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The Dual Role of Carbon Sink Protected Areas in Biodiversity Conservation and Carbon Reduction—Take Zhanjiang Mangrove National Nature Reserve as an Example

Chenrui Zhang [1,*]

[1] Shanghai Starriver Bilingual School, Shanghai, 201100, China
* Correspondence: Chenrui Zhang, Shanghai Starriver Bilingual School, Shanghai, 201100, China

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Abstract: Against the backdrop of accelerating global climate change, carbon sink protected areas like mangrove forests have attracted growing attention, as they can mitigate global warming while delivering co-benefits for biodiversity and livelihoods. This study focuses on a representative mangrove ecosystem in southern China to evaluate the outcomes of ecological restoration from the perspectives of carbon reduction and species protection. Using satellite remote sensing data, the study analyzed changes in mangrove coverage to estimate carbon sink potential. Simultaneously, bird monitoring records were reviewed to assess trends in biodiversity. The research investigates the impact of mangrove restoration on regional carbon storage and local biodiversity. Results show that the expansion of mangrove areas significantly increased carbon storage, while the abundance and diversity of indicator species increased. This synergistic effect amplifies the ecological benefits of carbon reduction and species protection, producing outcomes greater than the sum of their parts. The findings underscore the critical role of mangrove reserves in climate regulation and ecological recovery, and the potential of carbon sink protected areas as integrated solutions to climate and biodiversity crises.

Keywords: carbon sink protected area; mangrove ecosystem; biodiversity conservation; carbon storage assessment; ecological restoration

1. Introduction

Mangrove ecosystems are primarily composed of intertidal mudflats and mangrove vegetation. Typically distributed along tropical and subtropical coastlines, mangroves can extend several kilometers from the shore. They provide critical habitat for a wide range of terrestrial and marine species, including many that are endangered or commercially important [1]. Furthermore, in areas where mangroves were present, damage and mortality during the 2004 tsunami were significantly lower, highlighting the protective function of coastal vegetation [2]. In terms of carbon reduction, mangrove trees perform efficient photosynthesis, capturing and storing atmospheric CO_2. Importantly, the two key functions of mangrove ecosystems—carbon sequestration and biodiversity conservation—are not merely additive, but closely coupled and mutually reinforcing. Carbon storage contributes to ecological stability, while biodiversity enhances the system's resilience and capacity for long-term carbon sequestration. Together, they form a positive feedback loop, generating a synergistic ecological impact that is both ecologically and functionally significant.

The Zhanjiang Mangrove National Nature Reserve (hereinafter referred to as the Zhanjiang Reserve) is situated in Guangdong Province, southern China, covering an area of over 20,000 hectares. It is one of the largest and most ecologically functional mangrove reserves in China. The Zhanjiang Reserve is home to more than 20 species of mangrove trees and over 200 species of birds, serving as an important stopover site along the East Asian–Australasian Flyway [3]. In addition, professional assessments estimate that the carbon storage of the Zhanjiang mangroves can reach up to 917 tons of carbon per hectare, highlighting its substantial value in carbon sequestration and emission reduction as a carbon sink protected area [4]. Therefore, the Zhanjiang Reserve stands as a representative example of the synergy between ecological conservation and carbon mitigation in carbon sink-based protected areas. This paper focuses on these synergistic effects, examining the interactive dynamics between carbon and biodiversity benefits, and reinforcing the vital ecological role of mangrove ecosystems in addressing both climate change and environmental degradation.

2. Ecological Protection Function of Mangrove Forests

2.1. The Mechanism of Mangrove Forests Protecting Biodiversity

Mangrove forests play a pivotal role in protecting biodiversity from multiple dimensions. Firstly, they offer a highly complex ecosystem with diverse microhabitats that support a wide range of species. The three-dimensional structure of mangrove habitats gives rise to distinct horizontal and vertical distributions of macrofauna: animals inhabit surface sediments (as infauna) or sediment surfaces (as epifauna), while others thrive around pneumatophores and on tree trunks [5].

Mangroves are also critical for maintaining ecosystem stability and nutrient flow. Fallen leaves nourish benthic organisms, which feed migratory birds and predators, enhancing biodiversity. Secondly, mangrove forests also protect coastlines from erosion and damage, acting as natural buffers against storms and extreme weather events. Their intricate root systems protect shorelines from tsunamis and erosive storms, dissipating wave energy. Mangroves shield against boat wakes and wind waves, bolstering shoreline defense.

