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New perspectives on temperate inland wetlands as natural climate solutions under different CO_2-equivalent metrics

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There is debate about the use of wetlands as natural climate solutions due to their ability to act as a "double-edged sword" with respect to climate impacts by both sequestering CO_2 while emitting CH_4. Here, we used a process-based greenhouse gas (GHG) perturbation model to simulate wetland radiative forcing and temperature change associated with wetland state conversion over 500 years based on empirical carbon flux measurements, and CO_2-equivalent (CO_2-e.q.) metrics to assess the net flux of GHGs from wetlands on a comparable basis. Three CO_2-e.q. metrics were used to describe the relative radiative impact of CO_2 and CH_4—the conventional global warming potential (GWP) that looks at pulse GHG emissions over a fixed timeframe, the sustained-flux GWP (SGWP) that looks at sustained GHG emissions over a fixed timeframe, and GWP* that explicitly accounts for changes in the radiative forcing of CH_4 over time (initially more potent but then diminishing after about a decade)—against model-derived mean temperature profiles. GWP* most closely estimated the mean temperature profiles associated with net wetland GHG emissions. Using the GWP*, intact wetlands serve as net CO_2-e.q. carbon sinks and deliver net cooling effects on the climate. Prioritizing the conservation of intact wetlands is a cost-effective approach with immediate climate benefits that align with the Paris Agreement and the Intergovernmental Panel on Climate Change timeline of net-zero GHG emissions by 2050. Restoration of wetlands also has immediate climate benefits (reduced warming), but with the majority of climate benefits (cooling) occurring over longer timescales, making it an effective short and long-term natural climate solution with additional co-benefits.

The most recent Intergovernmental Panel on Climate Change (IPCC) assessment report states that a reduction to net-zero global greenhouse gas (GHG) emissions by 2050 is necessary to hold global average temperature rise to below a 2 °C increase above preindustrial levels[1]. To achieve net-zero GHG emissions by 2050, several countries (e.g., USA and Canada) have emphasized the potential of implementing natural climate solutions, which involves protecting, conserving, and restoring natural ecosystems to remove carbon dioxide (CO_2) from the atmosphere[2–4]. The use of wetlands as natural climate solutions is gaining popularity given their ability to sequester atmospheric CO_2 while simultaneously delivering multiple co-benefits beyond climate mitigation[2–5].

Inland wetlands can be broadly categorized into peatlands [wetlands that are characterized by water at or near the surface and an accumulation of a thick layer of partially decomposed organic matter (>40 cm of surface organic matter)] and mineral soil wetlands [wetlands that have water at or near the surface and an accumulation of a thinner layer of non-peat accumulating organic soil (<40 cm of surface organic matter)][6,7]. Mineral soil wetlands tend to accumulate less organic matter relative to peatlands due to their relatively high decomposition rates and smaller imbalances between production and decomposition[6,8]. Nevertheless, the waterlogged anaerobic conditions of mineral soil wetlands promote the long-term removal of CO_2 by sequestering this greenhouse gas (GHG) into organic matter that accumulates in these productive systems[6,9].

However, the same conditions that promote the long-term accumulation of carbon are also the conditions that result in wetlands being a considerable source of methane (CH_4) globally[10–12]. CH_4 is a more potent GHG, with a much higher radiative efficiency but shorter atmospheric lifetime (~12 years) as compared to CO_2 (atmospheric lifetime range from 3.4 to 10^8 years)[13,14]. Therefore, despite the fact that CH_4 fluxes in wetlands are typically considered orders of magnitude lower than CO_2 exchanges, the

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cooling effect of carbon sequestration in intact wetlands can be offset by the warming effect associated with CH_4 emissions[15,16]. Human-induced changes in mineral soil wetland states (e.g., wetland drainage and restoration) impose uncertainties in their GHG fluxes and therefore their potential to serve as natural climate solutions[4,10].

To effectively use mineral soil wetlands (hereafter wetlands) in temperate North America to achieve mid-century climate targets, it is essential to understand how protecting, restoring, and draining wetlands affect CO_2 and CH_4 emissions. Restoring drained wetlands can inhibit soil carbon oxidation and effectively reduce CO_2 emissions; however, this often comes at the cost of increased CH_4 emissions[10,12,17–19]. Conversely, draining and converting wetlands to other land uses can result in a substantial release of CO_2 to the atmosphere while reducing CH_4 emissions[18,20]. Despite extensive research on how intact and restored wetlands can deliver a net cooling effect on climate at the timescale of centuries[3,14,17], scientific debate continues on (1) whether the cooling effect of CO_2 sequestration in intact wetlands can be offset by the warming effect of CH_4 emissions, and (2) whether restored wetlands deliver short-term natural climate solutions for countries aiming to achieve mid-century net-zero emissions targets[2–4].

To better understand the climate footprint of wetlands and their capacity as natural climate solutions for mid-century climate targets, the atmospheric lifetime of wetland GHGs (i.e., CO_2 and CH_4) and the relative potential of these GHGs to absorb infrared radiation in the atmosphere (i.e., radiative efficiency) need to be assessed on a comparable basis[13,15,21–23]. To facilitate this comparison, wetland GHG fluxes need to be normalized to CO_2-equivalent (CO_2-e.q.) measures[15,24,25]. The 100-year variant of the Global Warming Potential (GWP_{100}) has been formally adopted in international climate policy (e.g., Paris Agreement) and is the standard CO_2-e.q. metric for expressing emissions in the scientific literature and general media[26]. Despite being broadly used, GWP_{100} and any GWP variant have been criticized[14,15,27],as they make the incorrect assumptions that wetland GHG emissions occur as a single pulse[15] and that wetland carbon-based GHGs have the same climate impact mechanism over time thereby ignoring the differences in climate warming associated with long-lived climate pollutants (e.g., CO_2) and short-lived climate pollutants (e.g., CH_4)[23,27]. CO_2 in the atmospheric reservoir persists for hundreds of years in the absence of active CO_2 removal efforts (e.g., afforestation/reforestation and direct air capture etc.)[24,28]. As a result, ongoing CO_2 emissions add cumulatively to the atmospheric stock, causing atmospheric temperatures to increase continuously over a span of hundreds of years[23,24,27]. Conversely, CH_4 in the atmospheric reservoir persists for a much shorter time because of natural removal mechanisms (e.g., reaction of CH_4 molecules with hydroxyl radicals)[23,24,29]. The shortcoming of commonly-used GWPs is that they overstate the cumulative effect of wetland CH_4 emissions on total warming given that natural removal mechanisms of atmospheric CH_4 are not captured, thereby resulting in misleading conclusions when assessing how wetland ecosystems may serve as natural climate solutions[23,27].

Several CO_2-e.q. metrics have been introduced that consider the effects of wetland GHG fluxes on radiative forcing over different timeframes. Neubauer and Megonigal[15] developed two alternative CO_2-e.q. metrics, known as the sustained-flux global warming potential (SGWP) and the sustained-flux global cooling potential (SGCP), accounting for GHG efflux and influx, respectively. SGWP and SGCP have been broadly adopted within the wetland research community and are frequently used to infer wetland climate impacts and the role of wetlands in climate mitigation strategies[3,16,17,30]. Recently, Allen et al.[22,23] and Cain et al.[27] introduced an alternative way of estimating CO_2-e.q. (i.e., GWP*) by relating a change in CH_4 emissions rate to a fixed quantity of CO_2. GWP* has been found to reflect the impact of anthropogenic CH_4 emissions more accurately on average global temperature as compared to the GWP and SGWP metrics[24,27]. Despite progress towards identifying a physically based CO_2-e.q. approach to assessing wetland climate footprints on a comparable basis, debate continues on what is the most appropriate way for simple yet effective CO_2-e.q. comparison of GHG emissions under different timeframes being considered[24,27,30–32].

