

A Study on Implementation Pathways for Carbon Emission Reduction in Salt Marsh Ecological Restoration Areas under China's Carbon Peaking and Carbon Neutrality Goals: A Case Study of the Zhaiqianwan Lagoon Wetland

Zhihuan Zhou¹, Jiayi Wang², Xinyu Song³, Xiaoyan Zhou⁴, Yuxuan Zhong⁵, Jinhan Niu⁶, Rui Xiao^{*}

1) College of Food Engineering, Qingdao Institute of Technology, 1029427332@qq.com

2) College of Food Engineering, Qingdao Institute of Technology, Wjy33693@163.com

3) College of Food Engineering, Qingdao Institute of Technology, 15650062670@163.com

4) College of Food Engineering, Qingdao Institute of Technology, zhou1806007145@qq.com

5) College of Food Engineering, Qingdao Institute of Technology, 1184584052@qq.com

6) College of Food Engineering, Qingdao Institute of Technology, 749297849@qq.com

* College of Food Engineering, Qingdao Institute of Technology, xiaoruil@qit.edu.cn

Abstract: Against the backdrop of global climate change and China's carbon peaking and carbon neutrality goals, salt marsh wetlands, as critical components of coastal blue carbon ecosystems, hold considerable scientific and practical significance for the synergistic transformation between ecological restoration and carbon sink functions. Nevertheless, salt marsh restoration areas in China still face prominent challenges, including insufficient baseline carbon sink data and unclear transformation pathways. Integrating field measurements, remote sensing monitoring, and literature data, this study systematically compiles key carbon pool parameters for China's salt marsh wetlands; comparatively analyzes restoration outcomes in the Liaohe Estuary, the Yellow River Delta, saline-alkali wetlands of the Songnen Plain, inland wetlands of Poyang Lake, and coastal salt marshes of Yancheng; and, with reference to the Zhaiqianwan Lagoon Wetland, examines the limitations of restoration models and pathways for enhancing carbon sinks. The results indicate that the carbon sequestration capacity of salt marshes exhibits pronounced spatial heterogeneity, and that hydrological regulation can effectively increase soil organic carbon stocks. Benthic organisms are sensitive to post-restoration environmental changes and can therefore serve as important indicators of ecological restoration effectiveness. Socioeconomic factors are also important drivers of wetland degradation. These findings suggest that carbon sink enhancement in restoration areas depends not only on hydrological and biological processes but also on long-term monitoring and adaptive management. Although the reviewed cases differ in climatic, hydrological, and socioeconomic contexts, they collectively highlight the importance of integrating carbon sink objectives into restoration planning. To achieve synergistic improvements in ecological and economic benefits, it is necessary to systematically ascertain carbon sink baselines, optimize restoration technology systems, improve policy and market mechanisms, and concurrently conduct biodiversity monitoring. This study provides a reference for blue carbon practices in lagoon-type salt marsh wetlands.

Keywords: Carbon Peaking and Neutrality; Blue Carbon; Ecological Restoration; Carbon Sinks; Lagoon Wetlands

1. Introduction

Coastal blue carbon ecosystems, mainly comprising mangroves, salt marshes, and seagrass beds, fix and store organic carbon over the long term through vegetation photosynthesis, thereby playing a critical role in mitigating global warming. China's salt marsh wetlands are extensively distributed and serve as important reservoirs of blue carbon. However, over the long term, anthropogenic activities such as enclosed-pond aquaculture, coastal engineering construction, and exotic species invasion have continuously compressed the spatial extent of salt marshes, leading to increasingly prominent habitat degradation and fragmentation. China has also long lacked systematic and complete observational data on salt marsh carbon sinks. Since the 1950s, the area of China's coastal salt marshes has shown a marked shrinking trend, making ecological restoration an important lever for safeguarding blue carbon resources.