Thirdly, mangroves function as natural water purifiers. By improving water quality, they create more favorable conditions for a wide array of species to thrive, further supporting ecosystem stability and biodiversity conservation. Studies on mangroves' water purification capacity using mesocosm tanks show that nitrogen removal rates ranged from 57 to 73 mg N/m²/day in standard tanks, and 164–425 mg N/m²/day in tanks supplemented with additional nutrients [6]. For phosphorus, removal rates ranged from 5.7 to 17 mg P/m²/day in standard tanks, compared to 48–97 mg P/m²/day in nutrient-supplemented tanks.

2.2. The Change of the Amount of Indicator Species

In this case, birds are employed as indicator species to assess the biodiversity of the Zhanjiang reserve. As highly sensitive organisms, birds typically respond rapidly even to subtle ecological changes and disturbances, making them effective bioindicators. Because many wetland bird species occupy high positions in the trophic chain, fluctuations in their abundance and distribution often reflect changes in populations of lower-ranking organisms. As noted in existing literature, "The occurrence of focal species of wetland birds can be safely used as an indicator of the general ecological status of a given area", which underscores the value of monitoring bird diversity for evaluating the overall health and stability of wetland ecosystems such as that of the Zhanjiang Reserve [7].

According to data recorded by the Guangdong Provincial Forestry Bureau in early 2025, while bird numbers dipped slightly in 2024, the population rebounded dramatically in 2025, rising from 28,230 to 54,211 [8]. This indicates a general upward trend in bird populations. Over the course of the same research project, a total of 178,672 individual birds were recorded, including the Spoon-billed Sandpiper (Eurynorhynchus pygmeus) and the Black-faced Spoonbill (Platalea minor).

This upward trend in bird populations strongly correlates with the recent expansion of mangrove forest area within the Zhanjiang reserve, as shown in Table 1 below.

Table 1. The expansion of the area of mangrove forest in Zhanjiang reserve from 2023-2025.

	2023	2024	2025
The area of mangrove forest in Zhanjiang reserve(hectare)	6521.85 [9]	6687.43 [10]	6800-7000 (estimated based on the restoration area data released by Guangdong Forest Bureau) [11]

The expansion of mangrove forests has led to a marked increase in bird species diversity and the occurrence of rare species, underscoring their pivotal role in biodiversity conservation. Mangrove ecosystems provide extensive habitats for bird species, including endangered or migratory species. The increased protected habitat area enhances the ecological capacity of the region, allowing for the recovery and flourishing of sensitive and rare species. This expansion is not only beneficial for carbon sequestration but also a key driver in restoring and enhancing regional biodiversity.

3. The Carbon Sink Function of Mangrove Forests

3.1. The Mechanism of Mangrove Forests Storing Carbon

Mangrove forests play a vital role in carbon storage through multiple interconnected mechanisms.

Firstly, mangrove vegetation—encompassing roots, trunks, branches, and leaves—functions as a highly efficient carbon sink through photosynthesis. These plants capture atmospheric carbon dioxide (CO_2) and store it in both aboveground and belowground biomass. Mangroves are especially effective due to their rapid growth and high productivity in tropical and subtropical coastal environments.

Secondly, mangrove soils serve as significant reservoirs of organic carbon. As leaves, branches, and other plant materials fall to the ground, they accumulate in the soil. In the waterlogged and oxygen-poor (anaerobic) conditions typical of mangrove ecosystems, decomposition occurs at a much slower rate. This deceleration limits the release of carbon back into the atmosphere, enabling organic matter to accumulate over time and form deep layers of carbon-rich sediment. Such anaerobic conditions are pivotal to the long-term preservation of carbon in mangrove soils, cementing their status as one of nature's most effective carbon stockpiles.

Thirdly, mangroves are core contributors to blue carbon sequestration—carbon storage in coastal and marine systems. Mangrove forests are among the most carbon-rich tropical forests in the world, and their ability to sequester and store 'blue carbon'—carbon stored in coastal and marine ecosystems—is significant for climate change mitigation [12]. As a core component of coastal wetland systems, mangroves not only trap carbon from terrestrial sources but also play a role in sequestering carbon from marine environments. They can absorb dissolved inorganic carbon from seawater and carbon derived from the metabolism and decay of plankton and other marine organisms. These inputs are either assimilated by the vegetation or buried in sediments, further enhancing long-term carbon storage.

Collectively, these interconnected processes establish mangroves as one of the most efficient and long-lasting carbon sinks on Earth, making them critical natural assets for climate change mitigation [13].

