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Managing the Global Wetland Methane-Climate Feedback: A Review of Potential Options

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ABSTRACT

Methane emissions by global wetlands are anticipated to increase due to climate warming. The increase in methane represents a sizable emissions source (32–68 Tg CH_4 year^{-1} greater in 2099 than 2010, for RCP2.6–4.5) that threatens long-term climate stability and poses a significant positive feedback that magnifies climate warming. However, management of this feedback, which is ultimately driven by human-caused warming and thus "indirectly" anthropogenic, has been largely unexplored. Here, we review the known range of options for direct management of rising wetland methane emissions, outline contexts for their application, and explore a global scale thought experiment to gauge their potential impact. Among potential management options for methane emissions from wetlands, substrate amendments, particularly sulfate, are the most well studied, although the majority have only been tested in laboratory settings and without considering potential environmental externalities. Using published models, we find that the bulk (64%–80%) of additional wetland methane will arise from hotspots making up only about 8% of global wetland extent, primarily occurring in the tropics and subtropics. If applied to these hotspots, sulfate might suppress 10%–21% of the total additional wetland methane emissions, but this treatment comes with considerable negative consequences for the environment. This thought experiment leverages results from experimental simulations of sulfate from acid rain, as there is essentially no research on the use of sulfate for intentional suppression of additional wetland methane emissions. Given the magnitude of the potential climate forcing feedback of methane from wetlands, it is critical to explore management options and their impacts to ensure that decisions made to directly manage—or not manage—this process be made with the best available science.

1 | Introduction

Methane is the second strongest contributor to global warming and is about 84 times stronger than carbon dioxide (CO_2) on 20-year timelines (Myhre et al. 2013). Atmospheric methane (CH_4) is increasing rapidly; levels since 2020 are higher than any previously recorded, with 14–18 ppb annual increases between 2020 and 2022 (NOAA 2023). The increase in atmospheric methane has been tied to anthropogenic emissions, changes in atmospheric chemistry, and microbial sources, primarily from wetlands (Peng et al. 2022; Skeie, Hodnebrog, and Myhre 2023)—especially in the tropics (Feng et al. 2023).

Methane emissions from wetlands are anticipated to increase globally due to the combination of changes in air temperature, precipitation, and wetland area associated with climate change (Zhang et al. 2017). The amplifying feedback for enhanced methane production is stronger with increasing warming; for example, cold regions (e.g., boreal wetlands) could nearly double their proposed contribution to global emission increases from

16% to 28% under the more intense projected warming scenarios (RCP6.0 and 8.5; Koffi et al. 2020). Ground-based estimates indicate that global wetland methane emissions are already on the rise, increasing at a rate of 1.3–1.4 Tg CH_4 year^{-1} from 2000 to 2021 (Zhang et al. 2023). Models suggest that this rate of increase will remain consistent for ~30 years under low and moderate emission scenarios or could accelerate further under higher emission scenarios (Zhang et al. 2023). Annual wetland methane emissions are projected to increase from 190 Tg CH_4 year^{-1} in 2010 to 222–338 Tg CH_4 year^{-1} by the end of this century (RCP 2.6–8.5, Zhang et al. 2017). The additional wetland methane (32–148 Tg CH_4 year^{-1}) is equivalent to 9%–41% of present-day emission from all anthropogenic sources combined (Saunois et al. 2020).

Mitigating climate change requires reducing total anthropogenic greenhouse gas emissions. Ideally, the reduction of greenhouse gas emissions would be achieved directly, via decreases in fossil fuel use. Due to many challenges associated with decreasing global fossil fuel consumption, there is widespread interest in other avenues for halting climate change. The wetland methane feedback is functionally an indirect, or secondary, anthropogenic emission; this represents an increase over baseline natural emissions and can be attributed to human activity (Ripple et al. 2023). While increasing methane emissions from wetlands are a natural response to a modified climate, this perturbation is still driven by anthropogenic change. Thus, a management choice arises: do we attempt to mitigate these additional wetland emissions directly or simply account for them in net greenhouse gas (GHG) budgets addressed via overall emissions reduction plans (see Comyn-Platt et al. 2018)? The direct management option does not mean the elimination of all wetland methane emissions but rather management of the additional secondary anthropogenic emissions directly attributable to human activity. An analogy could be made with forest fire suppression, by recognizing that fire is an inherent part of ecosystems but *increases* in fire associated with climate change might be managed without eliminating its fundamental ecological role (e.g., Phillips et al. 2022).

Management of natural wetland methane emissions is largely unpracticed, although options have been considered (Singh et al. 2010; Stolaroff et al. 2012). Challenges arise primarily because these emissions originate from non-point sources, are relatively low concentration, and are emitted over large spatial areas (Johannisson and Hiete 2020). Methane management has, however, been more thoroughly explored for constructed wetlands (Yu et al. 2023), rice paddies (Hussain et al. 2015), land conversion to and from wetlands (i.e., restoration and drainage; Abdalla et al. 2016), and via laboratory experiments (Zhu et al. 2021; Rubin, Anderson, and Ballantine 2020). Insights into wetland methane management may also be gleaned from "natural" (or unintentional) experiments. For example, atmospheric sulfate deposition associated with acid rain from industrial pollution was estimated to have reduced global methane production by 10–15 Tg year^{-1} from 1940 to 2000 (Gauci et al. 2004). It must be noted, however, that the negative consequences of acid rain, including acidification of surface waters and soils (Reuss and Johnson 2012), declines in tree health (Johnson 1983), and mobilization of heavy metals (Driscoll and Schecher 1990) were devastating for whole-forest ecosystems. Nonetheless, acid rain provided a natural experiment in methane management, if inadvertent.

The purpose of this paper is first to review wetland methane management opportunities and strategies covered in the literature. Second, we identify patterns in wetland methane feedback intensity at global and biome-scales to locate hotspots of future additional emissions. Note that hereafter, we refer to methane management in general terms, but the focus of our study was to address only those *additional* wetland methane emissions arising from the anthropogenic global warming and the related emissions feedback. Third, we conduct a thought experiment of a hypothetical management scenario—global wetland sulfate amendments—providing a first estimate of the scale of the potential impact on methane emissions. We emphasize caution; while the methane feedback phenomenon is well described, potential management solutions are not, and our goal is to guide research priority setting, both in terms of geographic location and management methodologies, rather than to propose immediate action.

2 | Materials and Methods

Below we describe the following methods: (1) the review process to identify potential wetland methane management techniques; (2) the feedback mapping methodology; and (3) the thought experiment of a sulfate intervention, based on findings from the literature (1) and applied to feedback hotspots (2).

2.1 | Literature Review

The first task involved considering what management actions may be feasible, if any. A Web of Science search using the terms (["methane" OR "CH4"] AND ["wetland*" OR "peat*" OR "marsh" OR "paddy" OR "mangrove"] AND ["manag*" OR "mitigat*" OR "suppress*"]) yielded 2537 results. We evaluated titles and abstracts to refine results to papers that explicitly test or review methods for reducing methane emissions.

For each study, we noted the type of wetland (Supporting Information S1: Table S1), the experimental design (lab, field, etc.), and then categorized management types into the following broad categories:

- Land management/land use conversion—this includes conversion of wetlands to other land uses, restoration of wetlands, and restoration approaches. This also includes management of surrounding/upstream environments.
- Hydrologic management—includes water level management, impoundment, connectivity and tidal control (including salinization).
- Amendments—includes chemical or organic additions to wetlands or the wetland substrate.
- Vegetation and crop management—includes plant species selection, harvesting, rotating, etc.
- Emerging technologies—covers a wide range of alternative strategies including technologies still in development or

ideas yet to be developed. This is also a catch-all category for novel management practices that do not fit neatly into another category.

2.2 | Feedback Mapping

Future wetland methane emissions for RCP2.6 and 4.5 were taken from Zhang et al. (2017), which models projected emissions to 2100 at 0.5° resolution; recent work by the same group has confirmed the model's accuracy over the last several years (Zhang et al. 2023). Estimates of methane growth from RCP4.5 represent a "middle of the road" future emissions scenario that aligns with our current emissions pledges and trajectory and RCP2.6 represents a more conservative estimate of future methane emissions increases from wetlands (Burgess et al. 2020; Meinshausen et al. 2020; Riahi et al. 2017). Though other future projections of methane emissions from wetlands exist (Kleinen et al. 2021), the estimates from Zhang et al. (2017) are more conservative. Use of less conservative methane emissions estimates may result in more total emissions to suppress. We summed the original methane emissions data, reported in g m^{-2} $month^{-1}$, to the year using a wetland area raster (described below). Zhang et al. (2017) reports a standard deviation of about 20% across all models used to generate their methane emissions projections; therefore, a 20% random error was applied at the pixel scale for each iteration of 100 Monte Carlo simulations.

We used the wetland area reconstruction from Fluet-Chouinard et al. (2022, 2023), which maps intact wetlands at 0.5° resolution. Note that there are numerous global wetland maps (see Xi et al. 2022; Zhang et al. 2024) with some discrepancies between them, particularly with respect to tropical wetland distribution. Despite the inherent uncertainty in wetland mapping efforts, the reconstruction from Fluet-Chouinard et al. (2023) provides a reasonable basis for the purpose of this paper. We limited the analysis to grid cells with greater than 3% wetland cover, an arbitrary threshold necessary for eliminating unrealistically high area-normalized flux estimates that can arise due to minor inconsistencies between the wetland area reconstruction and wetland methane emissions estimate. This cutoff decreases global emissions estimates by approximately 2% (171 Tg $year^{-1}$ compared to 175 Tg $year^{-1}$ in 1961), which we deemed acceptable. The cutoff also serves to narrow the opportunity space for action to places with higher wetland density and, therefore, more efficient for management. Results were robust to slight changes in this threshold (data not shown).

Historical climate data is from WoldClim 2.1 (https://www.worldclim.org/data/worldclim21.html) with 10-min resolution (Fick and Hijmans 2017). Future climate data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) with WorldClime 2.1 baseline is from (https://www.worldclim.org/data/cmip6/cmip6climate.html, Eyring et al. 2016). For both historical and future climate data, air temperature maps were extracted and resampled to 0.5° resolution via bilinear interpolation.

