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Coastal Restoration May Not Necessarily Enhance Blue Carbon Sink

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Key Points:

- Paired eddy covariance measurements were used to assess the full impact of saltmarsh-mudflat-mangrove restoration on carbon sink capacity
- Restoration efforts through excavation and burial of *Spartina alterniflora* reduce carbon sink and increase methane emission tenfold
- Pulse methane emission negates carbon sink benefit and causes a significant climate debt, potentially taking over 3 decades to offset

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Abstract

Large-scale restorations being implemented in coastal China involve replacing invasive *Spartina alterniflora* with mangroves, yet the full effects of such saltmarsh-mudflat-mangrove land-use change on the blue carbon sink are largely unknown. This study, using paired eddy covariance measurements of greenhouse gases (GHGs) before and after *S. alterniflora* removal, reveals that such restoration efforts through excavation and burial of *S. alterniflora* inadvertently cause pulse methane emission. The emission negates the carbon sink benefit and causes a significant climate debt, potentially taking over 3 decades to offset. These findings highlight the risk of GHG changes from coastal restoration in neutralizing potential blue carbon sink and call for refining current restoration practices to mitigate unintended environmental impacts. This has important implications for achieving climate benefits along with other ecosystem service co-benefits in coastal restoration, particularly for China's coastal wetlands where *S. alterniflora* removal is being implemented as the world's largest ecosystem restoration effort.

Plain Language Summary

Coastal blue carbon ecosystems, for example, mangrove and tidal saltmarsh, contribute to over half of global carbon burial in the oceans and provide other important co-benefits. The restoration of these ecosystems has therefore been frequently discussed in recent political discourse and incorporated as nature-based climate solutions into Nationally Determined Contributions, yet the potential environmental costs of the restoration are rarely included in the discussions. China has recently launched the world's largest coastal restoration campaign to intensively remove invasive *S. alterniflora* along its 18,000 km of coastline, which could potentially act as large greenhouse gas sources. Here we demonstrate, using paired eddy covariance measurements and scenario analyses, such restoration efforts through excavation and burial inadvertently increase methane emission tenfold, which could negate the carbon sink benefit resulted from mangrove restoration. These results call for refining current restoration practices to relieve the unintended environmental impacts and have important implications for achieving climate benefits along with other co-benefits in coastal ecosystem restoration. Our findings will be of significant interest to a wide range of scientific disciplines, policy making bodies, and affected communities.

1. Introduction

Vegetated coastal wetlands are intensive sinks of atmospheric carbon dioxide (CO_2), accumulating disproportionately large amounts of carbon as a result of high photosynthetic/sediment inputs and low respiratory loss under tidally driven anoxic conditions (Alongi, 2020; Daniel, 2023; X. Zhu, Qin, & Song, 2021). The importance of these blue carbon ecosystems as nature-based solutions to mitigate the on-going climate crisis has been increasingly recognized (Howard et al., 2023; Wang et al., 2023). However, the climate benefits of CO_2 sequestration could be partially offset via emission of other greenhouse gases (GHG) like methane (CH_4) (Bartolucci & Fulweiler, 2024; Cotovicz Jr et al., 2024; Eyre et al., 2023; Mueller et al., 2020; Rosentreter et al., 2023; X. Zhu, Sun, & Qin, 2021). Notably, the benefits of climate change mitigation are vulnerable to anthropogenic disturbances, especially those leading to habitat changes (Kirwan et al., 2023; Sasmito et al., 2019). Although blue carbon benefit might not be a predominant reason for ecosystem restoration, coastal

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restoration has been frequently discussed in recent political discourse around blue carbon strategies (McMahon et al., 2023). For example, coastal and marine ecosystems as mitigation solutions have been incorporated by 46 countries into their Nationally Determined Contributions (NDCs, i.e., the country-level climate action plans under the Paris Agreement) (Lecerf et al., 2021).