Here, we explore the potential of wetlands in temperate North America as natural climate solutions using different CO_2-e.q. metrics (GWP, SGWP, GWP*). We focus on inland mineral soil wetlands, which make up most of the wetland area in temperate regions, where human settlements and associated wetland losses are greatest, and where restoration of wetlands holds great promise in terms of serving as an effective natural climate solution[3,4,9]. To test the various CO_2-e.q. metrics for mid-century natural climate solutions targets we: (1) compiled yearly (snow-free season) GHG flux rates for inland mineral soil wetlands (Fig.1) (see Methods section for detailed description on the compiled dataset); (2) sorted these GHG flux rates into three scenarios (i.e., wetlands that remained intact, wetlands that were drained, and wetlands that were drained and then restored); and (3) used the GHG flux rates for each wetland state conversion scenario as input to a GHG perturbation model[13] to simulate the changes in atmospheric concentration of wetland GHGs and the instantaneous radiative forcing, cumulative radiative forcing, and the impact on average temperature associated with changes in wetland GHG fluxes following a change in wetland state. Further, (4) we calculated the mean surface temperature switchover time (i.e., the length of time after which the warming effect due to CH_4 emissions is overtaken by the cooling effect of CO_2 sequestration) associated with the change in wetland state[20,33]. Finally, (5) we created cumulative CO_2-e.q. carbon budget profiles over 500 years for each of the CO_2-e.q. metrics (i.e., GWP, SGWP, GWP*), assessing the influence of the CO_2-e.q. metrics on interpretation of wetlands as natural climate solutions.

Results

Wetland CO_2 and CH_4 fluxes

The CO_2 fluxes ranged from −810 (±490 kg C-CO_2 ha^{-1} yr^{-1}) for intact wetlands, to −2420 (±1415 kg C-CO_2 ha^{-1} yr^{-1}) for restored wetlands, and to 4898 (±1223 kg C-CO_2 ha^{-1} yr^{-1}) for drained wetlands (Fig. 1). The CH_4 fluxes were not normally distributed; therefore, a K-means cluster analysis was conducted on all CH_4 flux data from which two clusters of CH_4 fluxes were identified: low (0.02–149 kg C-CH_4 ha^{-1} yr^{-1}) and high (326–724 kg C-CH_4 ha^{-1} yr^{-1}) (Fig. 1). Low and high CH_4 fluxes were observed in intact wetlands, but with a majority of the CH_4 flux data (67%) falling within the low cluster (Fig. 1). Only low CH_4 fluxes were observed in drained and restored wetlands.

Net cooling vs. warming effect of wetlands

We focused on the effect of wetland state conversion on radiative forcing and changes in mean surface temperature (see Methods section for detailed information on wetland state conversion scenarios). The GHG perturbation model was used to simulate the atmospheric inventories of wetland-derived CO_2 and CH_4 at any given time, and to estimate the pattern of radiative forcing (instantaneous and cumulative) and mean surface temperature change (K) following the conversion of wetland state (from intact to intact, intact to drained, and drained to restored). The model input was the compiled wetland GHG flux data (by low vs. high flux categories for CH_4) for each wetland state. The model output was the atmospheric concentration of wetland-derived carbon-based GHGs at any given time, which was then used to calculate the instantaneous radiative forcing (Wm^{-2}) and cumulative radiative forcing (Wm^{-2}) of the wetland carbon-based GHG fluxes. Meanwhile, the approximate impact of instantaneous and cumulative radiative forcings on the mean surface temperature were estimated as ~1 K per 1.23 Wm^{-2} radiative forcing.

For each of the wetland state conversion scenarios, a 50-year pre-conversion and a 500-year post-conversion time-period was used, as a 500-year allows for successional steady states to occur in many terrestrial ecosystems, including wetland ecosystems[15,21]. For each conversion scenario, the baseline was what would happen if the wetland conversion did not take place. For example, for the scenario of draining of intact wetland with low or high CH_4 flux, the baseline was maintaining intact wetland with low or high CH_4 flux, respectively. Further, for the scenario of restoring of drained wetlands, the baseline was remaining as drained wetlands (See Methods section for details on how the comparisons to baseline scenarios were made).

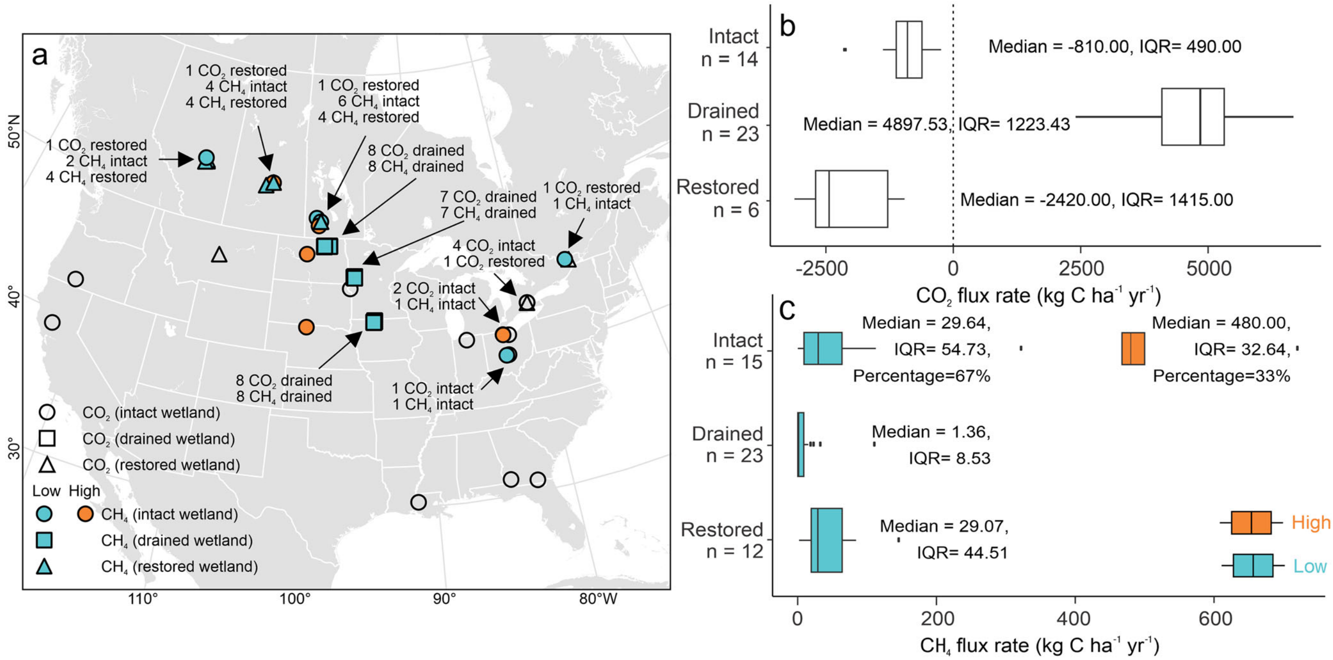

Fig. 1 | Carbon sequestration and greenhouse gas flux rates of inland marshes. **a** Geographic location of complied study. **b** Central tendency of the compiled CO_2 flux data for intact wetland, drained wetland, and restored wetland [the vertical dash line distinguishes between a CO_2 sink (left) vs. source (right)] and (**c**) compiled CH_4 flux data for intact wetland, drained wetland, and restored wetland. CH_4 flux data is separated into different categories (low and high) using K-means cluster analysis for intact wetland. There are no drained and restored wetlands in the high CH_4 flux clusters. The median, interquartile range (IQR), and total number of observations (total n) are provided for each wetland state. Meanwhile, percentage of data falling within each K means CH_4 flux category are provided.