Biome delineations are from the Köppen-Geiger climate zone maps (present day 1991–2020; Beck et al. 2023a; Beck et al. 2023b). The biomes were grouped into boreal, temperate, and tropical regions to facilitate broad comparisons (Supporting Information S1: Table S2 & Figure S1). Data were analyzed at the global scale, and as separate regions for tropical, temperate, and boreal biomes.

The methane feedback strength was calculated as the difference between estimated emissions in 2099 compared to a baseline set at 2010. Although 2010 includes some feedback emissions associated with anthropogenic warming prior to that point, it was chosen because it corresponds to the atmospheric sulfur (S) deposition map relevant to the potential management thought experiment (below).

Hotspots for methane feedback strength were identified by calculating the emission intensity percentiles for total wetland pixels ($g\,m^{-2}$). Pixels greater than the 95th percentile of emission intensity were classified as hotspots. Rather than total emissions per pixel, we chose intensity of emissions because management actions will likely be implemented based on intensity and at a finer resolution than the 0.5° pixel sizes. We chose the 95th percentile threshold arbitrarily; sensitivity tests to this threshold indicated that spatial distribution of the hotspots was generally unchanged with increasing or decreasing the percentile threshold.

2.3 | Sulfate Intervention Thought Experiment

Sulfate application is one of the most well-studied wetland methane reducing strategies (see Results). As a thought experiment to explore the outcome of potential methane management, we modeled the application of sulfate at broad scales based on literature-derived relationships between historic atmospheric sulfur (S) deposition, air temperature, and rising wetland methane production. For the thought experiment, we use a one-time sulfate treatment of 15 kg SO_4-S ha^{-1} across all wetlands (global), corresponding to the experiment from which the methane suppression model (described below) was derived (Gauci et al. 2004; Gauci et al. 2005). Above this level, wetlands may become sulfate saturated, and the suppression of methane emissions begins to level off (Gauci et al. 2004).

Pre-existing atmospheric sulfur deposition must first be considered, as methane suppression asymptotes with increasing sulfate (Gauci et al. 2004), so ongoing atmospheric sulfur deposition derived from industrial sources would constrain the potential intentional additional suppression (we note that excess sulfate in soils may have other consequences for wetland ecology, see Section 4). We account for baseline atmospheric sulfur deposition with a global map of wet and dry atmospheric sulfur deposition from Rubin et al. (2023). Gauci et al. (2004) used a Michaelis-Menton model and global dataset of methane emissions estimates and atmospheric sulfur deposition rates to calculate potential methane suppression:

$$\text{Percent } CH_4 \text{ suppression} = \left(V_{max} \times S_{DEP}\right) / \left(S_{DEP} + K_m\right) \quad (1)$$

where the maximum reaction rate, $V_{max} = 38.6 \pm 10.7$, the Michaelis constant, $K_m = 8.71 \pm 10.6$, and S_{DEP} is the atmospheric sulfur deposition rate in kg SO_4-S ha^{-1} $year^{-1}$. Equation (1) is used in conjunction with the global atmospheric sulfur deposition map (Rubin et al. 2023) to arrive at a map of baseline S-mediated methane emissions suppression.

We then calculated the potential for additional methane suppression via intentional management as the difference between the maximum calculated potential suppression (e.g., with zero present-day deposition) from (1) and modeled present day deposition (Rubin et al. 2023). The effect of including current atmospheric sulfur deposition is to account for sulfur saturation in the soil in areas with atmospheric sulfur deposition rates high enough to negate the methane suppressing effects of additional sulfate applications. This approach has no effect on areas with low current atmospheric sulfur deposition rates. The maximum potential suppression is ~30% (per Gauci et al. 2004 and equation (1), reached at rates of application at or above ~20 kg SO_4-S ha^{-1} $year^{-1}$).

Air temperature also modifies the sulfate–methane suppression relationship, although it is less studied. In lab tests of rice paddy soil slurries by van Bodegom and Stams (1999), methane formation rates increased 5.4 times faster than sulfate reduction rates with air temperature. This result indicates that at warmer air temperatures, the suppressive effects of sulfate on methane formation are reduced. The potential suppression for locations above 14°C was therefore reduced accordingly, assuming a linear decline in effectiveness (van Bodegom and Stams 1999). For air temperatures above 14°C, the percent suppression was reduced according to the following:

$$\text{Percent effectiveness reduction} = -1.525(x) + 51.35 \quad (2)$$

where x is the mean annual temperature of a pixel. This value was subtracted from the maximum potential (30%) taking into account current suppression already occurring from (1). The end result is an estimate of the potential suppression of additional sulfate at a given location, given mean annual air temperature and current atmospheric sulfur deposition patterns. We then apply the potential percentage emission reduction to the total emissions of the cell, both for current climate and future (2099) air temperature scenarios. We note that some studies do not report significantly decreased methane with higher sulfur, despite high air temperatures (e.g., dos Santos Fonseca, Marinho, and de Assis Esteves 2019). In contrast, inundation in frequently flooded wetlands (e.g., floodplain wetlands in the Amazon) would likely inhibit sulfate movement into soils, decreasing treatment efficacy. As there are few systematic studies of sulfate driven methane suppression across different types of wetlands, particularly tropical wetlands, our results should be considered illustrative only.

2.4 | Statistical Analysis

To account for uncertainty, all steps, including methane feedback calculations, hotspot identification, and sulfate potential calculations, were repeated 100 times in a Monte Carlo type process, randomly drawing from the error raster and the uncertainty ranges for all applicable calculations. We conducted all processing in R (Version 4.2.3), using the 'terra', 'sp', 'rgdal', 'raster', 'bioclim', 'geodata', 'vtable', and 'ggplot2' packages (Hijmans 2023a; Pebesma and Bivand 2005; Bivand, Keitt, and Rowlingson 2023; Hijmans 2023b; Serrano-Notivoli 2023; Hijmans et al. 2023; Huntington-Klein 2023; Wickham 2016).

3 | Results

3.1 | Literature Review

A total of 2537 papers were returned from the literature search, and we identified 619 as relevant after an initial screening. The resulting wetland types can be described as undisturbed/unmanaged, drained/degraded, managed (for cultivation or other purposes), restored, or constructed (including some artificial waterbodies such as aquaculture ponds and waste lagoons). Although the focus of this study is on methane management in natural or unmanaged wetlands, studies in these systems are very limited. Therefore, we draw insight from studies conducted in other types of wetlands including constructed wetlands and rice paddies. Most of the relevant papers ($n = 465$) concern rice paddies, but our review focuses on approaches relevant for use in unmanaged wetlands. The results also included a small number of papers on the management of the land within a wetland's catchment (uplands) for the purpose of influencing wetland methane emissions ($n = 4$). Finally, the literature search also returned several reviews and meta-analyses ($n = 13$ for non-rice wetlands, $n = 31$ for rice paddies), each pertaining to a single methane management approach or wetland type, but none are comprehensive across all approaches and wetland types. The main reason for exclusion from our analysis was a lack of intention for methane reduction; instead, most studies evaluated environmental controls on methane emissions. We note that in all cases, these studies focus on reducing total methane emissions from wetlands, not the additional fraction associated with climate change. Below we briefly outline the processes underlying the control of methane emissions in wetlands and then synthesize the outcomes of each class of management strategy observed in the literature (see Supporting Information S2 for full list).

3.1.1 | Processes Controlling Methane Emissions From Wetlands

As methane emissions in wetlands are largely governed by microbial processes that produce and consume methane, it follows that controlling methane emissions requires managing microbial community structure and processes (Singh et al. 2010). The most prominent pathway of controlling methane emissions is by inhibiting methanogens—the bacteria that produce methane—via the introduction of oxygen or other more energetically favorable terminal electron acceptors (Yu et al. 2023). Methanogen activity can also be inhibited by managing the availability of the carbon source (Liu et al. 2019). Alternate approaches for management of methane include cultivation or promotion of methanogens, the microbes that consume methane in situ (Singh et al. 2010). The last process involved in the management strategies reviewed here is the transport of methane which is addressed by technologies for methane capture (Stolaroff et al. 2012).

3.1.2 | Amendments

The most common manipulative studies performed in unmanaged wetlands are those that test the effect of various amendments on methane emissions, generally iron, humic acids, nitrogen compounds, sulfate, and biochar (Table 1). Study aims were usually centered on existing pathways of amendment introduction, for example, nitrate and sulfate additions studies designed to explore the effects of acid rain deposition (Gauci, Dise, and Fowler 2002; Dise and Verry 2001). Miller et al. (2015) aimed to mimic enhanced inputs of these compounds resulting from accelerated glacial melting. Finally, the biochar addition experiments by Sun et al. (2021) aimed to mimic conditions following a peat fire.

The strongest methane reduction achieved through treatment with amendments was nearly complete (99.6%) reduction following dissolved organic matter and bromoethane sulfonic acid ($C_2H_5BrO_3S$) additions by Blodau and Deppe (2012) in a lab study that did not consider potential environmental toxicity. Generally, studies conducted in the lab achieved stronger methane reduction than those done in the field (see Gao, Chen, and Zeng 2014). Iron additions (applied as 5 mM Fe(III)-nitrilotriacetic acid) produced a mild suppression of methane production (26%) from the sole study of its application to unmanaged wetlands in the field (Miller et al. 2015).

Nitrogen (NH_4 and NO_3) and sulfate additions were tested in multiple studies achieving variable effects on wetland methane emissions (Eriksson, Öquist, and Nilsson 2010; Gao, Chen, and Zeng 2014; Gauci, Dise, and Fowler 2002; Hu et al. 2017). Results from sulfate additions range from no significant effect (Eriksson, Öquist, and Nilsson 2010; Hu et al. 2017) to 21%–42% reduction observed in the field (Gauci, Dise, and Fowler 2002) to 64% reduction achieved in a lab setting (Gao, Chen, and Zeng 2014). Hu et al. (2017) indicated that their marsh system in the Min River in China is sulfate saturated, explaining the lack of response from additional sulfate.