The Chinese coastline has been significantly transformed by invasive *Spartina alterniflora* since its introduction in the 1970s, exerting both positive and negative impacts on tidal mudflats and saltmarshes (Nie et al., 2023). Deeming that the harm outweighs the benefits, China has recently launched the world's largest coastal restoration plan, aiming to remove over 90% of *S. alterniflora* along its entire coastline by 2025 (Stokstad, 2023). It has been reported that *S. alterniflora* invasion results in a climate benefit by promoting carbon sequestration over CH_4 emission (Yuan et al., 2015), but the impact of large-scale *S. alterniflora* removal on the magnitude and variability of GHG fluxes is largely unknown. Physical means of restoration that are applied at an unprecedented scale, such as excavation and burial, may greatly impact the GHG balance. Quantifying the changes in GHG fluxes before and after the removal of *S. alterniflora* is a prerequisite for assessing the potential environmental costs of restoration, in relation to the role of coastal wetlands as nature-based climate solutions (Macreadie et al., 2019). However, high-quality time-series GHG flux measurements covering both pre- and post-removal periods are extremely limited but necessary for accurate assessments of climate mitigation potential.

In southern China, mangrove afforestation is commonly practised in coastal restoration after *S. alterniflora* removal (Gu & Wu, 2023; Z. Liu et al., 2016). However, it may cost several decades to convert the habitat from mudflat to mature mangroves (Sasmito et al., 2019). It is therefore critical to assess the impact of the restoration on GHG-induced climate benefits by considering the full effects of land-use change (LUC) (Mello et al., 2014). At the beginning stage of the mudflat-mangrove LUC, annual net climate benefit (i.e., net combination of radiative effect from annual GHG sequestrations and radiative effect from annual GHG emissions) from the restoring habitat is less than that of lost *S. alterniflora* saltmarsh, leading to a “climate deficit.” The cumulative loss of annual net climate benefit over this stage is referred to as the “climate debt” of the LUC. Over time, establishing mangroves can repay this climate debt when the habitat provides more annual net climate benefit than that of the lost *S. alterniflora* saltmarsh (i.e., “climate surplus”). Until the time when the climate debt is eventually paid off, the “payback time” incurring from the LUC (Fargione et al., 2008; Mello et al., 2014; Mitchell et al., 2012) is estimated as the number of years since *S. alterniflora* removal. Here, the payback time denotes the time span that the mudflat-mangrove LUC would need to compensate the climate debt due to LUC (i.e., cumulative loss of annual net climate benefit over the beginning years following the removal).

Here, we report on a paired eddy covariance (EC) study that measures net ecosystem CO_2 and CH_4 exchanges over 2 consecutive years, 1 pre-removal (November 2021 to October 2022) and 1 post-removal (November 2022 to October 2023) year, for 2 adjacent coastal wetland habitats: (a) a saltmarsh undergoing LUC with *S. alterniflora* removal via excavation and burial and (b) an intact mature mangrove. Such comparative studies are rare for coastal wetlands globally, especially for capturing the climate impact of ongoing large-scale restoration activities. The difference in GHG fluxes (i.e., CO_2, CH_4) between the pre- and post-removal years at the restoration site is used to calculate the initial climate debt, while the contrast between net climate benefit of lost *S. alterniflora* saltmarsh and establishing mangroves is used to calculate annual climate deficit (or surplus) and then to estimate payback time incurred by the LUC. The key aim of this study is to assess the impact of restoration on GHG-induced climate benefits and its risk in offsetting blue carbon potential by considering the full effects of the saltmarsh-mudflat-mangrove LUC.

2. Materials and Methods

The study area is a subtropical estuarine wetland in the estuary of Zhangjiang river on the southeast coast of China (Figure 1). The study area experiences a monsoon climate (mean annual rainfall of 1,165.5 mm, air temperature of 21.1°C, and relative humidity of 88.0%) and an irregular semidiurnal tidal regime (mean tidal range of 2.1 m and surface water salinity of 12.6 PSU) (Lu & Zhu, 2021; X. Zhu, Hou, et al., 2019; X. Zhu, Hou, et al., 2021; X. Zhu, Song, et al., 2019). It is located within a natural reserve mainly for mangrove conservation and restoration, and the bare mudflat of this study area has experienced a decade of range expansion of *S. alterniflora* prior to 2022, converting bare mudflat into vegetated tidal saltmarsh (X. Zhu, Meng, et al., 2019). Starting from late October 2022, an intensive coastal restoration effort was initiated by the government to remove *S. alterniflora* mainly using industrial excavators, converting the *S. alterniflora* saltmarsh back to mudflat in a couple of weeks (X. Zhu,