We simplified the modelling of the effect of wetland carbon dynamics on the climate by assuming that yearly wetland carbon sequestration rates and the GHG emission factors were constant within each wetland state.

Initiating intact wetlands with low CH_4 fluxes (at year −50) resulted in a small and short net warming effect and maintaining these wetlands with low CH_4 fluxes (at year 0) resulted in a net cooling effect over the 500-year timeframe (Fig. 2a, d). In contrast, initiating intact wetlands with high CH_4 fluxes (at year −50) resulted in a net warming effect over the entire 500-year timeframe, with a switchover time to a net cooling effect after approximately 1000 years (instantaneous radiative forcing-derived temperature) and 2000 years (cumulative radiative forcing-derived temperature) (Fig. 3). Given that intact wetlands were on the landscape for thousands of years[8,34,35], intact wetlands (including those with low and high CH_4 fluxes) are currently contributing to a net cooling effect.

Draining intact wetlands with low CH_4 fluxes resulted in an immediate net warming effect that was sustained over the 500-year timeframe (Fig. 2b, e). In contrast, draining intact wetlands with high CH_4 fluxes resulted in a small and short climate benefit (i.e., smaller warming compared to remaining as an intact wetland with high CH_4 fluxes (Fig. 2b, e)). However, this climate benefit switched to a climate detriment (i.e., larger warming) that was sustained over the remainder of the 500-year timeframe.

Restoring drained wetlands to restored wetlands with low CH_4 fluxes resulted in an immediate climate benefit (i.e., smaller warming) (Fig. 2c, f) compared to drained wetlands, followed by a net cooling effect. There were no restored wetlands with high CH_4 fluxes, and therefore these conversions were not modelled.

Carbon sinks vs. source status

A CO_2-e.q. metric was used to assess wetland carbon sinks vs. source status on a comparable basis, thereby directly relating change in net cumulative CO_2-e.q. GHG emissions to their temperature responses. The GWP*-derived net carbon sink vs. source status most closely aligned with the GHG perturbation model net cooling vs. warming effect (Fig. 4). Therefore, we focused on comparing the cumulative carbon sink vs. source status of conversion of wetland states (intact-to-intact, intact-to-drained, drained-to-restored) using GWP* vs. earlier GWP and SGWP CO_2-e.q. metrics, but also provide the information for GWP and SGWP CO_2-e.q. metrics.

Based on GWP*, initiating an intact wetland at year −50 with low CH_4 fluxes resulted in a relatively small increase in the net CO_2-e.q. carbon source for about 30 years followed by a decrease for about 10 years and then a switch to a net CO_2-e.q. carbon sink effect (Fig. 4a). In contrast, initiating an intact wetland at year −50 with high CH_4 fluxes resulted in a larger magnitude of net CO_2-e.q. carbon source effect with an even faster increase in the net CO_2-e.q. carbon source effect for the initial 20 years after wetland initiation, and maintaining an intact wetland with high CH_4 fluxes (at year 0) resulted in a net CO_2-e.q. carbon source effect over the 500-year timeframe (Fig. 4d). For most intact wetlands (i.e., 67% with low CH_4 fluxes), intact wetlands functioned as net CO_2-e.q. carbon sinks once the suddenly introduced CH_4 associated with wetland establishment was neutralized by sustained CO_2 uptake, while intact wetlands with high CH_4 fluxes functioned as net CO_2-e.q. carbon sources with a minor increase in their cumulative CO_2-e.q. carbon source strength over the 500-year period. In contrast, based on GWP_{500} and $SGWP_{500}$, intact wetlands with low CH_4 fluxes functioned as net CO_2-e.q. carbon sinks immediately, while intact wetlands with high CH_4 fluxes functioned as net CO_2-e.q. carbon sources, with their cumulative CO_2-e.q. carbon source strength increasing rapidly over the 500-year period (Fig. 4a, d).

Draining intact wetlands with low CH_4 fluxes resulted in a short-lived (about 5 years) reduced net CO_2-e.q. carbon sink effect due to the cessation of CH_4 emissions associated with wetland drainage, followed by an enhanced CO_2-e.q. carbon source effect using GWP*, GWP_{500}, and $SWGP_{500}$ metrics (Fig. 4b). Based on GWP*, draining intact wetlands with high CH_4 fluxes resulted in a slightly longer period of net CO_2-e.q. carbon sink effect (65 years), after which drained wetlands exhibited a linear increase in CO_2-e.q. carbon source effects (Fig. 4e). In contrast, based on GWP_{500} and $SGWP_{500}$, draining intact wetlands with high CH_4 fluxes resulted in a failure to capture the initial post-drainage carbon sink effect as expressed by a reduction in warming effect and thus an overestimation of the cumulative CO_2-e.q. carbon source effect over the 500-year period.

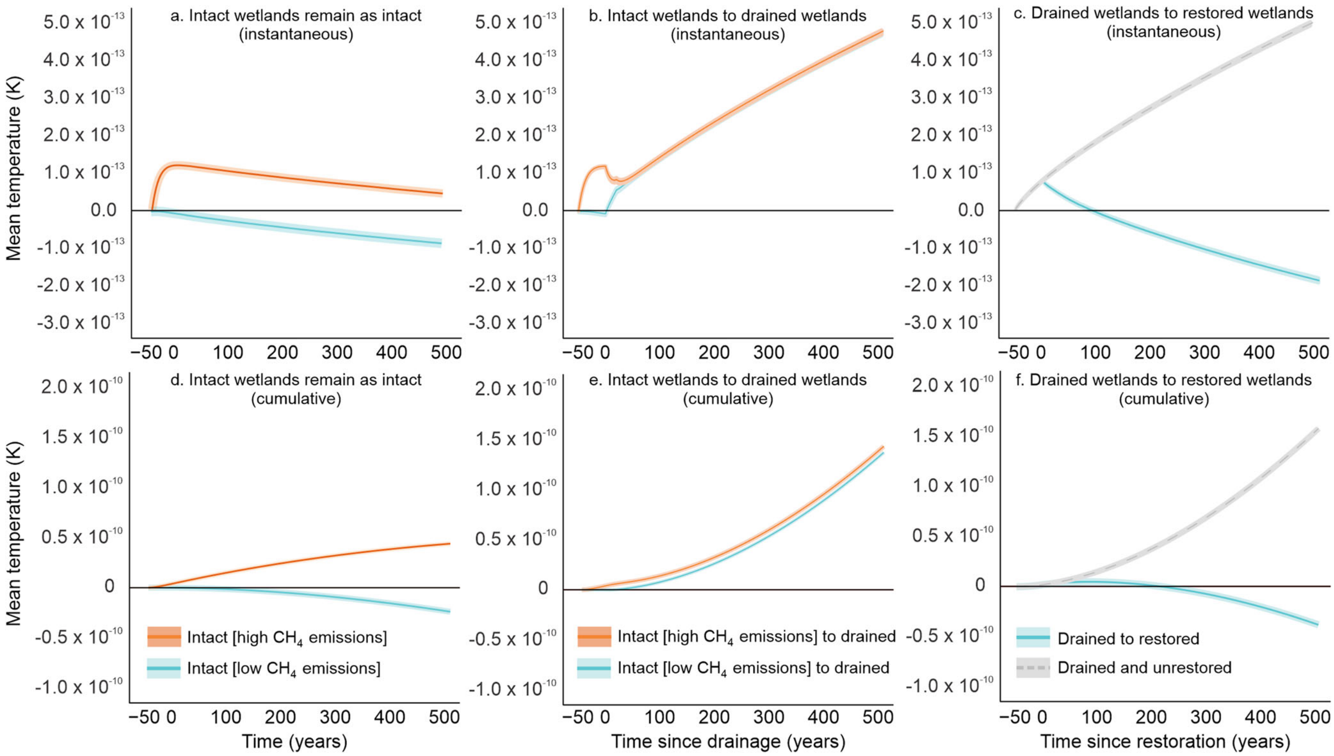

Fig. 2 | Instantaneous and cumulative radiative forcing derived mean temperature profile. Mean temperature profile for scenarios of (**a** and **d**) intact wetland remains intact, (**b** and **e**) intact wetland to drained wetland, and (**c** and **f**) drained wetland to restored wetland. Panels **a**–**c** represent instantaneous radiative forcing derived mean temperature profile; panels **d**–**f** represent cumulative radiative forcing derived mean temperature profile. Shaded areas around lines shows Monte Carlo simulation results.