Effects of nitrogen additions were more variable: 50%–57% reduction observed in peatlands of the Tibetan Plateau (Gao, Chen, and Zeng 2014), no significant effect observed in a northern Minnesota fen in the USA (Dise and Verry 2001), and significant enhancement (262%) of methane emissions in an estuarine marsh in Southern China (Hu et al. 2017). Eriksson, Öquist, and Nilsson (2010) observed an interaction between nitrogen and sulfate treatments whereby at low levels of sulfate and nitrogen additions stimulated methane production, but at high levels of sulfate, the nitrogen addition had no effect on methane.

Finally, our literature search yielded two studies that examined the effects of biochar on wetland methane production (both in a laboratory setting) with mixed results (Sun et al. 2021; Yan et al. 2020). Sun et al. (2021) observed a 13%–24% reduction in methane emissions while Yan et al. (2020) observed elevated methane emissions following biochar application, although still a reduction in overall global warming potential (GWP) through reductions in N_2O and CO_2 emissions. We note but do not review here an extensive body of literature on the use of biochar in rice farming, which shows significant uncertainty surrounding long-term efficacy in methane suppression (Nan et al. 2021).

3.1.3 | Vegetation

Liu et al. (2019) demonstrated that reed harvesting (removal of a carbon source) by native residents for their economic value reduced annual cumulative methane emissions by 64% compared to unharvested controls. Other vegetation-based strategies for methane control in rice paddies include the co-cropping with plants like Azolla species (aquatic ferns) to promote oxygenation of the rooting zone or the incorporation as green manure, such as Chinese milkvetch (*Astragalus sinicus*), as a fertilizer replacement; however, these approaches would likely have limited application in natural wetland settings (Liu et al. 2017; Zhou et al. 2020).

3.1.4 | Technological

While there have been numerous studies on emerging technologies in constructed wetlands (e.g., microbial fuel cells, artificial aeration) and aspirations for metagenomic approaches to methane control through cultivated methanotrophs (Silva-Gónzalez et al. 2018), these are yet to be tested in natural wetlands. In one unique case, direct methane capture from Lake Kivu on the border of the Democratic Republic of the Congo and Rwanda has been effectively used since 2016 (Bartosiewicz, Rzepka, and Lehmann 2021).

3.1.5 | Hydrological

Generally, drainage of wetlands reduces methane emissions, but at the expense of extensive CO_2 and N_2O emissions that generally negate any climate benefit (Murdiyarso, Hergoualc'h, and Verchot 2010; Laine et al. 2019). In a comparison of unmanaged, drained, and restored shrub bogs in North Carolina, Wang et al. (2021) observed a strong relationship between water table depth and methane emissions, with a threshold effect whereby water levels at least 5 cm below the peat surface markedly reduced methane emissions. The restoration of tidal flows, or the reconnection of impounded wetlands to coastal waters, shows considerable promise for reducing wetland methane emissions, but is limited to coastal contexts (Holmquist et al. 2023). The reintroduction of seawater, naturally rich in sulfate and other redox active compounds, efficiently reduces methane production in coastal wetlands (Kroeger et al. 2017; Sanders-DeMott et al. 2022). Despite being limited to coastal settings, recent work by Holmquist et al. (2023) demonstrates tremendous opportunity (~0.5 million hectares) for this kind of restoration in coastal regions of the continental United States alone.

3.1.6 | Upland Management

Less intensive land use (either agricultural or urban) is correlated with lower wetland methane emissions (Peacock

TABLE 1 | Select natural wetland amendment mitigation studies (or samples taken from natural wetlands). For other treatments on other wetland types, and full citations/descriptions, see Supporting Information S2.

Amendments	Details	Effect on methane emissions (reduction, unless otherwise specified)	Scalability and trade-offs	Citation
Humic acid amendments	DOM (dissolved organic matter) and BES (bromoethane sulfonic acid) tested in laboratory setting to peats from the Mer Bleue bog in Canada	39% (DOM 70 mg/L) 72% (BES 100 μmol/L) 99.6% (DOM + BES)	Yet to be tested at field scale. BES might not be safe to those applying it.	Blodau and Deppe (2012)
Iron and humic acid	Field experiment in wet sedge tundra near Barrow, Alaska FE(III)-nitrilotriacetic acid and Sigma Aldrich Humic Acids	26% (5 mM Fe(III)) 25% (1 g HAs/L)	Experiment does not capture seasonal dynamics	Miller et al. (2015)
Nitrogen and sulfate	Mixed mire peatland in Sweden. Reports the effects after 10 years of annual S + N treatments 2 or 30 kg NH_4NO_3-N /ha/year 3 or 10 kg Na_2SO_4-S /ha/year	No effect of sulfate alone. Interaction effect between S and N treatments	At low S levels, SxN treatment enhanced emissions, but at high S levels, SxN had no effect on methane emissions.	Eriksson, Öquist, and Nilsson (2010)
Nitrogen and sulfate	High altitude peatland in the Tibetan Plateau (laboratory experiment) NH_4NO_3, 5 g N m^{-2} Na_2SO_4, 2.5 g S m^{-2}	50%–57% (N) 64% (S, low water table only)	Under high water table, the S treatment slightly enhanced CH_4 emissions The N treatment enhance N_2O emissions	Gao, Chen, and Zeng (2014)
Nitrogen and sulfate	Estuarine marsh of the Min River in China $NH_4Cl + KNO_3$ (24 g N m^{-2} $year^{-1}$) K_2SO_4 (24 g S m^{-2} $year^{-1}$)	Insignificant effect of sulfate addition on CH_4 production (−20%, n.s.) NH_4Cl led to an increase in CH_4 (262%)	Sulfate saturated marsh showed no CH_4 response to additional sulfate	Hu et al. (2017)
Nitrogen and sulfate	Ombrotrophic fen in Finland (lab experiment) KNO_3 (10 mM NO_3^-) Na_2SO_4 (10 mM SO_4^{2-})	20%–94% reduction	Microbial biomass varied greatly with depth and peat microform type	Lozanovska et al. (2016)
Sulfate	Simulated acid rain sulfate deposition—pristine peat bog in Northern Scotland Dissolved Na_2SO_4 (25, 50, 100 kg S ha^{-1} $year^{-1}$)	21%–42% reduction	Treatments intended to simulate acid rain, not a test of a management strategy	Gauci, Dise, and Fowler (2002)

(Continues)

TABLE 1 | (Continued)

Amendments	Details	Effect on methane emissions (reduction, unless otherwise specified)	Scalability and trade-offs	Citation
Sulfate	Lab investigation of peat monoliths from Northern Scotland Na_2SO_4 15 kg SO_4^{2-} S ha^{-1} $year^{-1}$	30% reduction	Greater suppression observed at low temperatures	Gauci et al. (2005)
Nitrogen and sulfate	Peatland in northern Minnesota NH_4NO_3 (4-fold increase over natural deposition) $(NH_4)_2SO_4$ (~6-fold increase) This is 1–2 orders of magnitude higher than acid rain (but it gets diluted in the porewater)	37% reduction on average (sulfate) Total flux was 32% lower (sulfate) No sig effect of N treatment	One concern is that sulfate additions would need to be very frequent to maintain suppression of methanogen activity	Dise and Verry (2001)
Biochar	Coastal wetlands in the Yellow River Delta, China (lab incubation experiment—not under anoxic conditions) Biochar from *Spartina alterniflora* and *Phragmites communis* at three different treatment levels (1, 5, 10%)	Raises CH_4 emissions, however controls conditions were already taking up more CH_4 that releasing—so this might not have been a good test case	Reduces CO_2 emissions, but raises CH_4 emissions, and either raises or lowers N_2O emissions depending on water level. Net reduction in GWP	Yan et al. (2020)
Biochar/land use management	Pyrogenic carbon from controlled peat fire (boreal peatlands) in lab incubated peat from the Mclean Bog, New York	13%–24% reduction	Potential hazard of peat fires getting out of control	Sun et al. (2021)

et al. 2017; Vermaat et al. 2011; Jones et al. 2018). The effect of excess nutrients from agricultural runoff has been shown to produce contrasting effects on methane emissions in wetlands and should be the focus of future study (Pasut et al. 2021; Maucieri et al. 2017; Badiou et al. 2011).

3.2 | Geographic Locations of High Intensity Feedbacks

The increasing methane emissions associated with the positive feedback (above baseline emissions from 2010) are substantial, from 32 (SD: 0.7) to 68 (0.8) Tg CH_4 year^{-1} by 2099. However, the vast majority of these emissions come from only a small fraction of global wetlands; pixels in the top 5th percentile of methane emissions intensity are associated with 64%–80% of these additional emissions at a global scale (Table 2, Figure 1). At the biome level, the emission hotspots are less dominant, with 46%–64% of emission increases associated with the top 5% of tropical wetland area. Anticipated increases in boreal wetland methane emissions are more evenly distributed with only 25%–35% arising from hot spots, and the temperate zone exhibits an intermediate level of hotspot stability, with respect to geographic distribution (Supporting Information S1: FigureS2).

3.3 | Sulfate Intervention Thought Experiment

The thought experiment scenario of a one-time 15 kg SO_4-S ha^{-1} application to all wetlands, incorporating air temperature sensitivities, suggests that ~21 Tg year^{-1} CH_4 emissions could be avoided globally, corresponding to 31%–64% of additional (feedback-derived) wetland methane emissions. Generally, additional wetland methane emissions suppression is higher in the boreal and temperate zones, but as the tropics contribute the largest portion of the global feedback, the global percentage is moderate (Table 3, Supporting Information S1: Figure S3). In boreal and temperate latitudes, potential methane emissions suppression can exceed 100% of additional methane, more than compensating for this emission burden and resulting in a modest reduction of baseline methane emissions.

If sulfate treatments are applied only on the hotspots of additional methane, suppression estimates are reduced to 10%–21% of that additional methane on a global scale (Table 3), with the suppression percentage lower in the higher warming scenario. There is substantial uncertainty around these estimates owing to the propagation of error from future methane emission estimates and the methane suppression model (Equation 1). Further, other factors, such as water table depth, may help explain some of the uncertainty and are important areas for future research (see Discussion).

