Carbon Cycle and Blue Carbon Potential in China' s Coastal and Offshore Zones: Postprint

Authors: Wang Xiujun, Haibo Zhang, Han Guangxuan

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Abstract

China possesses an extensive coastline and vast coastal waters with rich ecosystems, harboring tremendous potential for carbon sequestration and storage. Due to multiple stressors from natural processes and human activities, carbon sink processes in China' s coastal zones and offshore areas exhibit significant complexity and uncertainty. This article centers on blue carbon ecosystems and carbon sink processes, focusing on key carbon cycling processes in coastal and offshore regions to explore variation patterns of carbon sources and sinks, analyze the current state of research and development trends both domestically and internationally, and propose scientific questions to be addressed, future research directions, and the research methodologies and approaches that should be adopted.

Full Text

Preamble

Special Topic: Coastal Science and Sustainable Development
Carbon Cycle and "Blue Carbon" Potential in China' s Coastal Zone and Marginal Seas
Wang Xiujun[1], Zhang Haibo[2], Han Guangxuan[2]

Abstract

China possesses an extensive coastline and vast marginal seas, with rich ecosystems and tremendous potential for carbon sequestration and storage. Due to multiple stressors from both natural processes and human activities, carbon sink processes in China' s coastal zone and marginal seas exhibit significant complexity and uncertainty. This paper focuses on blue carbon ecosystems and carbon sink processes, examining key carbon cycle processes in coastal zones and marginal seas to explore the dynamics of carbon sources and sinks. We analyze current research status and development trends both domestically and internationally, and propose key scientific questions, future research directions, and methodological approaches to be adopted.

Keywords: Blue Carbon, Coastal Zone, Marginal Sea, Carbon Cycle
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"Blue Carbon" refers to carbon absorbed and sequestered by marine and coastal ecosystems, primarily stored as biological biomass and sediment carbon. The concept encompasses carbon sinks in marine habitats including coastal zones, wetlands, marshes, estuaries, marginal seas, shallow seas, and deep oceans. Over the past decade, recognition of the strong carbon sequestration functions of benthic ecosystems (e.g., seagrass beds) and coastal wetland ecosystems (e.g., mangroves, salt marshes), and their association with the "missing carbon sink," has shifted research focus toward blue carbon in coastal zones and continental shelf seas [1].

China has an 18,000 km continental coastline and over 2 million km² of continental shelf. China' s marginal seas cover more than 4.7 million km², including the Bohai Sea, Yellow Sea, East China Sea, and South China Sea. The Bohai and Yellow Seas are semi-enclosed shallow shelf seas, while the East China Sea has China' s widest continental shelf, which accounts for one-third of its total area. China' s coastal zone hosts various types of coastal wetlands, including shallow waters, sub-tidal aquatic layers, coral reefs, intertidal mangrove swamps, salt marshes, coastal brackish/freshwater lakes, estuarine waters, and delta wetlands, covering 59,400 km² (15.4% of China' s total wetland area).

The carbon sequestration capacity and storage potential of China' s coastal zone and continental shelf seas far exceed those of terrestrial and oceanic ecosystems in the same climate zones. However, dense coastal populations and intense human activities not only affect biological carbon sequestration processes in coastal zones but also influence various biogeochemical processes in offshore carbon cycling. Additionally, climate change effects (e.g., sea level rise, temperature increase, and ocean acidification) exacerbate impacts on these blue carbon ecosystems, directly or indirectly affecting carbon sink processes. This paper examines key carbon cycle processes in coastal zones and marginal seas, analyzes current research status and development trends, and provides a comprehensive evaluation of blue carbon accumulation processes and sink enhancement mechanisms under integrated land-sea management for sustainable coastal development in China, offering scientific support for national strategies and policies addressing global change.