In recent years, salt marsh restoration projects have been successively implemented in many regions of China, with measures such as returning aquaculture ponds to wetlands, *Spartina alterniflora* control, and hydrological connectivity restoration being relatively common. Scientifically sound restoration can contribute to habitat recovery and biodiversity enhancement, thereby strengthening the carbon sequestration potential of wetlands. However, most restoration projects focus on revegetation, lack quantitative accounting of post-restoration carbon sink increments, and have not yet established pathways for converting carbon sinks into economic benefits. The current obstacles are mainly concentrated in the following aspects: insufficient baseline data on carbon sinks, complex sediment-vegetation-benthic organism coupling processes, lagging supporting policies for blue carbon trading, and unclear post-restoration greenhouse gas budgets. This study takes the Zhaiqianwan Lagoon Wetland as its research object and integrates multiple case sets, including national salt marsh parameters, inland wetland evolution, flooding restoration experiments in saline-alkali wetlands, benthic animal surveys after *Spartina alterniflora* control, the effects of returning aquaculture ponds to wetlands in the Liaohe Estuary, and the impacts of *Spartina alterniflora* invasion on carbon sink potential. It systematically explores carbon reduction pathways in salt marsh restoration areas, with the aim of providing a reference for achieving ecological protection and blue carbon value transformation in Zhaiqianwan and other lagoon wetlands.

2. Methods

This study adopts an integrative literature analysis approach. The collected materials include published field measurement data and remote sensing interpretation results, specifically derived from journal articles, Landsat remote sensing imagery, local statistical yearbooks, and field monitoring datasets from selected wetlands.

National salt marsh parameters include distribution area, total carbon storage, carbon burial rate, and flux data for the two greenhouse gases CH₄ and N₂O were extracted from published literature on China's salt marshes (1). Poyang Lake wetland case bases on landscape pattern indices and socioeconomic statistical data from 1985 to 2005. Changes in the area of wetland landscape types and their natural, social, economic, and policy drivers were analyzed (2). Soda saline-alkali degraded wetlands in the Songnen Plain bases on field measurement data on biomass and physicochemical indicators of 1 m soil profiles under three vegetation conditions including alkali patch land, *Leymus chinensis* grassland, and flooded restored *Phragmites australis* marsh were integrated to analyze the patterns of change in soil organic carbon stocks and their influencing factors (3). Benthic organisms in restored salt marshes of the Yellow River Delta bases on data from a summer 2023 macrobenthic animal survey after *Spartina alterniflora* control were compiled, and to analyze species composition and diversity indices and to identify key environmental factors affecting the distribution of benthic animals (4). Liaohe Estuary case of returning aquaculture ponds to wetlands includes soil and vegetation carbon pools that were compared between aquaculture embankment tidal flats and restored salt marshes after aquaculture withdrawal, and the increase in carbon storage in the 0–30 cm soil layer after restoration was calculated (5). Yancheng coastal salt marsh case of *Spartina alterniflora* invasion mainly includes carbon fluxes (CH₄ and CO₂), vegetation biomass, and soil organic carbon content that were measured in *Spartina alterniflora* salt marshes invaded for 10 and 20 years, as well as in native bare tidal flats, *Suaeda salsa* salt marshes, and *Phragmites australis* salt marshes, to assess the impact of *Spartina alterniflora* invasion on salt marsh carbon sink potential (6). Analysis of coastal blue carbon sink enhancement measures is based on the natural endowment characteristics of coastal blue carbon and combined with the three ecosystems of mangroves, salt marsh wetlands, and seagrass beds, the advantages and disadvantages of existing restoration and carbon sink enhancement technologies that were comprehensively analyzed from the perspectives of natural restoration and artificial restoration (7). Research on carbon budgets and carbon cycle processes in China's coastal salt marsh wetlands is the progress in research on the carbon cycle and carbon budgets of China's coastal salt marsh wetlands was systematically reviewed from the perspectives of carbon pool composition, gaseous carbon inputs and outputs, and tidal effects