We can anticipate the impact on sulfate treatment efficacy as methane emissions increase and temperature warm throughout the 21st century. As methane emissions from wetlands rise, so does the capacity for methane suppression in boreal and temperate zones. In the tropics however, treatment efficacy declines as the air temperature threshold (14°C) governing the microbial processes is reached (Equation 2). Globally, the methane suppressing effects of sulfate treatments will approximately stay the same, with a decrease in net reductions in tropical zones offset by an increase in boreal and temperate zones (Table 4). The results presented here only reflect changes in sulfate treatment response to anticipated warming, not any change to the earth's temperature that might follow from the treatment itself.

4 | Discussion

In the context of wetlands, the climate-methane feedback represents *additional* emissions, above the baseline of "normal" wetland emissions and so is functionally anthropogenic. The anticipated increases in wetland methane emissions are substantial and highly sensitive to the degree of warming—twice as much methane in the warmer (RCP4.5) than the less warm (RCP2.6) scenario (~68 vs. 32 Tg additional methane, Zhang et al. 2017). Wetlands could surpass overall emission rates from direct anthropogenic sources by the latter half of the century (Zhang et al. 2017, 2023) making this an important source of emissions to address.

On a global scale, the strongest effect of climate-methane feedback on wetland methane emissions is in the tropics (25–53 Tg

TABLE 2 | Feedback strength by 2099 associated with the top 5th percentile of emitting wetland pixels. Hotspot emissions are mean (standard deviation) feedback emissions only (2099–2010 emissions), averaged over 100 model runs.

Biome	Total (km^2)	Hotspot (km^2)	Total (Tg)	Hotspot (Tg)	Fraction (%)
RCP 4.5					
Global	13,318,000	1,010,000 (11,000)	68 (0.8)	43 (0.9)	64 (0.6)
Boreal	3,820,000	172,000 (4000)	6.6 (0.1)	1.6 (0.1)	25 (0.8)
Temperate	4,010,000	211,000 (6000)	8.0 (0.2)	3.5 (0.1)	44 (1.1)
Tropical	5,490,000	381,000 (9000)	53 (1.1)	25 (1.0)	46 (1.3)
RCP 2.6					
Global	13,318,000	960,000 (15,000)	32 (0.7)	26 (0.6)	80 (0.8)
Boreal	3,818,000	215,000 (7000)	3.8 (0.1)	1.3 (0.1)	35 (0.8)
Temperate	4,014,000	203,000 (6000)	2.9 (0.2)	2.3 (0.1)	78 (2.2)
Tropical	5,487,000	371,000 (10,000)	25 (1.2)	16 (0.5)	64 (2.2)

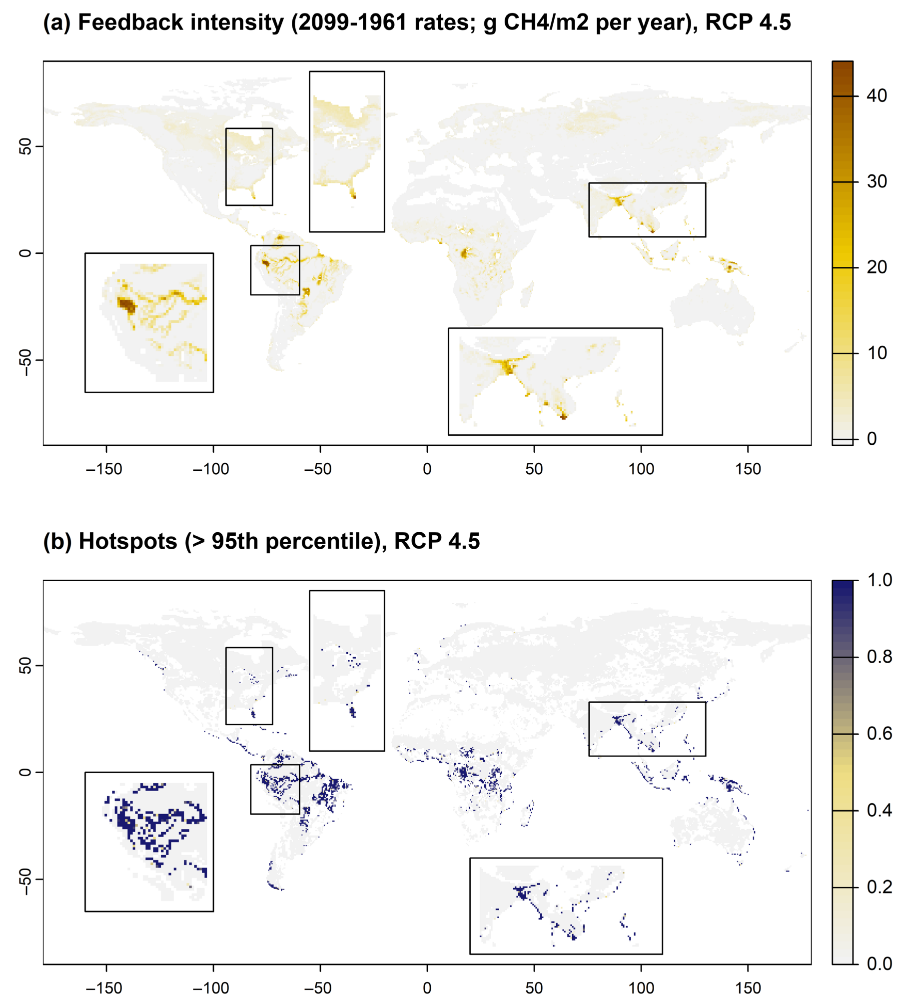

FIGURE 1 | Wetland methane feedback intensity and hotspots. (a) Feedback intensity is shown in g CH_4 per m^2 per year. (b) Hotspot gradations represent the percentage of iterations where a given pixel was in the top 5th percentile; higher values indicate stable high intensity emission estimates.

TABLE 3 | Estimates of sulfate addition reductions on methane emissions (SD) from wetlands, globally and biome-level, for treatments applied to all wetlands versus hotspots only. Includes 2010 sulfur deposition rates. The estimates for 2099 assume the same sulfur deposition as 2010. The fraction of additional methane suppressed is relative to 2099 feedback strength (see Table 1).

	2010		2099		Fraction of additional methane suppressed (2099)	
Biome	**All (Tg)**	**Hotspots (Tg)**	**All (Tg)**	**Hotspots (Tg)**	**All (%)**	**Hotspot relative to global total (%)**
RCP 4.5						
Global	21 (17)	8.5 (9.1)	21 (24)	7.1 (13)	31 (35)	10 (19)
Boreal	3.7 (1.1)	0.6 (0.2)	5.4 (1.1)	0.9 (0.2)	82 (17)	14 (3)
Temperate	4.5 (2.3)	0.9 (0.7)	5.2 (2)	1.0 (0.5)	65 (25)	13 (6)
Tropical	12 (13)	4.1 (4.3)	10 (20)	3.5 (3.1)	19 (38)	7 (6)
RCP 2.6						
Global	21 (18)	7.5 (7.8)	21 (20)	6.6 (9.4)	66 (63)	21 (29)
Boreal	3.7 (0.9)	0.7 (0.2)	4.7 (1.2)	0.9 (0.3)	124 (32)	24 (8)
Temperate	4.6 (2.4)	0.8 (0.5)	4.7 (2.6)	0.8 (0.7)	162 (90)	28 (24)
Tropical	13 (141)	3.9 (4.1)	11 (17)	3.5 (5.0)	44 (68)	14 (20)

TABLE 4 | Change in the potential suppressive capacity of the sulfate treatment scenario based on anticipated change in air temperature and wetland methane emissions between 2010 to 2099.

Biome	Global	Hotspots only
	Change total Tg CH_4 suppressed (percent)[a]	
RCP 4.5		
Global	0 (0%)	−1.4 (−16%)
Boreal	1.7 (+46%)	0.3 (+50%)
Temperate	0.7 (+16%)	0.1 (+11%)
Tropical	−2.0 (−17%)	−0.6 (−15%)
RCP 2.6		
Global	0 (0%)	−0.9 (−12%)
Boreal	1.0 (+27%)	0.2 (+29%)
Temperate	0.1 (+0.2%)	0 (0%)
Tropical	−2.0 (−15%)	−0.4 (−0.1%)

[a]Positive change indicates an increase in methane suppression (treatment efficacy) in 2099 relative to 2010.

year^{-1}), reflecting the warmer air temperatures and precipitation conditions expected with climate change. The additional emissions are not homogenously distributed; the top 5th percentile of tropical wetland pixels contributes 46%–64% of the additional methane, reflecting the heavily skewed distribution towards high intensity feedback locations (Figure 1). The upside of such spatial biases is opportunities for prioritizing interventions, though some interventions may be more or less viable in different locations. At middle latitudes, the southeast United States, parts of temperate Chile, and parts of China are also consistent hotspots of additional methane. Additional methane emissions in boreal regions are more diffuse in space, in part due to the error incorporated into the modeling framework, which generally overwhelms any spatial heterogeneity in the estimated feedback.

A question then becomes what, if any, direct mitigation options exist and what might their potential impact be? There have been many studies aimed at understanding methane management in wetlands, primarily and unsurprisingly focused on constructed/managed wetlands and rice paddies/agricultural settings. But to our knowledge, there are no studies looking at management of the feedback process itself, although it seems reasonable to assume initially that methods to influence baseline methane production would also impact additional methane brought on by warming. Similarly, there have been few studies on methane management which simultaneously investigate N_2O and CO_2 production (but see Cheng et al. 2021), which should be considered alongside any methane reduction.

Perhaps the only "treatment" that has been seen at scale over intact wetlands is atmospheric sulfur and nitrogen deposition, unintentionally via industrial pollution. Prior to the Clean Air Act and Amendments in the U.S., as well as similar regulation elsewhere, air pollution was global but heterogeneous, primarily downwind of industrial centers, and strongly impacted ecosystems (Vet et al. 2014; Grennfelt et al. 2020). Pollution controls have had significant positive effects, though they also raised unexpected issues such as the need for more sulfur fertilizers to meet crop needs to replace what was previously supplied through atmospheric deposition (Hinckley et al. 2020; Feinberg et al. 2021; Hinckley and Driscoll 2022) and increased methane from agricultural soils (Liu et al. 2020).