1.1 Mangrove Carbon Sequestration and Storage

Mangroves primarily grow in tropical and subtropical low-energy intertidal zones, periodically inundated by tides, forming evergreen shrub or tree communities dominated by mangrove plants. Mangrove productivity is high, accounting for 50% of total coastal wetland productivity [2]. Although global mangrove area represents only 0.5% of total nearshore area, mangroves bury 10–15% of carbon in sediments [3]. Based on above- and below-ground carbon storage estimates from 25 mangrove wetland types in the Indo-Pacific region, average above-ground carbon density is 159 Mg C ha ^{1}, while below-ground storage exceeds above-ground by more than fivefold, with most carbon distributed in soils/sediments 0.5-3 m deep [4]. Globally, mangrove ecosystems store an average total of 1,000 Mg C ha ^{1}, with over 70% sequestered in soils. Carbon fixed through photosynthesis is allocated roughly equally among leaves, stems, and roots (approximately one-third each) [3].

Key processes in mangrove carbon cycling include storage of root exudates and litter in soils/sediments, vertical exchange between mangrove communities and the atmosphere, and lateral transport of various carbon forms to adjacent marine waters. Global estimates suggest mangroves bury 18.4 Tg C annually in sediments and transport 24 ± 21 Tg C of dissolved organic carbon (DOC) and 21 ± 22 Tg C of particulate organic carbon (POC) to adjacent seas [2].

China's mangrove area is 22,700 ha, mainly distributed in Guangdong, Guangxi, Fujian, and Hainan. Total mangrove carbon storage in China is 6.91 ± 0.57 Tg C, with 82% in surface 1 m soils and 18% from mangrove biomass [5]. China has established mangrove eddy covariance flux observation networks and long-term research stations in Fujian, Guangdong, and Hainan to systematically investigate mangrove carbon cycling processes. Preliminary estimates indicate China' s mangroves have an average net carbon sequestration rate exceeding 200 g C m ^{2} a ^{1}, higher than the global average of 174 g C m ^{2} a ^{1} [3].

1.2 Salt Marsh Wetland Carbon Cycling Processes

Salt marshes are generally distributed in temperate coastal zones, with vegetation root-to-shoot ratios reaching 1.4–5. Large amounts of carbon fixed by primary productivity are stored in below-ground biomass and enter soil carbon pools through root turnover. Salt marshes have high carbon sequestration capacity, with a global average net carbon sequestration of 218 g C m ^{2} a ^{1}, higher than mangroves' average [3]. Their carbon accumulation rate is more than 40 times higher than terrestrial forest ecosystems [1]. As transitional ecosystems between terrestrial and marine environments, tidal salt marsh soil organic carbon can be exported to adjacent waters as dissolved organic carbon (DOC) through tidal and surface runoff processes. DOC migration and export represent a major pathway for soil carbon loss from salt marshes via hydrological processes [6].

China' s salt marsh vegetation grows in coastal wetlands of the Bohai, Yellow, and East China Seas, mainly including salt-tolerant plants such as reeds (*Phragmites australis*) and *Suaeda* species. Gross primary productivity (GPP) of China' s salt marsh vegetation is generally not high, averaging less than 1,000 g C m ^{2} a ^{1}, but net ecosystem CO exchange (NEE) is relatively high (Table 1). Comparing the Yellow River Delta with the Sacramento-San Joaquin Delta at similar latitudes, the Yellow River Delta salt marsh has GPP of 585–1,004 g

C m ^{2} a ^{1} and NEE of 164-261 g C m ^{2} a ^{1}, while the Sacramento-San Joaquin Delta has GPP of 1,506-2,106 g C m ^{2} a ^{1} and NEE of 368-397 g C m ^{2} a ^{1}. The Yellow River Delta thus shows significantly higher photosynthetic efficiency than its American counterpart.

1.3 Seagrass Bed Carbon Sequestration

Seagrass beds represent another important and typical marine ecosystem after mangroves and coral reefs, with global average carbon sequestration capacity of 138 ± 38 g C m ^{2} a ^{1} [3], higher than nearly all other marine ecosystem types [14]. Studies show seagrass provides crucial habitat for benthic algae attachment and reproduction, with up to 150 epiphytic microalgae species identified, mostly diatoms [15]. Epiphytic community productivity can account for 20-60% of total seagrass bed productivity [16].