on carbon budgets (8). Research on the structural status and protection optimization strategies of China's coastal blue carbon ecosystems is mainly from the distribution structure and changes of China's three major coastal blue carbon ecosystems, including mangroves, salt marsh wetlands, and seagrass beds, that were analyzed, and existing problems were discussed in terms of coastal blue carbon resources, ecosystem protection and restoration, the value of blue carbon resources, and the carbon sink trading market (9). Blue carbon functions and countermeasures of China's coastal wetlands is based on conservative data, the amount of carbon fixed annually through sediment burial in China's coastal wetlands that was estimated, and the carbon sink enhancement potential and protection and restoration countermeasures of coastal wetlands under carbon neutrality goals were analyzed (10).

3. Results and Discussion

3.1 Current Status of Carbon Sinks in Salt Marsh Wetlands

The distribution area of salt marsh wetlands in China is approximately $1.27\text{--}3.43 \times 10^5 \text{ hm}^2$, with a total carbon storage of approximately $7.5 \pm 0.6 \text{ Tg}$ and carbon burial rates ranging from 7 to $955 \text{ g C}/(\text{m}^2 \cdot \text{a})$. With respect to non- CO_2 greenhouse gases, CH_4 fluxes range from 23.6 to $986 \mu\text{g CH}_4/(\text{m}^2 \cdot \text{h})$, and N_2O fluxes range from 1.58 to $110 \mu\text{g N}_2\text{O}/(\text{m}^2 \cdot \text{h})$ (1). The large ranges of these parameters reflect significant differences in carbon sequestration capacity among salt marshes in different regions, vegetation types, and tidal flat positions. It is noteworthy that lagoon-type salt marshes are influenced by both tides and salinity gradients, and their carbon pool parameters should not be directly derived from data on estuarine salt marshes (8).

Between 1985 and 2005, the landscape pattern of the Poyang Lake wetland underwent significant changes, with marked fluctuations in the area of wetland landscape types and intensified landscape fragmentation. Analysis combined with socioeconomic statistical data indicated that natural factors (changes in hydrological conditions) and socioeconomic factors (population growth, agricultural development, and policy orientation) jointly drove the evolution of wetland landscape patterns, with the intensity of anthropogenic impacts increasing significantly over the past two decades (2). The driving-factor analysis method used in this case provides a methodological reference for understanding the degradation mechanisms of lagoon wetlands.

After flooding restoration, the *Phragmites australis* wetland had a vegetation biomass of 7807.78 g/m^2 and a carbon pool of 1.90 kg/m^2 , which were 383.15% and 216.67% higher, respectively, than those of *Leymus chinensis* grassland; alkali patch land had almost no vegetation carbon storage. After restoration, soil organic carbon storage in the 1-m profile of the *Phragmites australis* wetland was 17.38 kg/m^2 , 64.12% higher than that of alkali patch land and 4.45% higher than that of *Leymus chinensis* grassland, and deeper soil organic carbon storage was higher than that in the surface layer. Correlation analysis showed that soil organic carbon content and storage were significantly positively correlated with soil water content ($p < 0.05$) and significantly negatively correlated with total nitrogen, total phosphorus, electrical conductivity, and N:P ratio ($p < 0.05$) (3). These results indicate that flooding restoration can significantly enhance the carbon sink capacity of the plant–soil system in soda saline-alkali degraded wetlands; this approach also has reference value for hydrological regulation in lagoon salt marshes.