In our thought experiment, a one-time addition of sulfate at ~15 kg SO_4-S ha^{-1} might suppress some of the additional wetland methane associated with global climate change without altering baseline fluxes. This additional methane, estimated from 32 to 68 Tg year^{-1}, might be reduced by 21 Tg year^{-1}, or ~31%–66% at global scales (Table 3) by 2099. Focusing treatment on only the hotspots of the wetland climate-methane feedback may accomplish a fraction of those emissions reductions (10%–20%), but this estimate varies by biome. If focusing only on boreal and temperate latitude hotspots, where the cooler climate is not expected to undermine the sulfate treatment effectiveness, reduction estimates are higher: 13%–28% of temperate latitude emissions and 14%–24% of boreal emissions.

It is vital to consider that both the scale and potential side effects of sulfate applications are significant and may preclude broad application. Sulfate has direct effects on the pH of sediments and soils leading to the mobilization of heavy metals (Gerson and Hinckley 2023; Hinckley et al. 2020; Hinckley and Driscoll 2022). One of the most concerning effects of excess sulfate—particularly in moderate amounts in wetlands—is that its reduction can stimulate the methylation of mercury (MeHg), a potent neurotoxin that biomagnifies and bioaccumulates in the food web (Gerson and Hinckley 2023). Mercury methylation has been tied to sulfate reduction in multiple different environments, including forests (Kronberg et al. 2016; Skyllberg 2009), rice paddies (Lei et al. 2021; Zhao et al. 2016), and downgradient of agricultural areas (e.g., sugarcane, see Corrales et al. 2011; Orem et al. 2019). Other potential consequences of enhanced rates of sulfate reduction from excess sulfate in wetlands include phytotoxicity in response to elevated hydrogen sulfide concentrations (Lamers et al. 2013) and internal eutrophication caused by interactions of reduced sulfur and iron, which can liberate phosphorus (Chen et al. 2021). Due to these issues, which directly affect the health of ecosystems, wildlife, and people, it is critical to proceed with caution when considering additions of sulfate for mitigation of methane fluxes from wetlands; there will be trade-offs at any scale and especially at global extents. Our thought experiment is intended to complement the review by establishing the impact of one direct management option, at least by order of magnitude. More research is needed to determine if such an option is viable.

Nonetheless, it is worth evaluating the potential impacts of wetland sulfate additions. Sulfate may enter wetland systems in the future, regardless of the intent to suppress methane emissions, if stratospheric aerosol injections (SAI) of sulfate are employed as a climate change mitigation strategy (or geoengineering; NASEM 2021). Sulfate aerosols show promise for climate cooling, a concept with a natural analogue:

sulfate emissions during explosive volcanic eruptions (Irvine et al. 2016). Although sulfate deposition from volcanoes has been shown to reduce methane emissions from wetlands (Gauci et al. 2005; Gauci et al. 2008), SAI is intended to cool the earth, through a different mechanism – reflecting sunlight back into space (Irvine et al. 2016). However, whether the sulfate originates from a volcano or an aircraft deploying SAI, this material would eventually be deposited on the earth's surface (Visioni et al. 2020). One recent estimate suggests that SAI sufficient to offset all future warming under two emissions scenarios (RCP 4.5 and 8.5) would result in atmospheric deposition rates approximately equal to 11 Tg S year^{-1} and 19 Tg S year^{-1}, respectively, by the end of the century (Visioni et al. 2020). Given some projected declines of aerosol pollution rates in the future, these additions of sulfate to the atmosphere via SAI would effectively maintain the overall global sulfate deposition rates similar to those of 2010 (Visioni et al. 2020). However, as per the climate model results in Visioni et al. (2020), the spatial distribution of atmospheric sulfur deposition would change relative to 2010, with little occurring in the tropics and large increases in deposition in high precipitation areas at temperate latitudes (Northwest-North America, Himalayas) and in higher latitude areas due to large-scale stratospheric circulation. This would likely have an impact on the relative magnitude of the methane-S interactions in wetlands modeled in the previous sections and thus may affect how much SAI is considered necessary to offset global warming due to changes in methane emissions. Further work on the geographic distribution of sulfate deposition due to SAI in relation to wetlands is a key data need, as it is the incorporation of the net effects of SAI given this potential interaction. We also note that current climate models as those used in SAI studies have a horizontal resolution too coarse to properly resolve local deposition on wetlands, and therefore, higher resolutions or limited area modeling would be necessary to further investigate regional rates of atmospheric deposition for this purpose.

More research is also necessary before actual management should be considered, both on potential effectiveness (to reduce uncertainty) and on other environmental impacts. For many of the potential management strategies (Table 2) the unintended consequences are essentially unexplored; for sulfate applications, we hypothesize environmental impacts would be similar to some of those observed due to acid rain and potentially severe enough to preclude its use entirely. These impacts should be considered at the entire system level (e.g., co-measuring impacts on CO_2 and N_2O, heavy metal mobilization, water quality, and other metrics) relative to the impact of climate change in a risk–risk/tradeoff framework rather than in isolation.

4.1 | Caveats

Despite the likely global significance of the climate-methane feedback (Zhang et al. 2023), there is a dearth of information related to the management of this problem. Our literature review found no papers focused on management of the methane feedback in wetlands explicitly. While it is certainly possible that direct management will never be feasible or desirable, our work suggests a need to consider the full breadth of options.

Our expansion of the review of wetland methane emission suppression via the sulfate thought experiment suggests that direct management may be a partial option, with substantial emissions suppressed even when only applied to hotspots of the climate-methane feedback. This exploration is only illustrative, however, as other factors are important at multiple scales. Pre-existing soil sulfur concentrations (e.g., from historical pollution) may alter biogeochemical cycling (Johnston, Morgan, and Burton 2016) and impact the efficacy of sulfate additions. Further, the lack of data at tropical latitudes makes robust conclusions difficult. Across all latitudes, studies of methane management in natural or unmanaged wetlands are limited, hence our reliance on studies from rice paddies, constructed wetlands, and other 'wetland-like' systems. As these systems have some differences in their ecology and ecosystem functions, the results presented here should be viewed with this limitation in mind. Likewise, much of the literature on sulfate additions is conducted in boreal peatlands and bogs, and tropical peatlands are not well represented. Hydrologic flow regime varies greatly among these different types of wetlands. We note that in floodplain wetlands with frequent inundation, the use of sulfate for methane suppression would be challenging due to potential dilution and mobilization of the sulfate treatment. Substantial work is necessary to understand the full socio-ecological implications of large-scale ecosystem manipulation and should proceed with careful investigation and extreme caution.

Another factor to consider is the tradeoff between upfront and maintenance expenses with regards to wetland methane management. Reestablishing hydrologic connectivity might have a large upfront cost but minimal maintenance requirements, while amendments such as sulfate or biochar may need frequent reapplication to be effective (Dise and Verry 2001). Emerging technologies for methane capture are in development but currently require concentrations of methane of around 0.1% to even be feasible, let alone cost effective (at least an order of magnitude higher than concentrations observed in the highest wetland hotspots; Stolaroff et al. 2012). Other proposed strategies involving microbial solutions through various methanogen inhibitors or methanotroph enhancers are far from practical deployment (Yang, Shen, and Bai 2023; Silva-Gónzalez et al. 2018). Additionally, methane reduction via manipulations of microbial communities has the potential to pose significant risks to ecosystems. As with invasive species, ecosystem manipulations at such a fundamental level would be replete with unknowns.

Wetland restoration may present an opportunity for further study and testing methane mitigation strategies. Significant peatland restoration (50 million hectares globally) is called for to reach Paris Agreement climate objectives (Convention on Wetlands 2021). Peatland restoration of this magnitude, implemented strategically to maximize climate benefits (Laine et al. 2024; Niemi, Mattila, and Seppälä 2024) and potentially coupled with methane reducing strategies, could have a significant impact on global wetland methane budgets.

4.2 | Challenges and Research Recommendations

The challenges associated with direct management of additional wetland methane emissions raise questions about emissions feedback management more broadly. Direct emission mitigation of all GHGs addresses the root problem and may be easier and more cost effective; lower emission scenarios have much lower additional methane production from wetlands and thus may avoid the need for invasive management entirely (Zhang et al. 2023). Unfortunately, there is tremendous uncertainty regarding the likelihood of achieving the Paris Agreement goals (limiting warming to 1.5°C or 2.0°C above pre-industrial levels, IPCC 2018), especially in the context of additional GHG feedback loops from natural ecosystems like wetlands or permafrost thaw (Friedlingstein et al. 2023; Ito 2019). Thus, it is worth exploring every option available that might help reverse the course of anthropogenic climate change. This research outlines potential avenues of research. We recommend swift action toward intentional and targeted scientific testing of methane reducing management strategies (e.g., Table 1) in the areas of significant wetland methane hotspots, in case action becomes desirable.

5 | Conclusions

The wetland-methane feedback is of global significance. Increased methane production due to anthropogenic warming suggests that these emissions are functionally anthropogenic and thus should be considered in a management framework. Ultimately, the optimal solution would be a reduction in direct anthropogenic emissions via lower fossil fuel usage; this solution would reduce the wetland feedback while avoiding undesirable impacts of direct management in natural wetlands. In the interim, it is worth considering and studying potential avenues for direct wetland management. We find that while there is a broad suite of management options, ranging from direct addition of amendments to species management, little research has been done on this question directly or on the potential for secondary negative impacts (e.g., MeHg mobilization). Application of direct management at key hotspots may provide disproportionate benefits, but the costs still need to be determined. Research intentionally targeted at methane feedback reduction options is needed to identify or eliminate options from consideration of this and other critical bioclimatic feedback processes.

Author Contributions

Emily A. Ury: conceptualization, formal analysis, investigation, methodology, project administration, validation, writing – original draft, writing – review and editing. **Eve-Lyn S. Hinckley:** writing – review and editing. **Daniele Visioni:** writing – review and editing. **Brian Buma:** conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, validation, visualization, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study and code used to run the sulfate addition simulation are openly available on Figshare at: https://doi.org/10.6084/m9.figshare.c.7517784. Historical climate data from WorldClim 2.1 is available from: https://www.worldclim.org/data/worldclim21.html. Future climate data is available from the World Climate Research Program through its Working Group on Coupled Modelling at https://www.worldclim.org/data/cmip6/cmip6climate.html. Klöppen-Geiger climate zone maps is available on Figshare at https://doi.org/10.6084/m9.figshare.c.6395666.v1. The global wetland map is available from https://zenodo.org/records/7293597.