Carbon sequestration and storage in seagrass bed ecosystems occurs through several mechanisms. First, seagrass itself has high primary productivity: numerous biological communities attached to seagrass blades perform photosynthesis and fix carbon. A portion of carbon fixed through seagrass photosynthesis is transported to underground rhizomes and roots for storage. An estimated 15-28% of carbon fixed through primary productivity is buried long-term in seabed sediments annually [17,18], contributing approximately 50% to surface sediment organic carbon pools in seagrass beds [19]. Additionally, seagrass can intercept large amounts of organic suspended particles, promoting their deposition and long-term burial in sediments—another important seagrass carbon sequestration pathway [20]. Organic carbon stored in seagrass bed sediments remains in anaerobic conditions with decomposition rates lower than terrestrial soil organic carbon, making it relatively stable. China’ s seagrass beds are mainly distributed in the South China Sea and Yellow-Bohai Seas, with total area of approximately 8,765 ha [21]. Research in this area is just beginning in China; preliminary studies show *Zostera marina* seagrass bed primary productivity in Sanggou Bay is 543 g C m ^{2} a ^{1} [22].

2 Offshore Carbon Pools and Carbon Fluxes at Various Interfaces

2.1 Spatial and Temporal Patterns of Offshore Water Organic Carbon Pools

Offshore waters experience intense material and energy exchange with terrestrial ecosystems, becoming collection areas for various land-sourced materials (including organic carbon and nutrients). On one hand, land-sourced organic carbon in offshore waters has extended turnover times due to anoxic, high-salinity conditions unfavorable for microbial degradation. Particulate organic carbon (POC) sinks and buries in seabed sediments, while DOC is transported to other sea areas as refractory organic carbon, persisting long-term in seawater. On the other hand, nutrient input enables high offshore productivity—phytoplankton absorb

CO through photosynthesis, assimilating it into organic matter (biological carbon, DOC, and POC). Consequently, most continental shelf seas function as carbon sinks.

Domestic research over the past decade has investigated organic carbon in China' s offshore waters. Studies show DOC and POC exhibit distinct spatiotemporal patterns in China' s continental shelf seas [23]: (1) DOC concentrations follow the pattern Bohai Sea > Yellow Sea » East China Sea, with higher concentrations nearer to shore and significantly elevated levels in estuarine areas, indicating clear terrestrial contributions in high-value zones. (2) Overall, DOC concentrations are higher in spring than other seasons, with interannual variation exceeding seasonal variation. Seasonal changes are primarily driven by natural processes, while interannual variations mainly result from human activities. (3) Spatial differences and interannual variations in POC are less pronounced than for DOC, but seasonal patterns are strong, with higher values in spring than autumn. DOC and POC ranges in China' s offshore waters are 1.58-3.93 mg L ^{1} and 0.21-0.42 mg L ^{1}, respectively, significantly higher than other Pacific Ocean regions (DOC < 1 mg L ^{1}, POC < 0.2 mg L ^{1}), with increasing trends in recent years indicating intensifying coastal human activities.

2.2 Sediment Carbon Burial

Offshore sediments represent important sources and sinks in the carbon cycle. On one hand, atmospheric CO is transformed through biogeochemical processes into particulate carbon that ultimately settles in sediments, forming an important "sink." On the other hand, physical and biogeochemical transformation in offshore waters can reverse these processes, creating a "source." Therefore, the role of offshore sediments in carbon cycling cannot be underestimated. Key factors influencing organic carbon burial and enrichment in offshore sediments include marine biological primary productivity, sedimentary dynamic environments, and seabed physicochemical conditions [24].

Domestic studies on organic carbon in sediments of the Yellow, Bohai, and East China Seas show distinct spatial distribution patterns in surface sediment total organic carbon (TOC). Sediment TOC content decreases from north to south, ranging 0.52-2.09% in the Bohai Sea, 0.68-1.67% in the northern Yellow Sea, 0.21-0.97% in the southern Yellow Sea, and 0.2-0.8% in the East China Sea [25-27]. High TOC values are mainly distributed in estuarine and muddy areas. Sediment TOC varies significantly among major Chinese estuaries: 0.1-0.85% in the Yellow River Estuary, 0.35-0.70% in the Yangtze River Estuary, and 1.2-2.2% in the Pearl River Estuary [27-29]. Nearshore areas heavily impacted by human activities show higher surface sediment TOC content: 0.1-0.3% in Laizhou Bay, 0.76-1.25% in northern Yellow Sea nearshore, 0.28-0.41% in southern Yellow Sea nearshore, and 0.32-0.82% in East China Sea nearshore [30,31]. Estuarine sediment organic matter is primarily terrestrial-sourced, offshore central areas are mainly aquatic-sourced, while most shelf areas in the southern Yellow Sea and northern East China Sea contain mixed terrestrial and marine organic matter sources.