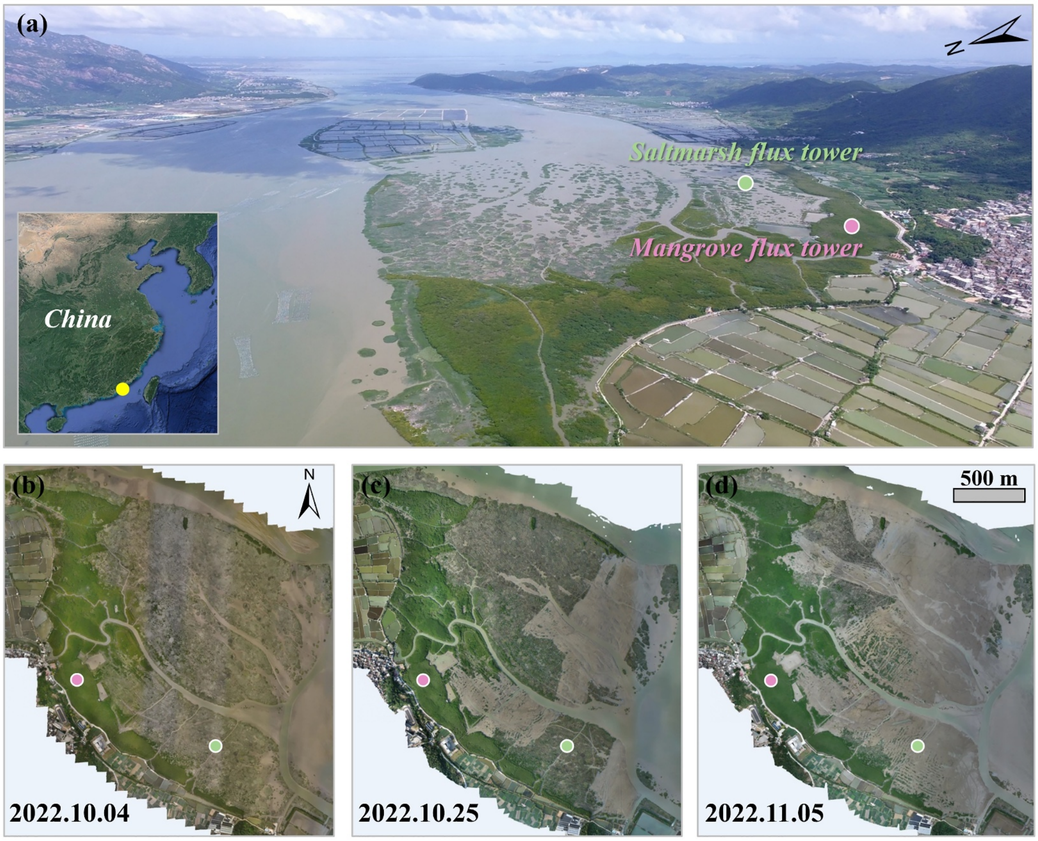

Figure 1. The location of flux towers shown with (a) an aerial photo and three successive orthophotos, mosaiced from unmanned aerial vehicle photos collected at low tide, (b) before, and (c, d) during the first intensive removal of *S. alterniflora* occurring in late October of 2022.

Ma, et al., 2024). A second less disruptive removal campaign mainly using hoes was conducted in late June 2023 to control the *S. alterniflora* regrowth. Mangrove afforestation following the *S. alterniflora* removal is now underway as a restoration scheme over this study area.

The EC measurements of net ecosystem exchanges of both CO_2 and CH_4 were simultaneously conducted for saltmarsh and mangrove sites from November 2021 to October 2023, except saltmarsh CH_4 starting from July 2022. The saltmarsh and mangrove EC sites (~1 km apart) are located in one habitat experiencing the saltmarsh-to-mudflat conversion and another intact habitat of mature mangrove, respectively (Figure 1). The close proximity of two EC sites within the same wetland landscape avoid potentially confounding factors such as climate differences in comparing CO_2 and CH_4 fluxes between the two sites. Thus, these paired EC sites provide robust flux measurements useful for evaluating the effect of LUC on the GHG balance (including CO_2 and CH_4 fluxes only). The EC system of saltmarsh and mangrove flux sites consisted of 2 open-path gas analyzers of CO_2 (LI-7500, Li-COR Inc., Lincoln, NE, USA) and CH_4 (LI-7700, Li-COR Inc.) and a three-axis sonic anemometer (CSAT-3, Campbell Scientific, Inc., Logan, UT, USA). Regular EC maintenance (e.g., manually cleaning the mirrors of gas analyzers weekly) and necessary quality controls (e.g., data removal with rainfall or insufficient nighttime atmospheric mixing) were conducted to ensure data quality (Z. Zhu & Zhu, 2025; X. Zhu, Chen, et al., 2024; X. Zhu, Qin, & Song, 2021; X. Zhu, Sun, & Qin, 2021). The EC flux footprint (i.e., the area "seen" by the gas analyzers on the tower) analyses indicated that approximately 80% of the flux contribution came from an area within 200 m (100 m) of the saltmarsh (mangrove) tower (X. Zhu, Ma, et al., 2024; X. Zhu, Sun, & Qin, 2021).