A summer survey in year 2023 collected 26 macrobenthic species, including 9 annelids, 7 mollusks, 8 arthropods, 1 chordate, and 1 nemertean; these could be divided into 3 communities, with *Hediste japonica* and *Macrophthalmus japonicus* as the dominant species. Mean biomass was $47.72 \pm 44.16 \text{ g/m}^2$, and mean density was $481.52 \pm 319.07 \text{ ind/m}^2$; the Shannon-Wiener diversity index ranged from 1.40 to 1.94, the evenness index from 0.73 to 0.95, and the richness index from 1.25 to 2.37. Soil bulk density, water content, pH, and ammonium nitrogen concentration in water were key factors affecting the spatial distribution of benthic animals (4). Notably, in newly formed salt marshes after *Spartina alterniflora* removal, biodiversity remains relatively low, and time is still needed for habitat quality and soil carbon pools to recover to ideal conditions.

After returning aquaculture ponds to wetlands, soil carbon storage in salt marshes averaged 22.04 t/hm^2 at 0–30 cm depth and 18.73 t/hm^2 at 30–60 cm depth; soil carbon sequestration capacity ranked from strong to weak as *Suaeda heteroptera* community, bare tidal flat, and *Phragmites australis* community. In the vegetation carbon pool, the carbon storage of *Phragmites australis* reached 3367.17 kg/hm^2 , significantly higher than that of *Suaeda heteroptera*. The returning aquaculture ponds to wetlands project increased soil carbon storage at 0–30 cm depth from 6.6 to 23.06 t/hm^2 (5). However, after aquaculture ponds are converted to salt marshes, complete recovery of soil organic carbon to native levels usually takes decades, and there is a pronounced time-lag effect in carbon sink enhancement through restoration.

The annual carbon emissions of Yancheng's coastal salt marshes 0.44 Tg/a were lower than carbon inputs (0.76 Tg/a), which was attributed to carbon fixation from the expansion of *S. alterniflora* communities and negative emissions from *Suaeda salsa* salt marshes. In 2021, the carbon sink potential of Yancheng's coastal salt marshes was 3.73 Tg, a decrease of 51.6% compared with 1987. Among these changes, the increased carbon sink due to *S. alterniflora* invasion (1.39 Tg) failed to compensate for the carbon sink loss caused by the shrinkage of *Suaeda salsa* and *Phragmites australis* salt marsh areas (1.59 Tg) (6). This case indicates that the impact of exotic species invasion on salt marsh carbon sink functions is dual in nature; when formulating management strategies in lagoon restoration areas, it is necessary to balance carbon sequestration benefits and native habitat protection.

However, current research on salt marsh blue carbon still has shortcomings. For example, the mechanisms by which sea-land gradient distribution patterns of vegetation affect carbon uptake capacity and carbon allocation remain unclear; soil organic carbon deposition and burial rates and their responses to global change lack systematic verification; research on the stability of soil carbon pools and lateral carbon flux in salt marsh wetlands is relatively weak; under climate change and sea level rise, simulation of blue carbon and assessment of carbon sink enhancement potential in salt marsh wetlands are insufficient; and technologies and pathways for enhancing blue carbon sinks in salt marsh wetlands have not yet been established (5,11). Specifically for lagoon salt marshes, research on salinity–tide coupling processes and the regulatory mechanisms of water exchange within the bay on carbon burial is even scarcer (8). In addition, the structure and functions of China's coastal wetland ecosystems generally show a degrading trend, blue carbon measurement and standardization remain immature, and the construction of blue carbon trading markets is slow; these factors jointly constrain the development of blue carbon in coastal wetlands (12). The protection and restoration models for China's coastal blue carbon ecosystems and the realization of blue carbon resource value transformation still need optimization, and deficiencies remain in blue carbon resource management and control systems and value realization (9). Global-scale systematic assessments further indicate that blue carbon ecosystems play an important role in the global carbon dioxide removal portfolio; currently, blue carbon ecosystems sequester approximately 270 Mt C annually, and protecting and restoring blue carbon ecosystems by 2050 could provide 60–96 Mt C/year of CO₂ emission reductions and 21–448 Mt C/year of removals. However, significant gaps remain in their inclusion in national greenhouse gas inventories and carbon accounting frameworks, and policy frameworks integrating carbon sequestration with fiscal incentive systems are urgently needed to promote practical implementation (13).