2.3 Air-Sea Vertical Carbon Flux

Current research suggests continental shelf marginal seas overall are atmospheric CO sinks, absorbing 0.21–0.45 Pg C annually [32,33]. Seasonally, most studies indicate spring is a CO sink while summer is a source [34]. Spatially, temperate seas are typically CO sinks, while subtropical and tropical seas are usually CO sources [35]. Although the spatiotemporal patterns of CO source-sink dynamics in continental shelf marginal seas are somewhat understood, air-sea CO exchange fluxes remain highly uncertain, with uncertainties reaching 50–70% [36].

China began studying offshore air-sea interface carbon fluxes in the early 1990s. Results show the South China Sea is a weak CO source, releasing approximately 18 Tg C to the atmosphere annually [37]; the East China Sea is a strong sink, absorbing CO at a rate of 6.9 ± 4.0 mmol m^{2} d^{1} [38]; the Bohai Sea is a CO sink, while major estuarine freshwater-brackish water mixing zones are CO sources, with some bays also acting as CO sources [39]. China’ s offshore air-sea CO exchange shows clear seasonality, functioning as an atmospheric CO sink in spring but with uncertainties in other seasons. The spring carbon sink in marginal seas is primarily due to biological carbon fixation—suitable seawater temperature, nutrient concentrations, and light conditions promote phytoplankton photosynthesis. Additionally, spring seawater CO solubility is significantly higher than in summer. Carbon cycling in offshore waters during other seasons is influenced by many factors, with the combination of natural processes and human activities creating uncertainties in air-sea CO fluxes.

2.4 Land-Sea Horizontal Carbon Exchange

Coastal zones contain numerous rivers and coastal wetlands, whose transport to oceans and estuaries constitutes the main pathway for land-sea horizontal carbon transport. Latest estimates indicate global rivers transport 0.85 Pg C to oceans annually, including 0.45 Pg C organic carbon and 0.40 Pg C inorganic carbon [36]. Additionally, tidal salt marsh soil organic carbon can enter adjacent waters as DOC through tidal and surface runoff processes, with DOC migration and export representing a major pathway for land-sourced carbon export via hydrological processes [40]. Studies show U.S. coastal wetlands export DOC fluxes of 180 (±12.6) g C m^{2} a^{1} to adjacent estuaries [41], while Ontario peat marshes in Canada export 8.3 (±3.7) g C m^{2} a^{1} of DOC [42].

China has conducted considerable related research. Results show the Yangtze River transported an average of 1.56 × 10 t of dissolved inorganic carbon (DIC) annually to the East China Sea during 2004–2008 [43]. In 2009, the Yellow River and Yangtze River transported 3.20 × 10 t and 1.58 × 10 t of DOC, respectively, and 3.89 × 10 t and 1.52 × 10 t of POC, respectively [44]. Additionally, submarine groundwater discharge (SGD) is an important pathway for land-to-sea material transport. Studies show that in the northern South China Sea, although SGD accounts for only 12-21% of Pearl River runoff, it may carry (1.84-4.16) × 10 t of DIC annually, equivalent to 23-53% of Pearl River DIC input [45], demonstrating SGD' s potential impact on coastal carbon budgets.

3 Impacts of Human Activities on Coastal Blue Carbon

Rapid population growth and economic development over recent decades have driven dramatic land-use changes in global coastal zones to meet agricultural and industrial land demands [46]. As a major means of acquiring new land resources, reclamation is the most significant human disturbance to intertidal wetlands. Global intertidal wetland carbon sink functions and carbon pool storage have significantly decreased over the past century and will likely continue declining under human disturbances (reclamation, eutrophication) and climate change factors (sea level rise, temperature increase) [47].

