Reframing the Restoration Assessment Framework for Blue Carbon under Timescale Constraints on China's Shelf: A Case Study of the East China Sea

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Abstract: As the pursuit of carbon neutrality progresses, the required accuracy of marine blue carbon accounting has risen considerably. Conventional accounting frameworks currently focus primarily on carbon fluxes while neglecting the persistence of sequestration. This paper synthesizes the carbon sink fluxes on the East China Sea shelf and introduces timescale as a core analytical dimension. By employing carbon-14 isotope tracing techniques, we systematically quantify the turnover times of diverse carbon pools in China's marginal seas. Our findings reveal significant temporal disparities among carbon pools on the East China Sea shelf, and further indicate that inputs of terrigenous "old carbon" and atmospheric "dead carbon" can seriously bias the estimation of genuine carbon sinks. Hence, it is imperative to integrate carbon age provenance techniques to establish a robust accounting system. On this basis, we propose three pivotal pathways: protecting habitats with high burial rates, advancing microbial carbon pump technologies for enhanced carbon removal, and developing timescale-integrated accounting standards. This study aims to facilitate a transition in China's blue carbon strategy from scale-based accounting toward quality-based certification, thereby providing scientific support for achieving carbon neutrality goals.

Keywords: Carbon Neutrality; Blue Carbon; Carbon Sink; East China Sea

1. Introduction

Against the backdrop of intensifying global climate change, China has set forth the ambitious goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. Attaining these targets relies not only on the low-carbon transformation of energy systems but also urgently requires tapping into the carbon sink potential of natural ecosystems. As the largest active carbon pool on Earth's surface, the ocean is estimated to have absorbed approximately one-quarter of anthropogenic carbon emissions. Among these, the "blue carbon" processes driven by coastal salt marshes, mangroves, seagrass beds, and marine microorganisms have emerged as a highly promising negative emission pathway in international climate governance [1].

The East China Sea represents a hotspot for carbon cycling in China's marginal seas. The Yangtze River transports substantial quantities of terrigenous organic matter, forming extensive muddy deposits and coastal wetlands, which endow the region with considerable blue carbon burial potential. At present, China has completed multi-regional carbon stock surveys in the East China

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Sea and has simultaneously implemented national-level marine ecological restoration projects. For instance, recent study presents a marine ecological restoration effectiveness index as a framework for cross-regional, multi-ecosystem assessment, emphasizing data accessibility and multidimensional evaluation of restoration stability, ecological benefits, and economic benefits [2]. However, current blue carbon accounting and restoration assessment suffer from two major limitations. On the one hand, traditional metrics focus solely on carbon burial fluxes while neglecting the timescale of carbon sequestration; the admixture of millennial-scale terrigenous old carbon and fossil-derived carbon into carbon sink statistics, coupled with substantial degradation of sinking particulate organic carbon (POC) in the water column, results in biased carbon sink estimations. On the other hand, existing marine restoration assessment frameworks lack carbon age constraints, making it impossible to distinguish between newly sequestered fresh carbon from restoration efforts and native geological carbon, and thus hampering the quantitative evaluation of the true contribution of restoration projects to carbon neutrality. In light of these issues, this paper analyzes the differences in turnover times among various carbon pools on the East China Sea shelf, constructs a comprehensive blue carbon assessment framework that integrates both quantity and longevity, and proposes tailored strategies for blue carbon enhancement and management in the East China Sea.

2. Marine Organic Carbon Pools and the Microbial Carbon Pump

The global marine dissolved organic carbon (DOC) pool is immense, with the vast majority comprising recalcitrant dissolved organic carbon (RDOC). The microbial carbon pump (MCP) concept, as proposed by Jiao et al. [3] and Cai et al. [4], clearly articulates that this RDOC is generated through the metabolic transformation of labile organic carbon by marine microbial networks. This RDOC typically exhibits relatively old carbon ages, indicating that it has persisted in the ocean for millennia [5]. By enhancing the operational efficiency of the MCP through ecological regulation or biotechnological approaches, atmospheric CO_2 can be converted into DOC that remains in the ocean for extended periods. This represents a crucial carbon enhancement mechanism that does not rely on geological burial processes.

As it is shown in Table 1, POC serves as a major carrier in the marine biological pump, yet its sources are compositionally complex. Ren et al. [6] found that atmospheric deposition over the Bohai and Yellow Seas carries POC with a high proportion of old carbon, whose formation can be traced back to fossil fuel combustion. Similarly, riverine POC is often laden with aged terrigenous organic matter [7]. These findings indicate that measuring POC burial fluxes alone is insufficient; it is essential to employ ^{14}C fingerprinting techniques to differentiate between new carbon, which is recently fixed from the atmosphere, and old carbon. Only the burial of new carbon constitutes a genuine contemporary carbon sink.