The raw 10-Hz EC data were processed into 30-min time series flux data and then temporally aggregated to daily data. Any days with daytime (or nighttime) valid 30-min data less than one fourth (or one eighth) were excluded in the temporal aggregation. Over the measurement period, the percentages of valid daily CO_2 and CH_4 fluxes for saltmarsh were 88.9% and 78.2%, respectively, while the values for mangrove were 81.8% and 77.0%, respectively. Missing daily data were gap-filled using the artificial neural network (ANN) method (J. Liu et al., 2020; X. Zhu, Sun, & Qin, 2021) with explanatory variables including daily cumulative photosynthetically active radiation (PQS1 PAR Quantum sensor, Kipp & Zonen, Delft, Netherlands), mean air temperature (HMP155A sensor, Vaisala, Helsinki, Finland), mean vapor pressure deficit (derived from air temperature and relative humidity measured by HMP155A sensor), maximum surface water level (HOBO U20L-04 Water Level Logger, Onset, Bourne, MA, USA), mean surface water salinity (derived from electronic conductivity measured by HOBO U24-002-C Conductivity Logger, Onset), and day of year. The ensemble mean approach was used to gap-fill the missing GHG fluxes based on a 1,000 ANN model simulations. For each simulation, the whole data set of model target (daily CO_2 or CH_4 fluxes) and inputs (explanatory variables) was randomly divided into training (75%), validation (15%), and testing (15%) subsets to develop an ANN model. The gap-filled daily GHG fluxes were then used to calculate cumulative GHG fluxes, net climate benefit, and payback time.

Specifically, the net climate benefit (N) was quantified from CO_2 (F_{CO2}) and CH_4 (F_{CH4}) fluxes using the sustained-flux global warming potentials (sGWP) metric for a 100-year time horizon (Equation 1), where F_{CH4} was calculated as CO_2 equivalents (CO_2e) with the sGWP constant of 45 (Neubauer & Megonigal, 2015, 2019). By assuming that the transition from mudflat to mature mangroves occurs over decades (i.e., mangrove regeneration period) with annual net climate benefit ($N(t)$) declining exponentially (He et al., 2024) (Equation 2), the payback time (T) was calculated as the difference between the "payback year" (t_p) and the removal year (t_0), over which the integral of $N(t)$ equals that of lost *S. alterniflora* saltmarsh (N_s) as a reference scenario (Equation 3):

$$N = F_{CO2} + F_{CH4} \times 45 \tag{1}$$

$$N(t) - N_m = \left(N_f - N_m\right) e^{-\lambda t} \tag{2}$$

$$\int_{t_0}^{t_p} N(t)\, dt = \int_{t_0}^{t_p} N_s dt \tag{3}$$

where, N_m and N_f indicate annual net climate benefit of mature mangroves and mudflat in the year after *S. alterniflora* removal, respectively and λ is the decay rate of $N(t)$. We used 4 decades as a first-order estimate of mangrove regeneration period, given the fact that mature mangrove forests around the mangrove EC site are approximately 40-year-old (Z. Zhu et al., 2022) and that mangrove regeneration efforts lead to biomass recovery after ~40 years (Sasmito et al., 2019; Su et al., 2021). We also constrained λ varying between 0.12 and 0.21 to meet two additional conditions: (a) annual net climate benefit of establishing mangrove after the regeneration period, $N(40)$, reaches over 95% of N_m (i.e., $\lambda \geq 0.12$) and (b) annual net climate benefit of establishing mangrove after half of the regeneration period, $N(20)$, stays below 95% of N_m (i.e., $\lambda \leq 0.21$). N_m was calculated from the 2-year CO_2 and CH_4 flux measurements of mangrove tower (Equation 1), that is, the average (−3,902.7 g CO_2e m^{-2} yr^{-1}) of pre-removal (−3,884.1 g CO_2e m^{-2} yr^{-1}) and post-removal (−3,921.4 g CO_2e m^{-2} yr^{-1}) years, while N_s (−2,292.7 g CO_2e m^{-2} yr^{-1}) and N_f (4,674.4 g CO_2e m^{-2} yr^{-1}) were calculated from the CO_2 and CH_4 flux measurements of saltmarsh tower in the pre- and post-removal year, respectively.

