estimating drainage-related CO₂ emissions at large scales. N₂O emissions were excluded because nitrogen cycle outputs were not consistently available across CMIP6 models, although undisturbed wetlands are typically weak N₂O sources.

Second, assumptions in the wetland scenarios. Wetland extent was prescribed rather than dynamically simulated and climate-driven changes in wetland area are not accounted for. Our results depend on the feasibility of protecting global wetlands and restoring ~0.8 Mkm² globally, assuming no additional conversion of the present-day wetland extent. Restoration was implemented linearly and the timing of restoration may influence the trajectory of GHG emissions and the resulting climate response by 2100. Large-scale restoration is assumed across all regions, whereas in reality implementation is likely to be uneven and driven by local policy. Despite these uncertainties, our spatially-explicit framework provides an assessment of the potential climate implications of large-scale

wetland protection and restoration and identifies regions where restoration could provide the greatest carbon and climate benefits.

Finally, our climate analysis considers only GHG feedbacks. Biophysical processes, such as changes in albedo and evapotranspiration, were not considered and may also influence global temperature responses. Wetland restoration may reduce surface albedo and generate a positive radiative forcing effect due to replacing croplands with darker wetland vegetation and water (Wang et al., 2023). Conversely, increased evapotranspiration from restored wetlands may lead to a cooling effect (Hesslerová et al., 2019). The magnitude and net effect of these biophysical feedbacks may vary geographically and would require coupled land-atmosphere modeling to be fully quantified.

7. Conclusion

In this study, we assessed the future GHG balance of large-scale wetland restoration under contrasting land use and climate scenarios, using wetland area reconstructions, process-based GHG models and a reduced-complexity climate model. We compared the effects of protecting current wetlands versus restoring historically degraded areas (0.8 Mkm²) under low and high warming pathways (2°C and 4°C). Wetland restoration enhances carbon sequestration and reduces CO₂ emissions from drained soils, but also increases CH₄ emissions. The net climate outcome depends on both the warming pathway and the balance between these competing fluxes, highlighting the importance of using multiple metrics (NECB, net GHG flux and temperature responses) to assess climate impacts.

Wetland restoration enhances net CO₂ uptake in temperate and high-latitude regions where historical drainage has been extensive. By 2100, restoration increases net carbon uptake, with NECB strengthening by −0.4 to −0.6 Gt C yr^{−1}. This corresponds to a mitigation potential of 1.6–2.3 Gt CO₂ yr^{−1} by 2100 for the restored area, consistent with independent estimates of peatland restoration potential. The strongest carbon uptake gains occur in the Northern Hemisphere, especially Europe, North America and parts of Asia, where avoided drainage emissions and enhanced CO₂ sequestration dominate.

However, restoration increases CH₄ emissions, with global wetland CH₄ emissions rising by 11%–57% by 2100 across scenarios and the largest increases under higher warming (4°C). While NECB indicates that restored wetlands remain a net carbon sink, CH₄ emissions reduce the climate benefit when expressed as a net GHG flux in CO₂-equivalent terms. This trade-off varies regionally. In temperate and boreal Northern Hemisphere regions, where historical drainage has been more extensive, restoration-driven CO₂ gains and avoided emissions generally outweigh increases in CH₄. In contrast, in tropical and Southern Hemisphere regions, where restoration area is smaller and warming-driven CH₄ amplification is stronger, CH₄ emissions play a larger role and can partially offset carbon sequestration gains. Overall, restoration reduces net GHG fluxes by up to 0.5 Gt CO₂-eq yr^{−1} relative to protection alone, emphasizing the value of accounting for both CO₂ and CH₄.

Climate simulations show that CH₄ increases alone would produce 0.04–0.05°C of additional warming by 2100, consistent with previous estimates of wetland CH₄ feedbacks. However, when CO₂ sequestration and avoided drainage emissions are included, the net temperature effect becomes slightly negative in both scenarios (−0.03°C under 2C and −0.007°C under 4C). Therefore, managed large-scale wetland restoration does not generate a global temperature penalty, even under high warming. The small magnitude of cooling highlights that temperature responses provide a different perspective than carbon-based metrics, reinforcing the need to evaluate multiple climate metrics.

Overall, our results suggest that large-scale wetland restoration is a potentially beneficial nature-based climate solution when aligned with strong mitigation. By improving carbon storage and reducing net GHG fluxes, restoration can contribute to net-zero targets, particularly in regions with historically drained wetlands. While CH₄ emissions constrain the net benefit, especially under high warming, restoration still reduces net GHG fluxes relative to protection alone and the global temperature response is small and neutral to slightly beneficial. These findings highlight the importance of evaluating multiple metrics to fully capture the climate implications of wetland restoration, as the slight differences between the net GHG flux and FaIR results reflect the different ways these metrics account for the climate effects of CH₄ and CO₂.

Finally, our results also emphasize the need for improved data sets and modeling capabilities to better represent wetland-specific processes in future assessments. Restoration may also generate regional trade-offs, for example

through impacts on air quality (e.g., tropospheric ozone), which should be considered alongside benefits for biodiversity, water regulation and other ecosystem services. When implemented strategically, wetland restoration can contribute to climate mitigation while preserving ecosystem services.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Data sets of methane emissions and carbon sequestration for global wetlands, along with the analysis scripts used to generate all figures and tables are provided Wagner et al. (2026). The historical wetland area data set used in this analysis is described in Fluet-Chouinard et al. (2023a) and is publicly available at Fluet-Chouinard et al. (2023b). Climate model output used in this study is from the Coupled Model Intercomparison Project Phase 6 (CMIP6) and is accessed through the Centre for Environmental Data Analysis (CEDA) archive at CEDA Archive Web Browser (2026). The reduced-complexity climate model FaIR is open source and available at Github: Finite-amplitude Impulse Response (FAIR) simple climate model (Github, 2024).

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