Table 1. Timescale characteristics and effectiveness assessment of different carbon pools in China's marginal seas

Carbon pool type	Typical carbon age	Effectiveness assessment
Coastal wetland sediments	-8000yr BP	High- quality long- term carbon sink
Shelf muddy sediments	~5000yr BP	Stable carbon sink
DOC	~3500yr BP	Implicit long- term carbon sink
Water- column POC	~55yr BP	Short- term unstable carbon sink
Atmospheric POC	~17000yr BP	Invalid carbon interference

Coastal wetlands, such as salt marshes and mangroves, inherently exhibit high carbon sequestration efficiency. For instance, studies on the Spartina alterniflora salt marsh in Hangzhou Bay have demonstrated relatively high and stable carbon burial rates in this region. However, Pendleton et al. [8] issued a cautionary note: the carbon sinks formed by coastal wetlands have been accumulated over millennia, and once these habitats are disturbed by reclamation or development, this stored carbon can be rapidly oxidized and released, generating substantial legacy carbon emissions. Therefore, protecting well-preserved coastal wetlands to avoid such emissions is no less important than establishing new carbon enhancement projects.

In constructing a time-oriented blue carbon management strategy that grounded in the understanding of timescale characteristics, the future direction of China's blue carbon development should shift from a sole emphasis on burial quantity towards a greater focus on carbon quality. Specifically, the following strategies can be adopted. First, implement differentiated enhancement and protection strategies. Priority should be given to protecting high-deposition areas, concentrating limited resources on regions with confirmed high burial rates and stable sedimentary conditions, such as large river deltas, typical coastal wetlands, and shelf muddy zones, thereby ensuring the continued stability of existing high-quality carbon sinks. Concurrently, research on MCP-based carbon enhancement technologies should be encouraged, with particular support for exploring marine microbial community regulation and the mechanisms of RDOC production. By modulating the state of coastal ecosystems, the practical function of the MCP can be further reinforced [3, 5], opening up novel pathways for marine carbon sequestration. Second, establish accounting methods and standards that integrate carbon age. The use of ^{14}C provenance tracing should be made a mandatory step in national or industry-level blue carbon project methodologies, requiring carbon isotope source apportionment of sedimentary organic carbon to accurately quantify and subtract the contributions of terrigenous old carbon and fossil carbon [6, 7], thereby ensuring the environmental integrity of carbon credits. Additionally, a carbon sink permanence rating mechanism should be introduced, assigning different permanence classes (e.g., centennial, millennial) based on the turnover times of various carbon pools. This differentiation should be reflected in carbon credit pricing and offsetting rules, thereby incentivizing the implementation of long-lasting carbon sink projects. Third, deploy a long-term observation and assessment network for carbon age. The existing marine observation system should be upgraded by incorporating routine monitoring of radioisotopes such as ^{14}C, ^{230}Th, and ^{210}Pb into current stations, so as to continuously obtain spatiotemporal data on carbon age in China's marginal seas [9]. Moreover, relying on relevant timescale databases and models, this network can provide support for assessing the climate impacts of major engineering projects, scientifically evaluating the long-term carbon costs imposed by reclamation, coastal construction, and watershed hydraulic projects on offshore carbon sink functions, thereby furnishing reliable evidence for decision-making.

3. Assessment of Carbon Sink on the East China Sea and Implementation for Blue Carbon Enhancement

3.1 Carbon Sink Flux Illusion on the East China Sea Shelf and Deficiencies of Current Restoration Assessment Frameworks

The East China Sea shelf is among the regions with the highest carbon fluxes in China's marginal seas. The Yangtze River discharges vast amounts of sediment and organic matter annually, giving rise to extensive muddy deposits and highly productive estuarine wetlands. Despite the apparently high carbon burial fluxes in this region, recent observations based on ^{14}C reveal that the age structure of this carbon is extremely complex, and not all of it represents fresh, climate-regulating carbon.