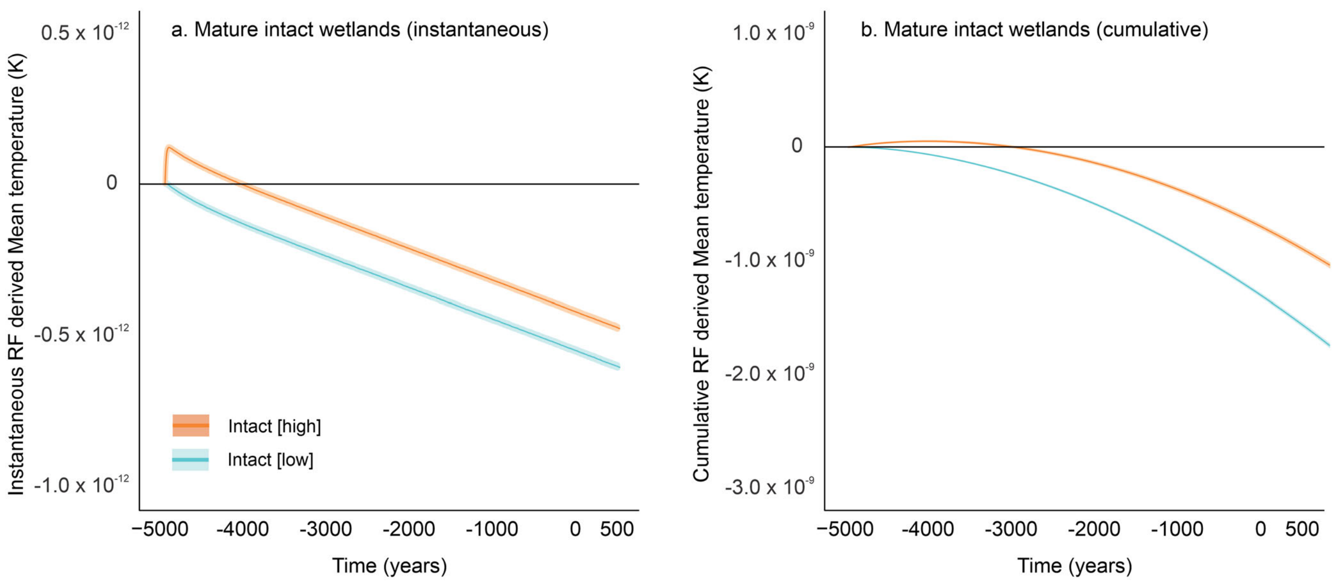

Fig. 3 | Mean temperature profile of mature intact wetlands (5000 years old). **a** Instantaneous radiative forcing (RF) and **b** cumulative radiative forcing (RF) derived mean temperature profile. The point in time on the x-axis when the y-axis value switches from positive to negative represents the time that intact mature wetlands start to deliver a net cooling effect on climate (i.e., the switchover time). Mature intact wetlands emitting low and high CH_4 impose a net cooling climate impact in contemporary times (year 0) under both instantaneous and cumulative radiative forcing derived mean temperature profile. Shaded areas around lines shows Monte Carlo simulation results.

Restoring drained wetlands with low CH_4 fluxes resulted in a 110-year reduced net CO_2-e.q. carbon source effect followed by an increasing net CO_2-e.q. carbon sink effect calculated using GWP*, GWP_{500}, and $SWGP_{500}$ metrics (Fig. 4c). Restored wetlands with high CH_4 fluxes were not observed.

Discussion

The goal of the Paris Agreement is to keep the rise in the Earth's average temperature well below 2 °C above pre-industrial levels and to actively work towards restricting the temperature increase to 1.5 °C. As stated by the most

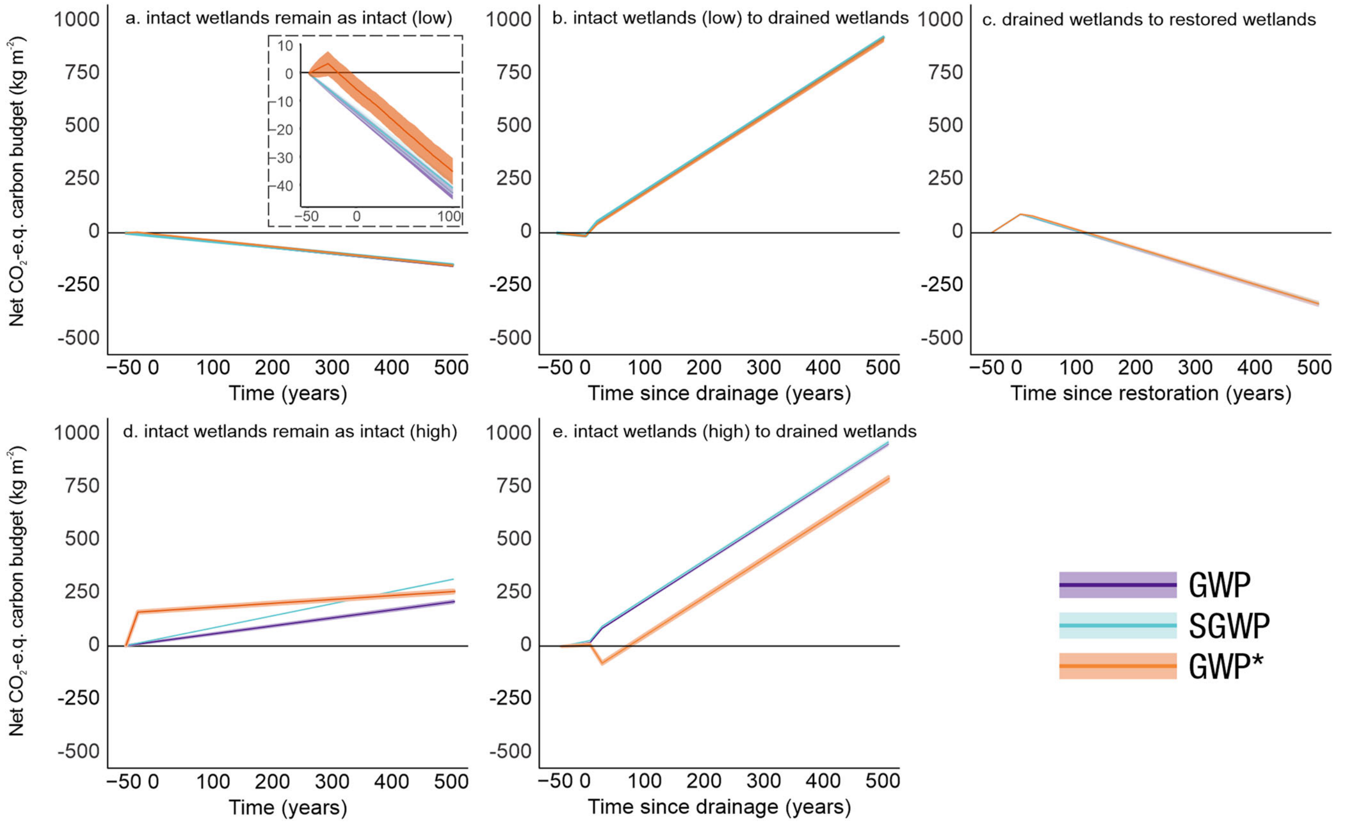

Fig. 4 | Cumulative net CO_2-e.q. carbon budget ($CH_4 + CO_2$) under different CO_2-e.q. metrics. Intact wetlands with (**a**) low and (**d**) high CH_4 fluxes remain as intact. Converting an intact wetland with (**b**) low and (**e**) high CH_4 fluxes to a drained wetland. Restoring drained wetland to restored wetland with (**c**) low CH_4 fluxes. Inset map represent net CO_2-e.q. carbon budget of intact wetland with low CH_4 emissions remaining intact during the year of −50 to 100. Shaded areas around lines shows Monte Carlo simulation results.