3. Results and Discussion

The saltmarsh acted as a consistent CO_2 sink with daily uptake up to 7.4 g C m^{-2} d^{-1} over the pre-removal year, following a typical seasonal pattern (Figure 2a). After the removal, it turned into annual CO_2 neutral with both negative and positive daily fluxes. The saltmarsh emitted CH_4 throughout the measurement period, with emission boosted by the removal of *S. alterniflora*. Pulse emission occurred right after each of the two major removal events with the first pulse emission (up to 0.6 g C m^{-2} d^{-1}) over 20 times higher than the pre-removal level (0.03 ± 0.01 g C m^{-2} d^{-1}; mean ± std). Meanwhile, the mangrove consistently acted as a CO_2 sink (−3.3 ± 1.6 g C m^{-2} d^{-1}) and CH_4 source (0.01 ± 0.01 g C m^{-2} d^{-1}) without a significant difference between the pre- and post-removal years (Figure 2b).

For the saltmarsh, cumulative CO_2 sequestration and CH_4 emission over the pre-removal year were estimated at −748.1 g C m^{-2} yr^{-1} (or −2,743.0 g CO_2e m^{-2} yr^{-1}) and 7.5 g C m^{-2} yr^{-1} (or 450.0 g CO_2e m^{-2} yr^{-1}), respectively (Figure 3). The removals canceled out CO_2 sequestration and resulted in CH_4 emission more than

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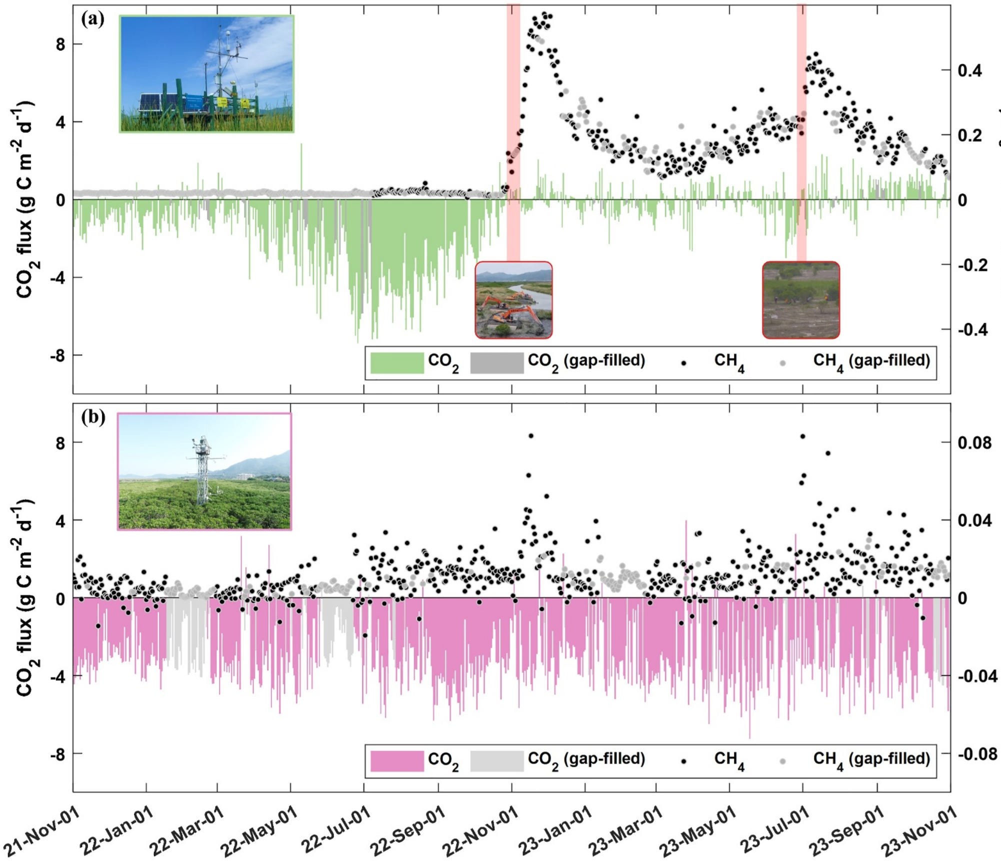