3.2 A Multi-Case Analysis of Carbon Emission Reduction Pathways for Salt Marshes in the Zhaiqianwan Lagoon

Based on the findings of the above case studies, for the salt marsh restoration area of the Zhaiqianwan Lagoon, carbon emission reduction pathways can be outlined from the dimensions of baseline carbon sink survey, ecological space restoration, carbon sequestration technology optimization, policy-market alignment, and biodiversity synergy.

First, the baseline carbon sinks in the restoration area should be systematically ascertained. Following the practices of the Liaohe Estuary and the Yellow River Delta, in situ monitoring of soil-vegetation carbon pools and greenhouse gas fluxes should be conducted to establish pre-restoration baseline data, thereby providing a basis for subsequent carbon sink accounting and market trading (4,5). The survey should comply with domestic technical specifications for salt marsh blue carbon surveys, and sampling must cover the 0–1 m deep carbon pool to avoid underestimating total carbon storage (14). In addition, the methods for carbon flux measurement and carbon sink potential assessment used in the Yancheng *Spartina alterniflora* invasion case can be referenced to conduct comparative sampling under different vegetation conditions, so as to accurately quantify the baseline carbon sinks of the restoration area (6). Research on carbon budgets in China's coastal salt marsh wetlands should strengthen systematic studies on carbon pool composition, gaseous carbon inputs and outputs, and the effects of tidal action on carbon budgets (8).

Second, ecological restoration should be advanced according to local conditions. Models such as returning aquaculture ponds to wetlands and hydrological connectivity restoration can be referenced, while the control of invasive alien species must be strengthened and accompanied by the configuration of native vegetation (5). For lagoon wetlands, maintaining tidal channels and hydrological connectivity within the bay is particularly critical; selecting native suitable species along salinity gradients is more reliable than directly copying the configuration schemes of estuarine salt marshes (8). Research on coastal blue carbon sink enhancement technology systems indicates that the synergistic application of restoration technologies, auxiliary technologies, and management technologies is an important guarantee for achieving restoration and carbon sink enhancement goals (7). According to conservative estimates, China's coastal wetlands currently fix up to 0.97 Tg C·a⁻¹ annually through sediment burial; protecting existing coastal wetlands and restoring degraded areas is an important pathway for enhancing coastal carbon sink functions (10). Historical experience shows that global coastal wetland area loss exceeded 50% in the 20th century, with reclamation and

aquaculture being key anthropogenic drivers of wetland degradation; restoration efforts therefore need to fully recognize the complex interactions between vegetation and geomorphic dynamics (15).

Third, a monitoring system should be established and improved. Experience from benthic animal surveys in the Yellow River Delta indicates that incorporating benthic organisms, soil physicochemical indicators, and fluxes of non-CO₂ greenhouse gases such as CH₄ and N₂O into long-term monitoring helps to simultaneously assess carbon sequestration benefits and biodiversity status (4). It is worth emphasizing that the effectiveness of salt marsh restoration cannot be measured solely by CO₂ sequestration, but should be comprehensively assessed in terms of the net climate effect of the full suite of greenhouse gases (1). Carbon fluxes in coastal blue carbon are influenced by multiple factors; accurately assessing the scale of newly added carbon sinks from restoration requires systematic observations of carbon exchange processes across multiple interfaces, including water-air, soil-air, and groundwater exchange (9). Meanwhile, the carbon sink potential of global blue carbon ecosystems and their feedbacks to climate change have attracted widespread attention (9,10). The impact of sea level rise on salt marsh carbon sink functions is nonlinear: moderate sea level rise can enhance carbon sink functions by increasing plant productivity, promoting vertical accretion, and facilitating inland migration of wetlands; excessive rise may weaken carbon sink functions by increasing vegetation mortality, sediment erosion, and organic carbon mineralization. Future research should focus on spatiotemporal monitoring and precise quantification of the effects of sea level rise on coastal blue carbon, adaptive and feedback mechanisms of key carbon process responses, predictive models of carbon sink functions, and carbon-optimized sea level rise adaptation strategies and technologies (16).