recent IPCC report[1], to achieve this goal, CO_2-e.q. carbon emissions need to reach net-zero (i.e., the balance of carbon sources and sinks) by 2050[26,27]. To assess the efficacy of wetlands as natural climate solutions for achieving mid-century net-zero emissions, it is essential to have a method for calculating, reporting, and comparing CO_2-e.q. carbon budgets that can establish a reliable connection between wetland carbon sink vs. source status and their corresponding warming vs. cooling effects for various wetland management scenarios. The findings of this study demonstrate that simulating the sustained CO_2 and CH_4 fluxes as they are emitted from or sequestered by wetlands and their atmospheric behaviour is essential for predicting their warming/cooling effect. Further, using a suitable CO_2-e.q. metric that reflects the warming/cooling effect is essential for predicting carbon sink/source status of wetlands in temperate North America (Fig. 5). These findings focus on inland mineral wetlands in temperate North America; however, the GHG perturbation model and CO_2-e.q. metrics can be applied to understand the climate impact and carbon role of wetlands in other geographical regions based on regional-specific wetland carbon sequestration and GHG emission factors.

GWP* offers a straightforward approach to calculating wetland CO_2-e.q. fluxes that correspond to their warming/cooling effects (Fig. 5)[24,27]. The dynamic CO_2-e.q. metric (GWP*) provided the most reliable indicator of warming/cooling and established a connection between warming/cooling and the cumulative CO_2-e.q. carbon budgets (Fig. 5); other predefined period CO_2-e.q. metrics (i.e., GWP, SGWP) obscured these effects (Table 1)[23,24]. Predefined period CO_2-e.q. metrics directly equate wetland CH_4 emissions by a single conversion factor and represent only one particular impact over a fixed timeframe (e.g., 100 and 500 years). In contrast, GWP* shares the same characteristics as the GHG perturbation model, allowing for the generation of a dynamic CO_2-e.q. carbon budget over any timeframe of interest following wetland state conversion (Table 1), which is essential for the detection of climate benefit/detriment periods[24,27]. GWP* captures the distinct climate impacts associated with short- and long-lived climate pollutants and more accurately represents the status of net CO_2-e.q. carbon source vs. sink following wetland state conversion, which is crucial to understanding the potential of wetlands in serving as effective solutions for mid-century climate targets.

Based on GWP* and the GHG perturbation model, our findings show that intact wetlands with low CH_4 fluxes (67% of the intact wetlands in our database) consistently served as cumulative net CO_2-e.q. carbon sinks and delivered a net cooling effect (Figs. 2a and 3a). The GHG perturbation model captured the short atmospheric lifetime of CH_4 and showed that maintaining intact wetlands characterized by high CH_4 fluxes delivered an initial net warming effect with a switchover time to a net cooling effect after approximately 1000 years (instantaneous) and 2000 years (cumulative) (Fig. 3). Given that most intact wetlands in North America have been on the landscape for thousands of years[8,34,35], intact wetlands with high CH_4 fluxes are effective net CO_2-e.q. carbon sinks and deliver net cooling effects on climate in contemporary times. Thus, protecting existing intact wetlands is an effective means of promoting wetlands as natural climate solutions and helping countries to meet their climate change mitigation and adaption targets by 2050[2–4].

Restoring drained wetlands has been widely promoted as an effective means of delivering natural climate solutions[4,10,17]. There is evidence that suggests that early restored wetlands often exhibits a deficiency in organic matter[36,37], imposing constraints on the establishment and activation of microbial communities responsible for CH_4 production and, therefore, resulting in lower CH_4 fluxes in early restored wetlands compared to intact wetlands. Despite this evidence, concerns have been raised that the overall climate benefit may be offset by the production and release of CH_4, since wetland restoration favours environmental conditions (i.e., prolonged