Figure 2. Temporal changes in observed and gap-filled daily net ecosystem CO_2 and CH_4 exchanges from a paired eddy covariance study on adjacent saltmarsh and mangrove wetlands. Daily CO_2 and CH_4 fluxes in (a) saltmarsh and (b) mangrove from November 2021 to October 2023, covering the first intensive and second moderate *S. alterniflora* removal campaigns indicated by red vertical bars, with inset photos of flux towers and removal campaigns.

tenfold that of the pre-removal level. CH_4 emission over the post-removal year (78.3 g C m^{-2} yr^{-1} or 4,698.0 g CO_2e m^{-2} yr^{-1}) was even an order of magnitude higher than the amount of absorbed CO_2 (6.0 g C m^{-2} yr^{-1}). This post-removal annual CH_4 emission was nearly a hundred times that of the median emission of saltmarsh sites (0.8 g C m^{-2} yr^{-1}) and twice that of the median emission of freshwater marsh sites (43.2 g C m^{-2} yr^{-1}) in a global EC-based CH_4 synthesis study (Knox et al., 2019). This extremely high emission was presumably due to sediment disturbances (i.e., excavation and burial) during the intensive (using industrial excavators) and less disturbing (using hoes) removal campaigns (Figure 2a). This finding provides important evidence to address an identified key controversial question on blue carbon science—how are GHG dynamics in blue carbon ecosystem altered following disturbance (Macreadie et al., 2019).

Although the saltmarsh became a weak carbon source (72.2 g C m^{-2} yr^{-1} as CH_4) after the removals, annual net climate benefit changed from a pre-removal cooling effect of −2,292.7 g CO_2e m^{-2} yr^{-1} to a post-removal warming effect of 4,674.4 g CO_2e m^{-2} yr^{-1}, leading to a climate deficit of 6,967.1 g CO_2e m^{-2} yr^{-1} incurring from the saltmarsh-mudflat LUC (Figure 4a). For mangroves, there was no significant difference in annual CO_2 sink (−1,099.9 vs. −1,155.8 g C m^{-2} yr^{-1}, Figure 3a), CH_4 source (2.5 vs. 5.3 g C m^{-2} yr^{-1}, Figure 3b), and net climate benefit (−3,884.1 vs. −3,921.4 g CO_2e m^{-2} yr^{-1}, Figure 4a) between the pre- and post-removal years. Depending on the assumed decay rate of annual net climate benefit for establishing mangroves ($\lambda = 0.21$–0.12), the annual climate deficit declined exponentially and vanished (net climate benefit equals that of pre-removal saltmarsh) in 10–16 years after the removals (i.e., between 2031 and 2037) and then shifted into annual climate surplus (Figure 4b). The payback time for the climate debt incurring from the saltmarsh-mudflat-mangrove LUC was estimated between 30 and 48 years after the removals (i.e., payback year between 2051 and 2069).