3.2. Regional Carbon Stock Variation

The data and methodology in this article are based on the research conducted by Lingyun Lv and other scholars on the carbon storage of mangrove forests in the Zhanjiang Reserve. The formula used to calculate mangrove carbon storage is as follows:

Mangrove wetland carbon storage (Mg C) = (121.3 + 1181.3) Mg C/hm^2 × mangrove wetland area (hm^2).

The following Table 2 presents the results of Lv Lingyun et al.'s study on changes in mangrove wetland area and corresponding carbon storage in Zhanjiang reserve from 1977 to 2017 [14]:

Table 2. Changes in mangrove area and carbon storage in the Zhanjiang Reserve from 1977 to 2017 [13].

Year	1977	1986	1992	1998	2013	2017
Mangrove forest area/hm2	432.90	233.01	247.40	704.16	670.77	704.23
Carbon storage/Mg C	564116.74	304414.48	323845.06	918512.40	874691.06	917987.31

The data in Table 2 reveal a strong positive correlation between mangrove area expansion and carbon storage growth over the 40-year period. Between 1986 and 2017, for instance, mangrove area more than tripled, which corresponded with carbon storage increasing nearly threefold. This strong positive correlation underscores the significance of mangrove restoration and conservation, not only for biodiversity but also for climate change mitigation.

4. The Synergy Effect between the Biodiversity Protection Function and the Carbon Sink Protection Function of Mangrove Forests

4.1. The Relationship between Biodiversity Protection and Carbon Sink Function

The carbon sequestration capacity and biodiversity conservation functions of mangroves are not merely additive—they form a self-reinforcing synergistic loop. This loop amplifies ecological benefits: stronger carbon sinks enhance habitat quality, which in turn boosts biodiversity, while greater biodiversity further improves carbon sequestration efficiency. When functioning in tandem, these two functions generate amplified ecological benefits, reinforcing one another and enhancing the overall health and resilience of the mangrove ecosystem. This synergy can be understood through several interconnected ecological mechanisms.

Mangroves' carbon sequestration plays a crucial role in mitigating global climate change. By capturing atmospheric CO_2 through photosynthesis and storing it in biomass and sediments, they help reduce greenhouse gas concentrations. Their structural complexity, including dense root systems and canopy cover, provides a natural barrier against extreme weather events, ensuring a stable environment for various animal species. Carbon sequestration also contributes to soil enrichment, enhancing soil structure and fertility for benthic fauna, fish, and invertebrates. As sediments decompose, they trap pollutants and excess nutrients, improving habitat quality. Mangroves also serve as primary sources of detrital carbon, supporting consumer biomass and trophic structure.

Importantly, the relationship also flows in the opposite direction. Biodiversity within mangrove ecosystems directly enhances their capacity for carbon sequestration. In the Zhanjiang reserve, for example, the coexistence of multiple mangrove species—such as Kandelia obovata and Aegiceras corniculatum—increases overall primary productivity and supports more efficient carbon fixation. Species diversity also fosters ecological resilience: complex interspecies interactions, including mutualism and commensalism, contribute to greater ecosystem stability, which in turn sustains long-term carbon storage.

The Zhanjiang Reserve offers a compelling real-world case study of this synergistic relationship. In recent years, ecological restoration and species reintroduction efforts have led to substantial improvements in both biodiversity and carbon storage. Between 2023 and early 2025, the number of individual birds recorded in the Leizhou Bay area of the Reserve increased from 28,230 to 54,211, with a concurrent significant rise in bird species diversity [8].

This uptick in avian diversity—often considered a strong indicator of broader ecosystem health—occurred alongside a measurable rise in soil carbon content, according to monitoring reports from the Guangdong Provincial Department of Ecology and Environment [15]. Such trends reflect a broader pattern: restoring and protecting biodiversity not only supports the food web and ecosystem functions but also reinforces the carbon sink capacity of mangroves.

4.2. The Significance of the Mangrove Forest's Synergic Effect of Carbon Sink Function and Biodiversity Protection Function

The synergistic interplay between mangrove biodiversity conservation and carbon sequestration strengthens their role as a critical nature-based solution (NbS)—one that addresses the interlinked crises of climate change and biodiversity loss simultaneously. Unlike siloed interventions, this synergy enables mangroves to mitigate climate change (through carbon storage) while reversing biodiversity decline (by providing habitats), forming a holistic response. These two ecological functions do not operate in isolation; rather, they reinforce each other, creating a positive feedback loop that increases the overall resilience, stability, and productivity of the ecosystem. As highlighted by Alongi, "the ability of mangroves to sequester and store carbon for millennia depends largely on their structural complexity and biological productivity," which are both closely linked to species diversity [15]. Biodiverse mangrove systems, rich in a variety of plant and animal life, support a more efficient cycling of nutrients and organic matter, thereby improving the soil's capacity to store carbon under anaerobic conditions. This function is particularly potent in mangrove soils, which can sequester carbon at rates up to four times higher than terrestrial forests [12]. In turn, the high carbon content and stable hydrological conditions of these environments foster the growth of complex root systems and microhabitats, sustaining a wide range of fauna—from fish and crustaceans to migratory birds and endangered species.