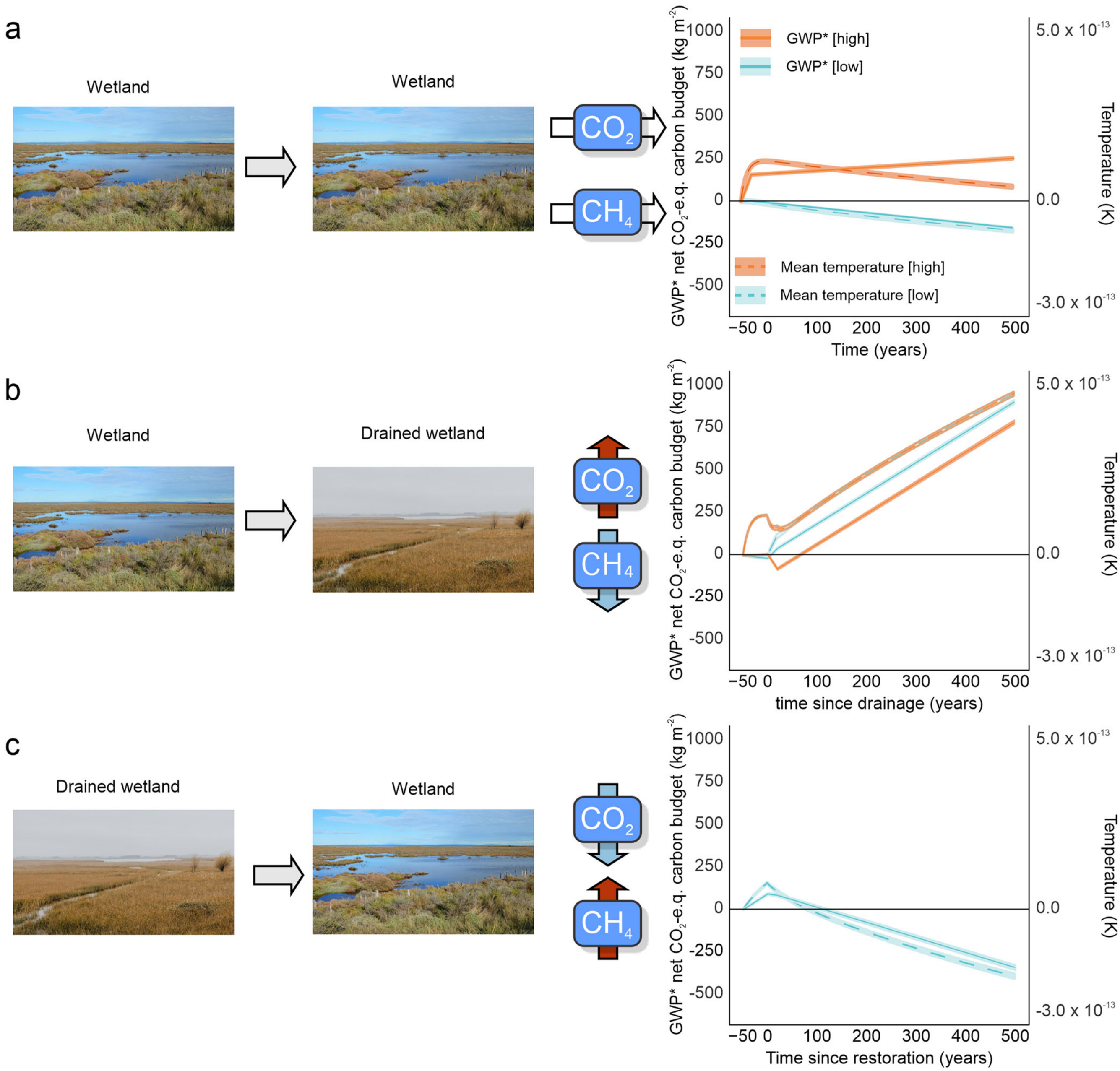

Fig. 5 | GWP* derived net CO_2-e.q. carbon budget vs. instantaneous radiative forcing derived mean temperature. a Intact wetland remains intact, **b** intact wetland to drained wetland and **c** drained wetland to restored wetland. The primary and secondary y-axis of **a**–**c** employs a consistent scale, respectively, to facilitate visual comparison. The changes in CO_2-e.q. carbon budget associated with wetland state conversion match closely with the instantaneous radiative forcing derived mean temperature profile. Shaded areas around lines shows Monte Carlo simulation results.

hydroperiod) that can promote CH_4 emissions[6,10–12,19,38]. Here, with a simple model of wetland radiative forcing of climate and GWP*, we suggest that, despite the increase in CH_4 emissions compared to drained wetlands, restored wetlands with low CH_4 fluxes are likely to provide immediate climate benefits (i.e., reduced climate warming effect), and help countries to meet their climate target of net-zero GHG emissions by 2050 while providing net climate cooling benefits 110 years after restoration (Figs. 2c and 4c). While this study did not have restored wetlands with high CH_4 fluxes, it is possible that such restored wetlands may take longer to reduce and then neutralize the warming effect caused by CH_4 efflux through sustained CO_2 uptake.

Taking a precautionary approach to restoring wetlands to achieve mid-century climate targets, it is crucial to adopt management interventions that minimize CH_4 fluxes from restored wetlands, since effective implementation of wetlands as natural climate solutions is likely to benefit most from simultaneous efforts to reduce both CO_2 and CH_4 emissions[20,24].

Management interventions could be designed to modify physical, chemical, and biological characteristics of restored wetlands to inhibit CH_4 production and emission. First, water levels in restored wetlands could be stabilized, since fluctuating water levels have been found to promote wetland CH_4 production and emission[38,39]. Second, loading of sulphate into restored wetlands could be minimised, since sulphate influences the dominant anaerobic metabolism pathway. Specifically, a large abundance of sulphate could suppress CH_4 production by altering the dominant anaerobic metabolism pathway from methanogenesis towards pathways that yield higher energy (e.g., SO_4^{2-} reduction)[40,41]. Third, the plant community composition

Table 1 | Summary of the advantages and disadvantages of the GHG perturbation model and CO_2-e.q. metrics

	Advantages	Disadvantages
GHG perturbation model	The GHG perturbation model facilitates understanding of the temporal pattern of wetland GHG fluxes, which benefit the identification of the radiative forcing switchover time (i.e., the length of time after which the warming effect due to CH_4 emissions is overtaken by the cumulative removal [cooling effect] of CO_2) associated with wetland state conversion[20,33].	The GHG perturbation model assumes wetland CO_2 and CH_4 fluxes to be constant over time, but they vary as a function of climatic variability and climate change[31]. Note: the limitation associated with the GHG perturbation model also applies to CO_2-e.q. metrics.
GWP	The GWP metric is easy to implement. The 100-year variant of the Global Warming Potential (GWP_{100}) has been formally adopted in international climate policy (e.g., Paris Agreement, Kyoto Protocol) and have become the standard for expressing emissions in the scientific literature and general media[15,24].	The GWP metric considers GHG emissions as a single pulse while ecosystem emissions are usually continuous throughout time[24,27]. The GWP metric does not consider the difference in atmospheric lifetime between CO_2 and CH_4, which has led to overestimation on cumulative effect of wetland CH_4 on total warming and resulted in incorrect conclusions on the climatic role of wetland ecosystems[24,27]. The GWP metric needs to be applied over a predefined period that is arbitrary and disconnected from policy timelines[24].
SGWP	The SGWP metric is easy to implement. The SGWP metric considers the sustained behaviour of wetland GHG fluxes by treating wetland GHG emissions as persistent – and not one time – events[15].	Like the GWP metric, the SGWP metric needs to be applied over a predefined period and therefore do not adequately capture the climate role of wetland GHG emissions[15].
GWP*	The GWP* metric allows for the generation of dynamic CO_2-e.q. carbon budget over any timeframe of interest following wetland state conversion and do not need to be applied over a predefined period. The GWP* metric has been shown to better track the temperature impacts of the integrated radiative forcing associated with CH_4 emissions[22,23].	Unlike the predefined period metrics (i.e., GWP and SGWP), the GWP* metric does not allow for direct conversion of wetland GHG emissions to CO_2-e.q. format. The GWP* metric requires the GHG emission profile over the 20-years preceding any value, as it considers a 20-year running average[23,27]. This requirement could potentially complicate broad implementation of the GWP* metric.

of restored wetlands could be optimized, since cutting and/or grazing *Typha* within restored wetlands could benefit the reduction of CH_4 production and emission[42]. Finally, riparian buffers could be established surrounding wetlands to restrict erosion and runoff induced mobilization of carbon and nutrients into restored wetlands, thereby constraining activities of CH_4-producing microbes and reducing wetland CH_4 emissions[43,44]. However, it is important to recognize the potential for synergies and tensions in the implementation of wetland CH_4 mitigation strategies in restored wetlands[43]. For instance, removing or altering vegetation (e.g., *Typha*) to control CH_4 emissions can lead to a rapid progression towards a less biodiverse wetland plant community composition[43,44], which may have cascading effects throughout the wetland ecosystem.

Our study had several limitations that should be addressed in future research. First, empirical data were sparse, making it impossible to "standardize" the data for individual wetlands (i.e., carbon sequestration and CO_2 and CH_4 measurements at the same wetland), using common sampling windows (e.g., year-round measurements) and common sampling techniques[30]. Continuous monitoring of wetland CO_2 and CH_4 fluxes at individual wetlands throughout the year using similar techniques are needed to reduce uncertainties in wetland radiative forcing and GHG budget analysis imposed by the available dataset[30]. For example, the growing flux tower networks in North America and the recently launched MethaneSAT mission satellite measurements[45] hold promise for the future.

Second, there is growing evidence of variability in annual wetland GHG fluxes in the early years after wetland state conversion[3,17], which suggests that using a constant emission factor to represent post conversion wetland GHG fluxes will likely impose biases in GHG budget assessments. Continuous monitoring of wetland CO_2 and CH_4 fluxes in wetlands that have undergone state conversions are needed to reduce uncertainties in short- and long-term GHG budgets[17].

Third, there is growing evidence of the importance of water table level changes on wetland carbon fluxes[19,39,46]. Lowering of the water table level associated with wetland drainage exposes SOC pools above the water table to oxygen, which enhances the rate of decomposition and CO_2 emission[18,19]. In contrast, wetland rewetting effectively inhibits CO_2 production and emission, but also enhances the production and emission of CH_4[20]. Our study did not explicitly consider the effect of water level change on wetland carbon flux patterns and their climate impacts, since detailed information on water level changes was not consistently provided for the studies from which we compiled the data, making it challenging to analyse the effects comprehensively. Future research is needed to explore further the effects of changes in water table levels on GHG fluxes.