China' s coastal zone accounts for 15% of national land area but supports over 40% of the population, 55% of economic output, and 70% of large and medium-sized cities. Increasing human activities such as coastal reclamation, aquaculture, coastal land development, dam construction in watersheds, and industrial production have significantly impacted coastal carbon sink functions [48]. Land development in coastal zones has been intense, causing coastal wetland area reduction and degradation or loss of wetland ecosystems (e.g., mangroves, seagrass beds, salt marshes), resulting in 0.45 Pg C a^{1} of additional CO emissions and economic losses of US$18.5 billion [48]. For example, China' s mangrove area has decreased from 4.2 × 10 ha four decades ago to 1.46 × 10 ha, with natural shoreline in China' s coastal zone declining to about 40% over the past 70 years. In the Yellow and Bohai Sea regions, reclamation activities over the past 50+ years have caused 65% of tidal flat wetland area to disappear [49]. Additionally, dam construction in watersheds directly affects river discharge and sediment load, altering total carbon and component inputs. Reduced sediment transport has led to substantial decreases in particulate carbon flux carried by riverine sediments.

4 Outlook for China' s Blue Carbon

China' s mainland coastline spans multiple climate zones, with thousands of rivers of varying sizes entering the sea, featuring various coastal types including estuarine, coral reef, and mangrove coastlines, as well as coastal wetlands with mangroves, reed communities, and *Suaeda* communities. These coastal wetlands have substantial carbon sequestration and storage capacity. Meanwhile, estuarine areas of the Yangtze, Yellow, and other rivers serve as both destinations and transfer stations for land-sourced carbon, and as important areas that utilize land-sourced nutrients to enhance productivity and reduce dissolved CO . Additionally, China has vast continental shelf seas with intense material and energy exchange with terrestrial ecosystems, featuring higher primary productivity than open oceans and playing important roles in blue carbon.

In recent years, China has implemented various protection measures for coastal ecosystems, establishing dozens of mangrove reserves, two seagrass bed reserves, and several salt marsh reserves [50]. While these measures aim to protect biodiversity, restoration of blue carbon ecosystems helps enhance carbon sinks and reduce emissions. Chinese scientists have proposed more specific ecological engineering strategies for China’ s “blue carbon sinks” under integrated land-sea management: rational fertilization and reduced land-sourced nutrient input to increase offshore carbon sinks [51].

China’s coastal zone and marginal seas have enormous blue carbon potential, but our understanding of carbon sink processes remains largely qualitative, lacking quantitative analysis, systematic research, and macroscopic assessment. Therefore, there is an urgent need to integrate domestic interdisciplinary research strengths and conduct multidisciplinary studies. By combining field observations, remote sensing retrievals, and model simulations, systematic research should be carried out integrating point-scale and regional-scale, microcosmic and macroscopic approaches. Through constructing integrated land-sea observation systems and regional carbon cycle models, we can improve scientific understanding of blue carbon sink enhancement mechanisms, enhance predictive capacity for future carbon sink strength, elevate China’ s international standing in carbon cycle and global change research, and provide scientific support for national policy formulation.

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Wang Xiujun[1]

[1] College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China

Zhang Haibo[2], **Han Guangxuan**[2]

[2] Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai 264003, China

Wang Xiujun, Professor at Beijing Normal University, is a chief scientist at the College of Global Change and Earth System Science and President of the Biogeosciences Section of the Asia Oceania Geosciences Society. She earned dual Ph.D. degrees in Soil Chemistry from the University of Melbourne and Marine Biogeochemistry from the University of Tasmania. With extensive expertise in global carbon and nitrogen cycles, she specializes in field observations, isotopic techniques, quantitative analysis, and model simulations. She has led multiple carbon cycle research projects and is among the few Chinese scientists conducting research in both oceanic and terrestrial carbon cycles, achieving innovative results in ecosystem carbon cycling processes and responses to climate change. E-mail: xwang@bnu.edu.cn

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