The study by Zhao et al. [7] highlights a sobering reality. Through ^{14}C dating of sediments from the Yangtze estuary to the Okinawa Trough, they found that riverine POC contains substantial proportions of pre-aged organic carbon derived from watershed soil erosion. These terrigenous carbon pools can have ^{14}C ages of several thousand years. When this ancient carbon is buried with sediments on the shelf, if counted indiscriminately as a carbon sink, it effectively attributes carbon fixed during geological periods to the contemporary ocean, thereby overestimating the region's sink contribution. The findings of Buesseler [10] and Le Moigne [11] have shown that the POC produced in the highly productive surface waters of the East China Sea shelf undergoes intensive filtering during its descent to deeper waters. The data indicate that over 90% of POC is degraded and mineralized by microbes within the water column. Moreover, the sedimentary environment in some parts of the region is unstable due to ocean currents, leading to an excessively long transit time from carbon fixation to final stable burial, which drastically reduces the fraction that ultimately constitutes a long-term carbon sink. This analysis of the East China Sea shelf, as a representative region, exposes a critical flaw in current accounting systems: a high carbon fixation rate does not equate to high climate benefit. The situation in this region clearly demonstrates that accounting without timescale constraints fails to distinguish between effective carbon sinks and geological carbon transfer.

3.2 Pathway I: Tiered Protection of High-Burial-Rate Habitats

This pathway aims to lock in millennial-scale carbon sinks and prevent the release of legacy carbon. Firstly, priority conservation areas should be delimited. Based on ^{14}C age data (Table 1), coastal wetlands (~8,000 years) and shelf muddy areas (~5,000 years) should be designated as first-tier protection zones. Activities such as reclamation and bottom trawling should be prohibited in regions with high sedimentation rates, including the central Yellow Sea and the Yangtze estuary. Secondly, ecological restoration projects should be implemented. For salt marshes and seagrass beds, Nature-based Solutions (NbS) should be adopted to restore tidal flushing channels, maintain anoxic sedimentary conditions, and prevent the oxidation and re-release of organic carbon.

For the timescale justification, protecting existing old-carbon reservoirs is the most cost-effective measure. As Pendleton et al. [8] cautioned that the release of ancient carbon due to wetland destruction could offset decades of emission reductions within a short time, underscoring that preserving is more critical than burying more.

3.3 Pathway II: Targeted Regulation of the Microbial Carbon Pump

This pathway seeks to activate the ocean's implicit carbon sink and extend the residence time of carbon in the water column. Developing MCP-based carbon enhancement technologies is necessary. Drawing on the theory of Jiao et al. [3], in coastal aquaculture areas or artificial upwelling zones, micronutrients (e.g., iron, nitrogen, phosphorus) can be added to manipulate microbial community structure, inducing the conversion of labile organic carbon into RDOC. The RDOC reservoirs should be built by using biotechnological approaches to screen for microbial strains that efficiently produce RDOC, thereby enhancing the ocean's intrinsic carbon sequestration capacity and reducing reliance on geological burial space. As for timescale justification, the ^{14}C dating indicates that marine RDOC has an age of approximately 3,500 years (Table 1). Compared with POC, which persists for only decades, RDOC can circulate stably in seawater for millennia, making it a key technological reserve for achieving the carbon neutrality.

3.4 Pathway III: Building Timescale-Integrated Accounting and Trading Standards

This pathway aims to eliminate interference from dead carbon and establish a high-quality carbon credit system. An ^{14}C provenance tracing should be mandated. All carbon sinks intended for trading must undergo carbon fingerprinting to accurately quantify and deduct the contributions of terrigenous old carbon (e.g., Yellow River POC, ~4,500 years) and fossil carbon (atmospheric deposition carbon, ~17,000 years) [6, 7]. Graded pricing based on carbon sink permanence must be implemented, and a rating system should be established to classify sinks as "centennial" or "millennial" based on their turnover times. For sinks with short turnover times (e.g., water-column POC), their credit weight should be reduced or their offset cycle shortened. For long-turnover sinks (e.g., sediments), premium subsidies should be granted to reflect the value of time-based differences. Moreover, current accounting, which neglects the time dimension, has led to carbon credit bubbles [12]. Only by using ^{14}C techniques to remove the illusion of geological carbon transfer can we ensure that every tonne of blue carbon credit represents a genuine climate contribution.

4. Conclusions

Carbon pool turnover time and carbon sink process duration are two core metrics for evaluating blue carbon effectiveness. A synthesis of recent research data reveals that the temporal attributes of different carbon pools in China's marginal seas differ markedly. Coastal wetland sediments represent the most high-priority existing long-term carbon sinks requiring the highest level of protection, whereas the old carbon contained in water-column POC and atmospheric deposition constitutes a confounding factor that must be rigorously excluded from accounting procedures. Future scientific research, management practices, and market operations related to blue carbon should deeply integrate carbon age information to establish a comprehensive assessment framework that unifies temporal, spatial, and quantitative dimensions. Such a framework would ensure that every blue carbon credit represents a genuine, reliable, and long-lasting climate commitment, thereby further consolidating the foundational role of the ocean in achieving carbon neutrality.

5. References

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