Fourth, ongoing climatic variability and climate change will impose complexities in developing a predictive understanding of GHG flux patterns of wetlands under different states. Our simulations of radiative forcing and CO_2-e.q. carbon budget change following wetland state conversion did not consider concurrent wetland responses to climatic variability or climate change. Future research is needed that considers the interactive effects of climatic variability and climate change on different wetland conversion scenarios, which is crucial for more accurately assessing wetland radiative forcing and GHG budget change associated with wetland management.

Fifth, our study assumed that carbon exchange due to lateral flux of dissolved organic carbon and dissolved inorganic carbon was negligible, which could be justified for inland marshes with no surface inflow or outflow[33]. To extend this study to coastal and tidal marshes, the lateral import and export of carbon must be considered[33,47,48].

Finally, our study focused on carbon-based wetland GHGs and did not take nitrous oxide (N_2O) into consideration when assessing wetland GHG radiative forcing and changes in CO_2-e.q. emission profiles associated with wetland state conversion. Although N_2O fluxes are found to be negligible compared to CO_2 and CH_4 fluxes in inland mineral soil wetland settings[17,49,50], a consideration of N_2O might allow more comprehensive assessment of the potential of wetlands to serve as natural climate solutions. Integration of long-term N_2O fluxes into the GHG budgets of inland mineral soil wetlands will likely increase the net climate benefit of wetland restoration given the considerable amount of N_2O production and emission from drained wetlands in agricultural settings during irrigation or precipitation events[17,51].

Wetland protection and restoration measures have typically focused on non-carbon benefits[5,52]. However, this study demonstrates that wetland protection and restoration measures can lead to substantial carbon benefits. Draining intact wetlands should be reduced if not stopped. Despite the existence of a short-term climate benefit period associated with cessation of CH_4 emissions, the continued increase in CO_2-e.q. carbon source strength, due to consistent CO_2 emissions from drained wetlands and the accumulation of CO_2 in the atmosphere, imposes a long-term warming effect on the climate that will persist for an indefinite period[3]. Most intact and restored wetlands served as natural climate solutions for mid-century net-zero emission initiatives. To achieve the initiative of net-zero carbon emission by 2050 and ultimately the Paris Agreement, it is crucial to protect intact wetlands and promptly restore drained ones, while simultaneously implementing effective interventions to control CH_4 fluxes from restored wetlands.

Methods

Wetland conversion scenarios

Three wetland scenarios (Supplementary Table SI-1) were established to assess the net warming vs. cooling effect and the carbon sink vs. source status (and the switchover time from carbon source to sink) associated with wetland conversion. For scenario 1, the pre- and post-conversion wetland states were intact. We assumed wetlands were initiated at year −50 and remained intact from year 0 to 500 years. For scenario 2, the pre-conversion wetland state was intact, and the post-conversion wetland state was drained. We assumed wetlands were initiated at year −50 and remained intact for 50 years before being drained at year 0, remaining drained for the next 500 years. Scenario 1 was used as a baseline scenario to compare against the conversion of intact wetlands to drained wetlands. For instance, the baseline scenario used to compare against draining intact wetlands with high CH_4 fluxes is maintaining intact wetlands with high CH_4 fluxes. For scenario 3, the pre-conversion wetland state was drained, and the post-conversion wetland state was restored. We assumed drained wetlands were drained at year −50 and remained drained for 50 years before being hydrologically restored at year 0, remaining restored for the next 500 years. Scenario 2 was used as a baseline scenario to compare against the conversion of drained wetlands to restored wetlands.

The decision to set the pre-conversion period as 50 years was made based on two factors. First, our GHG perturbation model results (Supplementary Figs. SI-1 and SI-2) indicated that the time for newly initiated wetlands, newly drained wetlands, and newly restored wetlands to reach their radiative balance steady state was approximately 50 years based on CH_4 (i.e., once the rate of CH_4 emission and atmospheric CH_4 removal are approximately balanced), while CO_2 radiative effects never reach steady state given its indefinite time to equilibrate with various external reservoirs including geological scale weathering of continental rocks[13,31]. Second, if we considered year 0 in our wetland conversion scenarios as the present year (approximately 2020), then the 50-year pre-conversion period allowed us to start our modelling from the year of 1970. This allowed us to better align our model results to the real-world, where extensive human induced wetland state conversion in North America started around 1970[52].

We compiled CO_2 and CH_4 flux data as inputs for the model, simulated the net warming effect associated with wetland CH_4 emission and cooling effect associated with wetland CO_2 uptake using the GHG perturbation model for each scenario, and calculated the net carbon source/sink status of the wetland conversion using CO_2-e.q. metrics for each scenario. For each wetland scenario, Monte Carlo simulations ($n = 1000$ iterations) of the GHG perturbation models and CO_2-e.q. carbon budget calculations were used to capture the uncertainty in switchover times due to the variability in compiled wetland carbon sequestration rates and carbon-based GHG fluxes from different published and unpublished sources[33].

Wetland carbon sequestration and GHG fluxes

Wetland carbon-based GHG flux data were compiled from published and unpublished (held by investigators) sources from the temperate region of North America (Fig. 1). Carbon sequestration data were estimated from eddy covariance measurements of net ecosystem exchange and from radioisotope dating of organic carbon in wetland sediments. Radioisotope measurements represent recent records (since 1963) of sediments derived from ^{137}Cs and ^{210}Pb dating[53]. Carbon based GHG fluxes (i.e., CO_2 and CH_4) data were estimated from eddy covariance- and chamber-based measurements (c.f. Supplementary Information 3 - Supplementary Data 1).

Our compiled wetland carbon sequestration and GHG flux data represents different types of freshwater mineral soil wetlands such as inland marsh, coastal/tidal marsh, constructed marsh, managed marsh, and swamps. However, it was not possible to assess wetland conversion induced radiative forcing and change in CO_2-e.q. carbon budget for all types of freshwater mineral soil wetlands due to the lack of data for all wetland states (i.e., intact, drained, and restored wetlands). We therefore restricted wetland carbon sequestration and GHG flux data to represent inland marshes only.

Compiled CO_2 data for the various inland marsh states were normally distributed (Shapiro–Wilk test, $p < 0.05$) (Supplementary Fig. SI-3). However, the compiled CH_4 flux data for different inland marsh states exhibited a large range of variability and were not normally distributed (Shapiro–Wilk test, $p < 0.05$) (Supplementary Fig. SI-3) but became normally distributed on a logarithmic scale (Supplementary Fig. SI-4). A K-means cluster analysis was conducted to establish two CH_4 flux ranges (low and high), and the CH_4 flux data from different wetland states were binned into low and high CH_4 fluxes (Fig.1).

Net cooling vs. warming effect of wetlands

The GHG perturbation model simulates the atmospheric inventories of wetland carbon based GHGs and estimates CO_2 and CH_4 induced radiative forcing by considering the following three factors[13].

First, the radiative efficiencies and atmospheric residence times of CO_2 and CH_4. The radiative efficiency of CO_2 is 1.75×10^{-15} Wm^{-2} per kg CO_2 and the radiative efficiency of CH_4 is 1.28×10^{-13} Wm^{-2} per kg CH_4[26]. CH_4 is a short-lived climate pollutant and has the atmospheric lifetime of 12 years, while there is no single lifetime can be defined for CO_2 (i.e., lifetimes range from 3.4 to 10^8 years)[13,14].

Second, the oxidation of CH_4 to CO_2. The oxidation of CH_4 in the atmosphere involves reaction with the hydroxyl free radical (OH), producing CO_2 and H_2O as the primary products[29].