Fourth, policy and market pathways should be opened up. China has currently issued the “Methodology for Greenhouse Gas Voluntary Emission Reduction Projects—Coastal Salt Marsh Vegetation Restoration”; the restoration area can actively align with this methodology, explore the transformation of carbon sink value, and realize the conversion of ecological benefits into economic benefits (17). However, the domestic blue carbon market still faces problems such as unclear definition of property rights and inconsistent accounting standards. Lagoon restoration areas can take the lead in conducting pilot carbon sink accounting and accumulate baseline data to prepare for future market entry (14,18,19,20). Practice in salt marsh carbon sink trading under the voluntary emission reduction system shows that difficulties remain, including difficult carbon sink assessment, high technical thresholds, and long investment return periods, requiring coordinated advancement across technical, economic, market, and policy dimensions (17). Research on the realization of blue carbon value in coastal wetlands from the perspective of carbon sink trading points out that China urgently needs to promote the realization of blue carbon value in coastal wetlands through carbon sink trading, so as to address issues such as insufficient endogenous incentive mechanisms in the protection and restoration of coastal wetlands (21).

In addition, salt marsh blue carbon has strong spatial heterogeneity; carbon parameters from other locations cannot be directly applied to Zhaiqianwan, and local field measurements are indispensable. The total carbon sequestration capacity of various types of marsh wetlands in China is 4.91 Tg C·a⁻¹, with mangrove wetlands and coastal salt marshes having the highest carbon sequestration rates. Restoring wetlands can enhance the carbon sequestration potential of China’s terrestrial ecosystems, among which the carbon sequestration potentials of returning farmland to lakes and returning farmland to marshes are 30.26 Gg C·a⁻¹ and 0.22 Gg C·a⁻¹, respectively (22). After restoration projects are completed, the long-term uncertainties arising from greenhouse gas emissions, sea level rise, and climate warming can only be addressed through long-term observations. Lagoons are notably disturbed by storm surges and seawater intrusion, and the potential risks of future sea level rise to the carbon sequestration function of salt marshes also require sustained attention (8). Research on coastal blue carbon should strengthen systematic studies on carbon cycle mechanisms, carbon sequestration and sink enhancement technologies, systematic quantification methods, and market trading mechanisms (9,23).

4. Conclusion

The blue carbon sequestration potential of salt marsh wetlands is considerable. Through ecological engineering measures such as hydrological connectivity restoration and returning aquaculture ponds to wetlands, wetland vegetation communities can gradually recover, and the organic carbon storage capacity of the plant-soil system can be enhanced accordingly. However, restoration effectiveness is constrained by regional environmental conditions, and improvements vary markedly among regions. It should also be recognized that ecological restoration should not focus solely on revegetation. Indicators such as the soil physicochemical environment and benthic communities are equally important. Only when the habitat is improved as a whole can the carbon sink functions and ecological service values of salt marshes be truly realized.

For the salt marsh restoration area of the Zhaiqianwan Lagoon, the primary task in implementing carbon emission reduction and carbon sink value transformation is to conduct a solid baseline carbon sink survey and to ascertain the actual status of local soil and vegetation carbon pools. During the restoration phase, priority should be given to native adaptive plant species to establish salt marsh communities compatible with the lagoon environment. At the same time, a long-term monitoring network can be established to continuously track changes in soil, vegetation, benthic communities, and greenhouse gas fluxes. On this basis, drawing on the existing blue carbon policy framework, channels for converting ecological benefits into economic benefits should be opened up, thereby promoting the synergistic development of ecological protection, biodiversity maintenance, and carbon sink enhancement and providing strong support for local implementation of China's carbon peaking and carbon neutrality goals.

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