Data Sources

The full record of sources evaluated in the review are listed in Supporting Information S2.

References

Abdalla, M., A. Hastings, J. Truu, M. Espenberg, Ü. Mander, and P. Smith. 2016. "Emissions of Methane From Northern Peatlands: A Review of Management Impacts and Implications for Future Management Options." *Ecology and Evolution* 6, no. 19: 7080–7102. https://doi.org/10.1002/ece3.2469.

Badiou, P., R. McDougal, D. Pennock, and B. Clark. 2011. "Greenhouse Gas Emissions and Carbon Sequestration Potential in Restored Wetlands of the Canadian Prairie Pothole Region." *Wetlands Ecology and Management* 19, no. 3: 237–256. https://doi.org/10.1007/s11273-011-9214-6.

Bartosiewicz, M., P. Rzepka, and M. F. Lehmann. 2021. "Tapping Freshwaters for Methane and Energy." *Environmental Science & Technology* 55, no. 8: 4183–4189. https://doi.org/10.1021/acs.est.0c06210.

Beck, H. E., T. R. McVicar, N. Vergopolan, et al. 2023a. "High-Resolution (1 Km) Köppen-Geiger Maps for 1901–2099 Based on Constrained CMIP6 Projections." *Scientific Data* 10, no. 1: 724. https://doi.org/10.1038/s41597-023-02549-6.

Beck, H. E., T. R. McVicar, N. Vergopolan, et al. 2023b. *High-Resolution (1 Km) Köppen-Geiger Maps for 1901–2099 Based on Constrained CMIP6 Projections*. Vol. 10, 724. Figshare: Collection. https://doi.org/10.6084/m9.figshare.c.6395666.v1.

Bivand, R., T. Keitt, and B. Rowlingson. 2023. "_rgdal: Bindings for the 'Geospatial' Data Abstraction Library_." R Package Version 1.6–6. https://CRAN.R-project.org/package=rgdal.

Blodau, C., and M. Deppe. 2012. "Humic Acid Addition Lowers Methane Release in Peats of the Mer Bleue Bog, Canada." *Soil Biology & Biochemistry* 52: 96–98. https://doi.org/10.1016/j.soilbio.2012.04.023.

Burgess, M. G., J. Ritchie, J. Shapland, and R. Pielke. 2020. "IPCC Baseline Scenarios Have Over-Projected CO_2 Emissions and Economic Growth." *Environmental Research Letters: ERL* 16, no. 1: 014016. https://doi.org/10.1088/1748-9326/abcdd2.

Chen, J., H. Zhang, L. Liu, et al., 2021. "Effects of Elevated Sulfate in Eutrophic Waters on the Internal Phosphate Release Under Oxic Conditions Across the Sediment-Water Interface." *Science of the Total*

Environment 790: 148010. https://doi.org/10.1016/j.scitotenv.2021.148010.

Cheng, S., C. Qin, H. Xie, et al. 2021. "Comprehensive Evaluation of Manganese Oxides and Iron Oxides as Metal Substrate Materials for Constructed Wetlands From the Perspective of Water Quality and Greenhouse Effect." *Ecotoxicology and Environmental Safety* 221: 112451. https://doi.org/10.1016/j.ecoenv.2021.112451.

Comyn-Platt, E., G. Hayman, C. Huntingford, et al. 2018. "Carbon Budgets for 1.5 and 2°C Targets Lowered by Natural Wetland and Permafrost Feedbacks." *Nature Geoscience* 11, no. 8: 568–573. https://doi.org/10.1038/s41561-018-0174-9.

Convention on Wetlands. 2021. *Global Guidelines for Peatland Rewetting and Restoration. Ramsar Technical Report No. 11*. Gland, Switzerland: Secretariat of the Convention on Wetlands.

Corrales, J., G. M. Naja, C. Dziuba, R. G. Rivero, and W. Orem. 2011. "Sulfate Threshold Target to Control Methylmercury Levels in Wetland Ecosystems." *Science of the Total Environment* 409, no. 11: 2156–2162. https://doi.org/10.1016/j.scitotenv.2011.02.030.

Dise, N. B., and E. S. Verry. 2001. "Suppression of Peatland Methane Emission by Cumulative Sulfate Deposition in Simulated Acid Rain." *Biogeochemistry* 53, no. 2: 143–160. https://doi.org/10.1023/A:1010774610050.

dos Santos Fonseca, A. L., C. C. Marinho, and F. de Assis Esteves. 2019. "Acetate and Sulphate as Regulators of Potential Methane Production in a Tropical Coastal Lagoon." *Journal of Soils and Sediments* 19: 2604–2612. https://doi.org/10.1007/s11368-019-02249-y.

Driscoll, C. T., and W. D. Schecher. 1990. "The Chemistry of Aluminum in the Environment." *Environmental Geochemistry and Health* 12: 28–49. https://doi.org/10.1007/BF01734046.

Eriksson, T., M. G. Öquist, and M. B. Nilsson. 2010. "Effects of Decadal Deposition of Nitrogen and Sulfur, and Increased Temperature, on Methane Emissions From a Boreal Peatland." *JGR Biogeosciences* 115, no. G4: G04036. https://doi.org/10.1029/2010JG001285.

Eyring, V., S. Bony, G. A. Meehl, et al. 2016. "Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization." *Geoscientific Model Development* 9: 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016.

Feinberg, A., A. Stenke, T. Peter, E. L. S. Hinckley, C. T. Driscoll, and L. H. Winkel. 2021. "Reductions in the Deposition of Sulfur and Selenium to Agricultural Soils Pose Risk of Future Nutrient Deficiencies." *Communications Earth & Environment* 2, no. 1: 101. https://doi.org/10.1038/s43247-021-00172-0.

Feng, L., P. I. Palmer, R. J. Parker, M. F. Lunt, and H. Bösch. 2023. "Methane Emissions Are Predominantly Responsible for Record-Breaking Atmospheric Methane Growth Rates in 2020 and 2021." *Atmospheric Chemistry and Physics* 23, no. 8: 4863–4880. https://doi.org/10.5194/acp-23-4863-2023.

Fick, S. E., and R. J. Hijmans. 2017. "WorldClim 2: New 1-Km Spatial Resolution Climate Surfaces for Global Land Areas." *International Journal of Climatology* 37, no. 12: 4302–4315. https://doi.org/10.1002/joc.5086.

Fluet-Chouinard, E., B. D. Stocker, Z. Zhang, et al. 2022. "Global Wetland Loss Reconstruction Over 1700–2020." *Zenodo*. https://doi.org/10.5281/zenodo.7293597.

Fluet-Chouinard, E., B. D. Stocker, Z. Zhang, et al. 2023. "Extensive Global Wetland Loss Over the Past Three Centuries." *Nature* 614, no. 7947: 281–286. https://doi.org/10.1038/s41586-022-05572-6.

Friedlingstein, P., M. W. Jones, R. M. Andrew, et al. 2023. "Global Carbon Budget 2023." *Earth System Science Data* 15, no. 12: 5301–5369. https://doi.org/10.5194/essd-15-5301-2023.

Gao, Y., H. Chen, and X. Zeng. 2014. "Effects of Nitrogen and Sulfur Deposition on CH_4 and N_2O Fluxes in High-Altitude Peatland Soil Under Different Water Tables in the Tibetan Plateau." *Soil Science and Plant Nutrition* 60, no. 3: 404–410. https://doi.org/10.1080/00380768.2014.893812.

Gauci, V., N. Dise, and D. Fowler. 2002. "Controls on Suppression of Methane Flux From a Peat Bog Subjected to Simulated Acid Rain Sulfate Deposition." *Global Biogeochemical Cycles* 16, no. 1: 4-1–4-12. https://doi.org/10.1029/2000GB001370.

Gauci, V., D. Fowler, S. J. Chapman, and N. B. Dise. 2005. "Sulfate Deposition and Temperature Controls on Methane Emission and Sulfur Forms in Peat." *Biogeochemistry* 71, no. 2: 141–162. https://doi.org/10.1007/s10533-004-9681-4.

Gauci, V., E. Matthews, N. Dise, et al. 2004. "Sulfur Pollution Suppression of the Wetland Methane Source in the 20th and 21st Centuries." *Proceedings of the National Academy of Sciences of the United States of America* 101, no. 34: 12583–12587. https://doi.org/10.1073/pnas.0404412101.

Gauci, V., S. Blake, D. S. Stevenson, and E. J. Highwood. 2008. "Halving of the Northern Wetland CH4 Source by a Large Icelandic Volcanic Eruption." *Journal of Geophysical Research: Biogeosciences* 113, no. G3. https://doi.org/10.1029/2007jg000499.

Gerson, J. R., and E.-L. S. Hinckley. 2023. "It Is Time to Develop Sustainable Management of Agricultural Sulfur." *Earth's Futures* 11: e2023EF003723. https://doi.org/10.1029/2023EF003723.

Grennfelt, P., A. Engleryd, M. Forsius, Ø. Hov, H. Rodhe, and E. Cowling. 2020. "Acid Rain and Air Pollution: 50 Years of Progress in Environmental Science and Policy." *Ambio* 49: 849–864. https://doi.org/10.1007/s13280-019-01244-4.

Hijmans, R. 2023a. "_terra: Spatial Data Analysis_." R Package Version 1.7-29. https://CRAN.R-project.org/package=terra.

Hijmans, R. 2023b. "_raster: Geographic Data Analysis and Modeling_." R Package Version 3.6-20. https://CRAN.R-project.org/package=raster.

Hijmans, R. J., M. Barbosa, A. Ghosh, and A. Mandel. 2023. "_geodata: Download Geographic Data_." R Package Version 0.5-9. https://CRAN.R-project.org/package=geodata.

Hinckley, E. L. S., J. T. Crawford, H. Fakhraei, and C. T. Driscoll. 2020. "A Shift in Sulfur-Cycle Manipulation From Atmospheric Emissions to Agricultural Additions." *Nature Geoscience* 13, no. 9: 597–604.