Third, the atmospheric CO_2 feedback among various non-atmospheric reservoirs. Atmospheric CO_2 equilibrates with three non-atmospheric reservoirs (i.e., external biological, hydrological, and geological reservoirs) over a variety of timescales, resulting in an exchange of CO_2 between the atmosphere and the non-atmospheric reservoirs. For instance, atmospheric CO_2 will have short-term exchange with the surface ocean, and long-term (geological scales) exchange with continental rocks. Therefore, atmospheric CO_2 fixed by wetlands essentially comes proportionally from each non-atmospheric reservoir.

The atmospheric inventory of CH_4 at any given time (t) therefore depends on the rate of wetland CH_4 fluxes and the loss rate of antecedent atmospheric CH_4 due to oxidation to CO_2. Meanwhile, wetland-derived atmospheric CO_2 inventory at any given time (t) depends on the rate of wetland CO_2 fluxes, and the gain rate of CO_2 due to the oxidation of CH_4 emitted from the wetland. Further, from a mathematical perspective, the interaction of atmospheric CO_2 with non-atmospheric reservoirs is modelled by considering the atmosphere as comprising four independent reservoirs of CO_2, each with its own reservoir fraction and a first-order CO_2 decay determined by the atmospheric perturbation lifetime[15,54]. Wetland-derived atmospheric CH_4 and CO_2 inventories at any given time (t) are therefore estimated using the following mathematical equations:

$$M_{CH4-C(t)} = F_{CH4-C}dt + \left[M_{CH4-C(t-1)} * e^{(-dt/\tau CH4)}\right] \quad (1)$$

where $M_{CH4\text{-}C}$ is the mass of atmospheric CH_4 (g C m^{-2}), $F_{CH4\text{-}C}$ is the emission factor (g C m^{-2} y^{-1}), dt is the time step (0.2 y), and $\tau CH4$ is the atmospheric perturbation lifetime of CH_4 (12.4 years).

$$M_{CO2-C(t)} = \sum_{i=1}^{4} f_i(F_{CO2-c}dt + M_{CH4-ox}) + [M_{CO2-Ci(t-1)} * e^{(-dt/\tau CO2i)}] \quad (2)$$

where F_{CO2-c} is the CO_2 flux factor (g C m^{-2} y^{-1}), with CO_2 fluxes having a negative sign representing carbon sequestration, dt is the time step (0.2 y), $\tau CO2\_i$ is the atmospheric perturbation lifetime for each of the four CO_2 pools (ranging from 4.3 to 394 years and one pool staying permanently in the atmosphere), and f_i is the relative fractional size of pool i (ranging from

0.217 to 0.282)[54]. M_{CH4-ox} is the $[M_{CH4-C(t-1)} * (1 - e^{(-dt/\tau CH4)})]$ term from Eq. (1), accounting for CH_4 oxidation to CO_2[15,55].

The atmospheric inventory of the wetland carbon-based GHG fluxes derived from the GHG perturbation model were subsequently converted into instantaneous radiative forcing of the wetland carbon-based GHG fluxes by multiplying the appropriate radiative efficiency value (i.e., 1.75×10^{-15} Wm^{-2} per kg CO_2 and 1.28×10^{-13} Wm^{-2} per kg CH_4)[26]. The radiative efficiencies for CH_4 were then multiplied by a factor of 1.65 to account for the indirect effects of CH_4 on the global radiation balance (e.g., the impact of CH_4 on the concentrations of ozone in the troposphere and water vapour in the stratosphere)[26]. The cumulative radiative forcing of the wetland carbon-based GHG fluxes was calculated by summing up the instantaneous radiative forcing values over the model period. Meanwhile, the impact of radiative forcing on the mean surface temperature was estimated to be 1 K for every 1.23 Wm^{-2} of radiative forcing[20,56].

Wetland carbon sinks vs. source status

GWP is defined as the time-integrated change in radiative forcing due to a pulse emission of a given climate pollutant relative to a pulse emission of the same quantity of CO_2[26].

SGWP is defined as the time-integrated change in radiative forcing due to the sustained emission of a given climate pollutant relative to a sustained emission of the same quantity of CO_2[15]. SGWP is like GWP, as both are calculated based on cumulative radiative forcing of each gas, but SGWP is considered superior to the GWP as it explicitly considers the sustained behaviour of wetland carbon-based GHG fluxes by treating wetland GHG emissions as persistent rather than pulse (one-time) events[15]. The emission of a given climate pollutant (e.g., CH_4) was converted into a CO_2-e.q. by multiplying the appropriate GWP or SGWP conversion factor (i.e., $GWP_{500} = 11$; $SGWP_{500} = 14$) for the specific time horizon using the following equation:

$$E_{CO2-eq} = E_{GHG} * GWP_H or SGWP_H \quad (3)$$

where E_{CO2-eq} is the CO_2-e.q. emission, E_{GHG} is the emission rate of the GHG (i.e., CH_4), GWP_H or $SGWP_H$ is the time specific conversion factor, and H is the selected time horizon for GWP indices (e.g., 20, 100, 500 years).

GWP* is defined based on the differences in the atmospheric behaviour between CO_2 and CH_4. Essentially, it considers a greater impact of new CH_4 emissions on temperature and recognizes that this impact diminishes after a specific period (i.e., 12 years) by treating (equalizing) sustained emissions of CH_4 as one-off release of a fixed amount of CO_2, since they both lead to a relatively stable increase in radiative forcing and mean surface temperature[24,27].

Accordingly, GWP* establishes means of CO_2 equivalence by relating a change in the rate of CH_4 emissions to a fixed quantity of CO_2. The wetland CO_2-e.q. CH_4 budget was therefore calculated by accounting for changes in wetland CH_4 emission rate (ΔCH_4) instead of the magnitude of CH_4[22,23]. Cain et al.[27] advanced Allen et al.'s[22,23] work by accounting for the delayed temperature response associated with thermal equilibration to past increases in CH_4 emissions using the following equation:

$$E_{CO2-w.e.} = \left(r * \frac{\Delta E_{SLCP}}{\Delta t} * H + s * E_{SLCP} \right) * GWP_H \quad (4)$$

where $E_{CO2-w.e.}$ is CO_2-e.q. emission derived from the GWP*, $SLCP$ refers to short-lived climate pollutants, ΔE_{SLCP} is the change in wetland CH_4 emission rate over the time interval Δt (years), E_{SLCP} is the current CH_4 emission rate, and r and s are the weighting factors assigned to the climate impacts of the change in CH_4 emission rate and the current wetland CH_4 emissions, respectively ($r + s = 1$).

The parameters in Eq. (4) (i.e., Δt, r, s) were estimated from published literature. We adopted the same r (=0.75), s (=0.25), and Δt (=20 years) values used by Cain et al.[27]. With these suggested parameters, the GWP* equation can be further simplified to:

$$E_{CO2-w.e.} = \left(4 * E_{SLCP(t)} - 3.75 * E_{SLCP(t-20)} \right) * GWP_H \quad (5)$$

where $E_{SLCP(t)}$ is the current CH_4 emission rate, and $E_{SLCP\ (t-20)}$ is the rate of CH_4 emissions 20 years ago.

Data availability

The compiled wetland carbon sequestration and GHG flux data is available in the Supplementary Document – Supplementary Data 1

Code availability

The codes to produce the analyses presented in this study are available upon request from the corresponding author.

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Author contributions

S.M. conceptualized and designed the study, performed the analysis, and wrote the first draft of the manuscript. I.F.C. compiled the data, contributed to the conceptualization and design of the study and manuscript preparation, and provided funding. P.B. assisted in the conceptualization and design of the study and manuscript preparation. All authors jointly revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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