This synergy gains added significance when viewed through the lens of climate adaptation and ecological resilience. As Duke notes, "species-rich mangroves are more likely to recover from disturbances such as cyclones and sea level rise, due to the functional redundancy of species and the diversity of physiological responses within the community." This functional redundancy—where diverse physiological responses ensure key roles (e.g., carbon uptake, sediment stabilization) persist under stress—acts as a critical buffer against disturbances [16]. At the same time, healthy mangrove systems—anchored by this biodiversity—accumulate more biomass and organic sediments, which translates directly into greater carbon storage both above and below ground. In this way, protecting biodiversity is not just a conservation goal but a climate strategy: each complements the other.

Empirical studies support this interdependence. For instance, research in China's Zhanjiang Reserve observed that "as restoration efforts expanded mangrove coverage, bird species diversity and population counts rose correspondingly" [17]. The increase in avian diversity—many of which are higher-trophic-level indicators—signaled a more robust ecosystem capable of sequestering more carbon due to reduced anthropogenic disturbance and improved ecological balance. This illustrates that biodiversity protection leads to increased carbon sequestration capacity, while the latter—by stabilizing climatic and environmental conditions—provides a secure habitat for diverse species to thrive. Moreover, the synergic benefit also amplifies the socio-economic value of mangroves. Local communities benefit from increased fisheries productivity, coastal protection, and ecotourism, all of which are enhanced by both higher biodiversity and a more stable, carbon-rich environment.

This interlinked dynamic is now being recognized in international climate and conservation frameworks. The IPCC's 2019 Special Report on the Ocean and Cryosphere emphasizes that "restoration and conservation of coastal blue carbon ecosystems, such as mangroves, can provide multiple co-benefits including mitigation, adaptation, and biodiversity enhancement." These findings urge policymakers and conservationists to move beyond siloed strategies toward integrated approaches that embrace the co-benefits and synergy of mangrove protection [18]. In essence, the simultaneous safeguarding of biodiversity and carbon stocks in mangrove ecosystems creates a mutually reinforcing system—one where ecological integrity, climate stability, and human well-being converge to mutual benefit.

5. Conclusion

The Zhanjiang Reserve stands as a compelling case study of how carbon sink protected areas can serve as a dual solution to the climate and biodiversity crises. Through integrated ecological restoration efforts, the region has seen measurable improvements in both carbon sequestration and species richness, particularly among indicator bird species. This paper has demonstrated that the biodiversity conservation and carbon storage functions of mangrove ecosystems are not only compatible, but mutually reinforcing. The ecological stability afforded by increased carbon stocks creates favorable conditions for species recovery, while heightened biodiversity enhances the resilience and productivity of the system, further supporting long-term carbon storage.

These findings underscore the importance of adopting nature-based solutions (NbS) that capitalize on such synergistic effects. The Zhanjiang Reserve serves as a model for holistic environmental strategies, showcasing how localized action can generate global co-benefits how localized action can generate global co-benefits. By promoting the interplay between ecological functions, policymakers, conservationists, and researchers can enhance climate mitigation and biodiversity protection, strengthen ecosystem health and provide socio-economic and environmental returns.

While this study offers valuable insights into the synergistic roles of mangrove ecosystems, it is not without limitations. First, carbon storage estimates were based on remote sensing and secondary data, lacking direct field measurements that would improve accuracy. Future research would benefit from on-site sampling of soil and biomass carbon across different mangrove zones.

Second, biodiversity analysis focused only on bird species as indicators. While effective, this narrow scope may overlook trends in other vital groups such as fish, invertebrates, or plant communities. A broader ecological assessment would give a more complete picture of biodiversity changes.

Third, the initial timeframe (2023–2025) limits the ability to assess long-term ecosystem trends. Longitudinal studies are needed to track sustained effects of restoration on carbon storage and species recovery.

Lastly, socio-economic factors such as community engagement and policy implementation were not addressed. Future studies should explore how human dimensions affect conservation outcomes.

Comparative studies across multiple carbon sink reserves and assessments of climate stressors like sea-level rise will further deepen understanding and inform adaptive strategies for mangrove protection.

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