Hinckley, E. L. S., and C. T. Driscoll. 2022. "Sulfur Fertiliser Use in the Midwestern US Increases as Atmospheric Sulfur Deposition Declines With Improved Air Quality." *Communications Earth & Environment* 3, no. 1: 324. https://doi.org/10.1038/s43247-022-00662-9.

Holmquist, J. R., M. Eagle, R. L. Molinari, S. K. Nick, L. C. Stachowicz, and K. D. Kroeger. 2023. "Mapping Methane Reduction Potential of Tidal Wetland Restoration in the United States." *Communications Earth & Environment* 4, no. 1: 1–11. https://doi.org/10.1038/s43247-023-00988-y.

Hu, M., B. J. Wilson, Z. Sun, P. Ren, and C. Tong. 2017. "Effects of the Addition of Nitrogen and Sulfate on CH_4 and CO_2 Emissions, Soil, and Pore Water Chemistry in a High Marsh of the Min River Estuary in Southeastern China." *Science of the Total Environment* 579: 292–304. https://doi.org/10.1016/j.scitotenv.2016.11.103.

Huntington-Klein, N. 2023. "_vtable: Variable Table for Variable Documentation_." R Package Version 1.4.6. https://CRAN.R-project.org/package=vtable.

Hussain, S., S. Peng, S. Fahad, et al. 2015. "Rice Management Interventions to Mitigate Greenhouse Gas Emissions: A Review." *Environmental Science and Pollution Research International* 22, no. 5: 3342–3360. https://doi.org/10.1007/s11356-014-3760-4.

IPCC. 2018. "Summary for Policymakers." In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global*

Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, edited by V. P. Masson-Delmotte, P. Zhai, H.-O. Pörtner, et al., 3–24. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157940.001.

Irvine, P. J., B. Kravitz, M. G. Lawrence, and H. Muri. 2016. "An Overview of the Earth System Science of Solar Geoengineering. Wiley Interdisciplinary Reviews." *Climate Change* 7, no. 6: 815–833. https://doi.org/10.1002/wcc.423.

Ito, A. 2019. "Disequilibrium of Terrestrial Ecosystem CO_2 Budget Caused by Disturbance-Induced Emissions and Non-CO_2 Carbon Export Flows: A Global Model Assessment." *Earth System Dynamics* 10, no. 4: 685–709. https://doi.org/10.5194/esd-10-685-2019.

Johannisson, J., and M. Hiete. 2020. "A Structured Approach for the Mitigation of Natural Methane Emissions—Lessons Learned From Anthropogenic Emissions." *Il Nuovo Cimento: C: Geophysics and Space Physics* 6, no. 2: 24. https://doi.org/10.3390/c6020024.

Johnson, A. H. 1983. "Red Spruce Decline in the Northeastern US: Hypotheses Regarding the Role of Acid Rain." *Journal of the Air Pollution Control Association* 33, no. 11: 1049–1054. https://doi.org/10.1080/00022470.1983.10465690.

Johnston, S. G., B. Morgan, and E. D. Burton. 2016. "Legacy Impacts of Acid Sulfate Soil Runoff on Mangrove Sediments: Reactive Iron Accumulation, Altered Sulfur Cycling and Trace Metal Enrichment." *Chemical Geology* 427: 43–53. https://doi.org/10.1016/j.chemgeo.2016.02.013.

Jones, C. N., D. L. McLaughlin, K. Henson, C. A. Haas, and D. A. Kaplan. 2018. "From Salamanders to Greenhouse Gases: Does Upland Management Affect Wetland Functions?" *Frontiers in Ecology and the Environment* 16, no. 1: 14–19. https://doi.org/10.1002/fee.1744.

Kleinen, T., S. Gromov, B. Steil, and V. Brovkin. 2021. "Atmospheric Methane Underestimated in Future Climate Projections." *Environmental Research Letters: ERL* 16, no. 9: 094006. https://doi.org/10.1088/1748-9326/ac1814.

Koffi, E. N., P. Bergamaschi, R. Alkama, and A. Cescatti. 2020. "An Observation-Constrained Assessment of the Climate Sensitivity and Future Trajectories of Wetland Methane Emissions." *Science Advances* 6, no. 15: 4444. https://doi.org/10.1126/sciadv.aay4444.

Kroeger, K. D., S. Crooks, S. Moseman-Valtierra, and J. Tang. 2017. "Restoring Tides to Reduce Methane Emissions in Impounded Wetlands: A New and Potent Blue Carbon Climate Change Intervention." *Scientific Reports* 7, no. 1: 11914. https://doi.org/10.1038/s41598-017-12138-4.

Kronberg, R. M., M. Jiskra, J. G. Wiederhold, E. Björn, and U. Skyllberg. 2016. "Methyl Mercury Formation in Hillslope Soils of Boreal Forests: The Role of Forest Harvest and Anaerobic Microbes." *Environmental Science & Technology* 50, no. 17: 9177–9186. https://doi.org/10.1021/acs.est.6b00762.

Laine, A. M., L. Mehtätalo, A. Tolvanen, S. Frolking, and E.-S. Tuittila. 2019. "Impacts of Drainage, Restoration and Warming on Boreal Wetland Greenhouse Gas Fluxes." *Science of the Total Environment* 647: 169–181. https://doi.org/10.1016/j.scitotenv.2018.07.390.

Laine, A. M., P. Ojanen, T. Lindroos, et al. 2024. "Climate Change Mitigation Potential of Restoration of Boreal Peatlands Drained for Forestry Can Be Adjusted by Site Selection and Restoration Measures." *Restoration Ecology* 32, no. 7: e14213. https://doi.org/10.1111/rec.14213.

Lamers, L. P., L. L. Govers, I. C. Janssen, et al., 2013. "Sulfide as a Soil Phytotoxin—A Review." *Frontiers in Plant Science* 4: 268. https://doi.org/10.3389/fpls.2013.00268.

Lei, P., C. Tang, Y. Wang, et al. 2021. "Understanding the Effects of Sulfur Input on Mercury Methylation in Rice Paddy Soils." *Science of the Total Environment* 778: 146325. https://doi.org/10.1016/j.scitotenv.2021.146325.

Liu, F., Y. Zhang, H. Liang, and D. Gao. 2019. "Long-Term Harvesting of Reeds Affects Greenhouse Gas Emissions and Microbial Functional Genes in Alkaline Wetlands." *Water Research* 164: 114936. https://doi.org/10.1016/j.watres.2019.114936.

Liu, J., H. Xu, Y. Jiang, K. Zhang, Y. Hu, and Z. Zeng. 2017. "Methane Emissions and Microbial Communities as Influenced by Dual Cropping of Azolla Along With Early Rice." *Scientific Reports* 7: 40635. https://doi.org/10.1038/srep40635.

Liu, Z., D. Li, J. Zhang, et al. 2020. "Effect of Simulated Acid Rain on Soil CO_2, CH_4 and N_2O Emissions and Microbial Communities in an Agricultural Soil." *Geoderma* 366: 114222. https://doi.org/10.1016/j.geoderma.2020.114222.

Lozanovska, I., Y. Kuzyakov, J. Krohn, S. Parvin, and M. Dorodnikov. 2016. "Effects of Nitrate and Sulfate on Greenhouse Gas Emission Potentials From Microform-Derived Peats of a Boreal Peatland: A 13C Tracer Study." *Soil Biology & Biochemistry* 100: 182–191. https://doi.org/10.1016/j.soilbio.2016.06.018.

Maucieri, C., A. C. Barbera, J. Vymazal, and M. Borin. 2017. "A Review on the Main Affecting Factors of Greenhouse Gases Emission in Constructed Wetlands." *Agricultural and Forest Meteorology* 236: 175–193. https://doi.org/10.1016/j.agrformet.2017.01.006.

Meinshausen, M., Z. R. J. Nicholls, J. Lewis, et al. 2020. "The Shared Socio-Economic Pathway (SSP) Greenhouse Gas Concentrations and Their Extensions to 2500." *Geoscientific Model Development* 13, no. 8: 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020.

Miller, K. E., C.-T. Lai, E. S. Friedman, L. T. Angenent, and D. A. Lipson. 2015. "Methane Suppression by Iron and Humic Acids in Soils of the Arctic Coastal Plain." *Soil Biology & Biochemistry* 83: 176–183. https://doi.org/10.1016/j.soilbio.2015.01.022.

Murdiyarso, D., K. Hergoualc'h, and L. V. Verchot. 2010. "Opportunities for Reducing Greenhouse Gas Emissions in Tropical Peatlands." *Proceedings of the National Academy of Sciences of the United States of America* 107, no. 46: 19655–19660. https://doi.org/10.1073/pnas.0911966107.

Myhre, G., D. Shindell, F.-M. Bréon, et al. 2013. "Anthropogenic and Natural Radiative Forcing." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, et al., 659–740. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Nan, Q., L. Xin, Y. Qin, M. Waqas, and W. Wu. 2021. "Exploring Long-Term Effects of Biochar on Mitigating Methane Emissions From Paddy Soil: A Review." *Biochar* 3, no. 2: 125–134. https://doi.org/10.1007/s42773-021-00096-0.

NASEM: National Academies of Sciences, Engineering, and Medicine. 2021. *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. Washington, DC: National Academies Press. https://doi.org/10.17226/25762.

Niemi, J., T. Mattila, and J. Seppälä. 2024. "Rewetting on Agricultural Peatlands Can Offer Cost Effective Greenhouse Gas Reduction at the National Level." *Land Use Policy* 146: 107329. https://doi.org/10.1016/j.landusepol.2024.107329.

NOAA. 2023. "Trends in atmospheric methane." https://gml.noaa.gov/ccgg/trends_ch4/.

Orem, W. H., D. P. Krabbenhoft, B. A. Poulin, and G. R. Aiken. 2019. "Sulfur Contamination in the Everglades, a Major Control on Mercury Methylation." In *Mercury and the Everglades. A Synthesis and Model for Complex Ecosystem Restoration*, edited by D. Rumbold, C. Pollman, and D. Axelrad. Cham: Springer. https://doi.org/10.1007/978-3-030-32057-7_2.