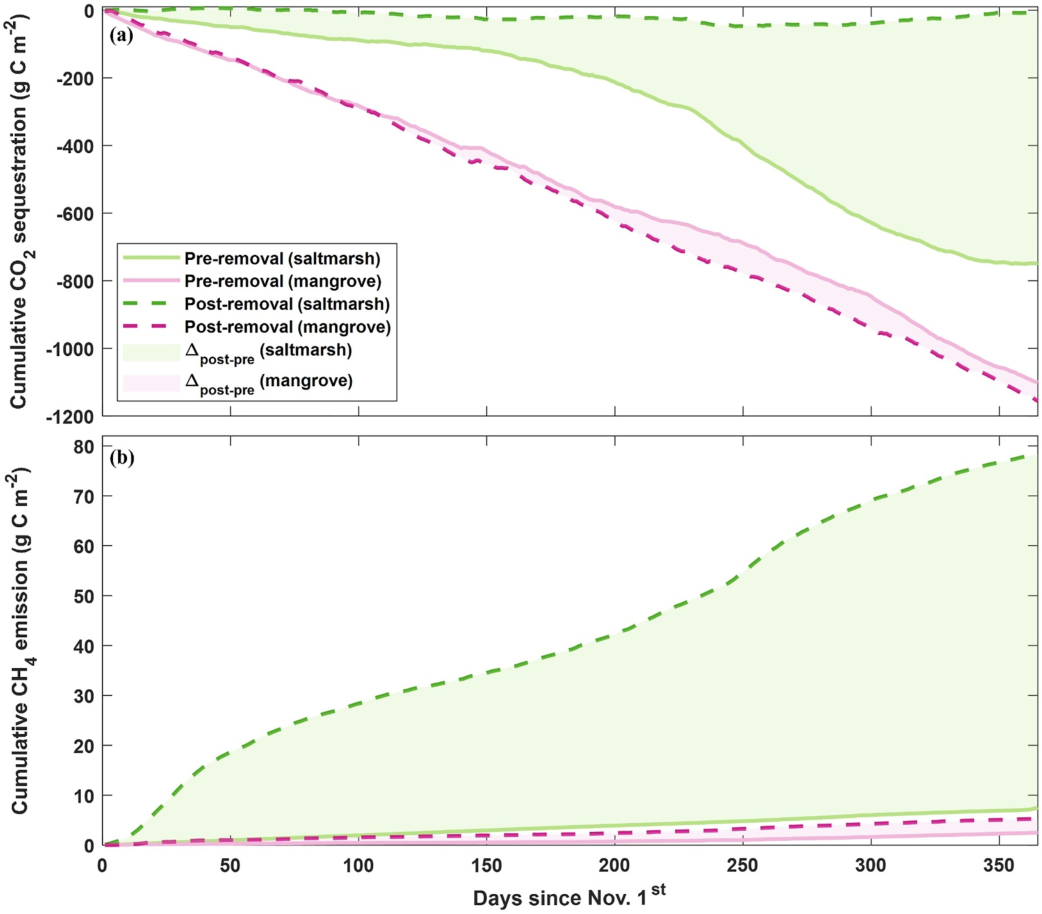

Figure 3. Temporal changes in (a) cumulative CO_2 sequestration and (b) CH_4 emission of saltmarsh and mangrove over the pre-removal (November 2021 to October 2022) and post-removal (November 2022 to October 2023) years.

Previous blue carbon assessments on coastal restoration focus more on net CO_2 balance (Su et al., 2021), since the assessment of net GHG balance and climate benefits remains extremely challenging due to the lack of concurrent flux measurements of GHGs across relevant time and spatial scales (Macreadie et al., 2019). In particular, site-specific continuous measurements of GHG fluxes both "before and after" the restoration are very limited (Rosentreter et al., 2021). Besides the paucity of data, the uncertainties also arise from a combination of differences in flux variability inherent in blue carbon ecosystems and flux measuring methods and timings (X. Zhu, Chen, et al., 2024). In this study, based on paired EC towers of consistent instrumentation setup within a single coastal wetland, the acquirement of concurrent measurements of year-round CO_2 and CH_4 fluxes before and after the restoration provides a unique opportunity to evaluate the effect of LUC on climate benefits. Our results suggest at least 3 decades are needed to repay the climate debt incurring from the saltmarsh-mudflat-mangrove LUC, implying the risk of GHG flux changes, especially pulse CH_4 emission, from coastal restoration via *S. alterniflora* removal in potentially neutralizing the blue carbon sink. Similar to many other EC studies, we are short on contemporary flux measurements of another potent GHG, that is, N_2O, since the EC applications for N_2O flux are still in the infant stage. Thus, here we are not able to incorporate N_2O flux and quantify its contribution to the net climate benefit. However, N_2O fluxes from coastal vegetated ecosystems are usually relatively small (Rosentreter et al., 2021, 2023). In light of the expected uncertainty in GHG fluxes during the LUC (e.g., removal campaign may actually need to be repeated over years to prevent the *S. alterniflora* regrowth), this study does not attempt to precisely quantify the payback time incurring from the restoration. Instead, we aim to demonstrate under current restoration schemes (i.e., removal method, frequency), LUC may lead to significant emission of CH_4 in brackish coastal wetlands, and climate neutrality, referring to reducing CO_2 and other GHGs like CH_4, should be embraced instead of solely focusing on CO_2-only carbon neutrality. Coastal restoration with intensive disturbances could take several decades of habitat regeneration to achieve climate benefits, highlighting the