Pasut, C., F. H. M. Tang, D. Hamilton, W. J. Riley, and F. Maggi. 2021. "Spatiotemporal Assessment of GHG Emissions and Nutrient Sequestration Linked to Agronutrient Runoff in Global Wetlands."

Global Biogeochemical Cycles 35: e2020GB006816. https://doi.org/10.1029/2020GB006816.

Peacock, M., L. M. Ridley, C. D. Evans, and V. Gauci. 2017. "Management Effects on Greenhouse Gas Dynamics in Fen Ditches." *Science of the Total Environment* 578: 601–612. https://doi.org/10.1016/j.scitotenv.2016.11.005.

Pebesma, E., and R. Bivand. 2005. "Classes and Methods for Spatial Data in R." *R News* 5, no. 2: 9–13. https://CRAN.R-project.org/doc/Rnews/.

Peng, S., X. Lin, R. L. Thompson, et al. 2022. "Wetland Emission and Atmospheric Sink Changes Explain Methane Growth in 2020." *Nature* 612, no. 7940: 477–482. https://doi.org/10.1038/s41586-022-05447-w.

Phillips, C. A., B. M. Rogers, M. Elder, et al. 2022. "Escalating Carbon Emissions From North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management." *Science Advances* 8, no. 17: eabl7161. https://doi.org/10.1126/sciadv.abl7161.

Reuss, J. O., and D. W. Johnson. 2012. *Acid Deposition and the Acidification of Soils and Waters*. New York, NY: Springer. https://doi.org/10.1007/978-1-4419-8536-1.

Riahi, K., D. P. van Vuuren, E. Kriegler, et al. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change: Human and Policy Dimensions* 42: 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Ripple, W. J., C. Wolf, T. M. Lenton, et al. 2023. "Many Risky Feedback Loops Amplify the Need for Climate Action." *One Earth* 6, no. 2: 86–91. https://doi.org/10.1016/j.oneear.2023.01.004.

Rubin, H. J., J. S. Fu, F. Dentener, R. Li, K. Huang, and H. Fu. 2023. "Global Nitrogen and Sulfur Deposition Mapping Using a Measurement–Model Fusion Approach." *Atmospheric Chemistry and Physics* 23, no. 12: 7091–7102. https://doi.org/10.5194/acp-23-7091-2023.

Rubin, R. L., T. R. Anderson, and K. A. Ballantine. 2020. "Biochar Simultaneously Reduces Nutrient Leaching and Greenhouse Gas Emissions in Restored Wetland Soils." *Wetlands* 40: 1981–1991. https://doi.org/10.1007/s13157-020-01380-8.

Sanders-DeMott, R., M. J. Eagle, K. D. Kroeger, et al. 2022. "Impoundment Increases Methane Emissions in Phragmites-Invaded Coastal Wetlands." *Global Change Biology* 28, no. 15: 4539–4557. https://doi.org/10.1111/gcb.16217.

Saunois, M., A. R. Stavert, B. Poulter, et al. 2020. "The Global Methane Budget 2000–2017." *Earth System Science Data* 12, no. 3: 1561–1623. https://doi.org/10.5194/essd-12-1561-2020.

Serrano-Notivoli, R. 2023. "_bioclim: Bioclimatic Analysis and Classification_." R Package Version 0.4.0. https://CRAN.R-project.org/package=bioclim.

Silva-Gónzalez, J. A., D. A. Fraire-García, C. V. Ochoa-Bañuelos, L. E. Montañez-Hernández, M. P. Luevanos Escareño, and N. Balagurusamy. 2018. "Methane Monooxygenase and Their Potential Role in Methane Mitigation." *Catalysis & Biocatalysis* 36, no. 3: 44–47.

Singh, B. K., R. D. Bardgett, P. Smith, and D. S. Reay. 2010. "Microorganisms and Climate Change: Terrestrial Feedbacks and Mitigation Options." *Nature Reviews. Microbiology* 8, no. 11: 779–790. https://doi.org/10.1038/nrmicro2439.

Skeie, R. B., Ø. Hodnebrog, and G. Myhre. 2023. "Trends in Atmospheric Methane Concentrations Since 1990 Were Driven and Modified by Anthropogenic Emissions." *Communications Earth & Environment* 4, no. 1: 317. https://doi.org/10.1038/s43247-023-00969-1.

Skyllberg, U. 2009. "Sulphur chemistry controls both transport of mercury forms and methylation reactions in sediments, wetland and forest soils. Does forestry contribute to mercury in Swedish fish? The Royal Swedish Academy of Agriculture and Forestry and Forestry (KSLA) Report." 40–45.

Stolaroff, J. K., S. Bhattacharyya, C. A. Smith, W. L. Bourcier, P. J. Cameron-Smith, and R. D. Aines. 2012. "Review of Methane Mitigation Technologies With Application to Rapid Release of Methane From the Arctic." *Environmental Science & Technology* 46, no. 12: 6455–6469. https://doi.org/10.1021/es204686w.

Sun, T., J. J. L. Guzman, J. D. Seward, et al. 2021. "Suppressing Peatland Methane Production by Electron Snorkeling Through Pyrogenic Carbon in Controlled Laboratory Incubations." *Nature Communications* 12, no. 1: 4119. https://doi.org/10.1038/s41467-021-24350-y.

Van Bodegom, P. M., and A. J. M. Stams. 1999. "Effects of Alternative Electron Acceptors and Temperature on Methanogenesis in Rice Paddy Soils." *Chemosphere* 39, no. 2: 167–182. https://doi.org/10.1016/S0045-6535(99)00101-0.

Vermaat, J. E., F. Hellmann, A. T. C. Dias, B. Hoorens, R. S. P. van Logtestijn, and R. Aerts. 2011. "Greenhouse Gas Fluxes From Dutch Peatland Water Bodies: Importance of the Surrounding Landscape." *Wetlands* 31, no. 3: 493–498. https://doi.org/10.1007/s13157-011-0170-y.

Vet, R., R. S. Artz, S. Carou, et al. 2014. "A Global Assessment of Precipitation Chemistry and Deposition of Sulfur, Nitrogen, Sea Salt, Base Cations, Organic Acids, Acidity and pH, and Phosphorus." *Atmospheric Environment* 93: 3–100. https://doi.org/10.1016/j.atmosenv.2013.10.060.

Visioni, D., E. Slessarev, D. G. MacMartin, N. M. Mahowald, C. L. Goodale, and L. Xia. 2020. "What Goes Up Must Come Down: Impacts of Deposition in a Sulfate Geoengineering Scenario." *Environmental Research Letters* 15, no. 9: 094063. https://doi.org/10.1088/1748-9326/ab94eb.

Wang, H., M. Ho, N. Flanagan, and C. J. Richardson. 2021. "The Effects of Hydrological Management on Methane Emissions From Southeastern Shrub Bogs of the USA." *Wetlands* 41, no. 7: 87. https://doi.org/10.1007/s13157-021-01486-7.

Wickham, H. 2016. *ggplot2: Elegant Graphics for Data Analysis*. New York, NY: Springer-Verlag.

Xi, Y., S. Peng, A. Ducharne, et al. 2022. "Gridded Maps of Wetlands Dynamics Over Mid-Low Latitudes for 1980–2020 Based on TOPMODEL." *Scientific Data* 9, no. 1: 347. https://doi.org/10.1038/s41597-022-01460-w.

Yan, Z., J. Wang, Y. Li, et al. 2020. "Waterlogging Affects the Mitigation of Soil GHG Emissions by Biochar Amendment in Coastal Wetland." *Journal of Soils and Sediments* 20: 3591–3606. https://doi.org/10.1007/s11368-020-02705-0.

Yang, W.-T., L.-D. Shen, and Y.-N. Bai. 2023. "Role and Regulation of Anaerobic Methane Oxidation Catalyzed by NC10 Bacteria and ANME-2d Archaea in Various Ecosystems." *Environmental Research* 219: 115174. https://doi.org/10.1016/j.envres.2022.115174.

Yu, G., J. Chen, G. Wang, et al. 2023. "Recent Advances in Constructed Wetlands Methane Reduction: Mechanisms and Methods." *Frontiers in Microbiology* 14: 1106332. https://doi.org/10.3389/fmicb.2023.1106332.

Zhang, X., L. Liu, T. Zhao, J. Wang, W. Liu, and X. Chen. 2024. "Global Annual Wetland Dataset at 30 m With a Fine Classification System From 2000 to 2022." *Scientific Data* 11, no. 1: 310. https://doi.org/10.1038/s41597-024-03143-0.

Zhang, Z., B. Poulter, A. F. Feldman, et al. 2023. "Recent Intensification of Wetland Methane Feedback." *Nature Climate Change* 13, no. 5: 430–433. https://doi.org/10.1038/s41558-023-01629-0.

Zhang, Z., N. E. Zimmermann, A. Stenke, et al. 2017. "Emerging Role of Wetland Methane Emissions in Driving 21st Century Climate Change." *Proceedings of the National Academy of Sciences of the United States of America* 114, no. 36: 9647–9652. https://doi.org/10.1073/pnas.1618765114.

Zhao, L., G. Qiu, C. W. Anderson, et al. 2016. "Mercury Methylation in Rice Paddies and Its Possible Controlling Factors in the hg Mining

Area, Guizhou Province, Southwest China." *Environmental Pollution* 215: 1–9. https://doi.org/10.1016/j.envpol.2016.05.001.

Zhou, G., S. Gao, C. Xu, N. Zeng, R. M. Rees, and W. Cao. 2020. "Co-Incorporation of Chinese Milk Vetch (*Astragalus sinicus* L.) and Rice (*Oryza sativa* L.) Straw Minimizes CH4 Emissions by Changing the Methanogenic and Methanotrophic Communities in a Paddy Soil." *European Journal of Soil Science* 71, no. 5: 924–939. https://doi.org/10.1111/ejss.12930.

Zhu, X., Y. Yuan, X. Wei, L. Wang, and C. Wang. 2021. "Dissimilatory Iron Reduction and Potential Methane Production in Chagan Lake Wetland Soils With Carbon Addition." *Wetlands Ecology and Management* 29: 369–379. https://doi.org/10.1007/s11273-021-09783-y.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.