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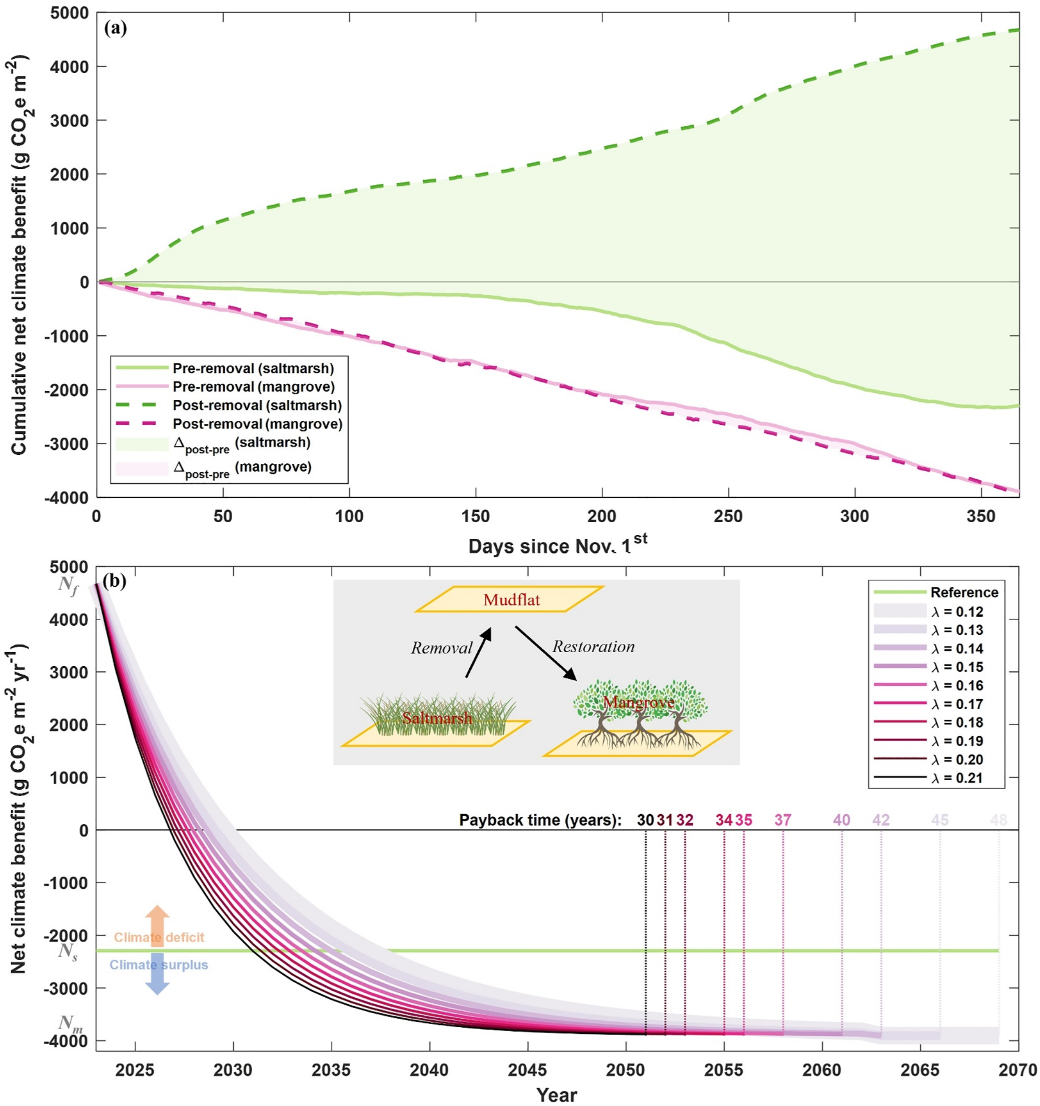

Figure 4. Temporal changes in net climate benefit and projected payback time for the restoration, where net climate benefit was quantified using the sustained-flux global warming potentials metric for a 100-year time horizon. (a) Cumulative net climate benefit of saltmarsh and mangrove over pre-removal and post-removal year. (b) Projected change in annual net climate benefit with the saltmarsh-mudflat-mangrove conversion and corresponding payback time, following various exponential transition curves from mudflat to mature mangrove with a range of decay rates (λ).

importance of considering the full, including the "hidden" (i.e., GHG emission), impact of LUC in assessing the ecosystem benefits of restoration of blue carbon ecosystems. This has important implications for refining restoration schemes to achieve climate benefits along with other ecosystem service co-benefits in coastal restoration, particularly for China's coastal wetlands where *S. alterniflora* removal is being implemented as the world's largest ecosystem restoration effort.

Conflict of Interest

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

Data Availability Statement

The data necessary to reproduce key findings in this paper can be accessed via X. Zhu (2025).

Acknowledgments

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