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Strategies for Enhancing Carbon Sequestration through Mangrove Restoration and Management

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Abstract In the context of global climate change, improving the carbon sink function of ecosystems is of great significance to achieving the goal of carbon neutrality. This study starts from the ecological mechanism of mangrove carbon sink function, analyzes the characteristics of mangrove biomass and soil carbon storage and their regional differences, and explores the impact of natural conditions such as tides and salinity on carbon sink capacity; analyzes the reasons for mangrove degradation and decline in carbon sink function due to factors such as coastal development, aquaculture and logging, as well as factors such as invasive species and natural disasters, and uses the mangrove loss and carbon emissions caused by large-scale shrimp pond farming in Southeast Asia as an example to illustrate. In addition, this study proposes the importance of building a mangrove carbon sink monitoring and evaluation system, introduces the application of satellite remote sensing and drone technologies in mangrove dynamic monitoring, as well as long-term monitoring methods for indicators such as soil carbon storage and biomass, and analyzes the practical experience of the Philippines in using remote sensing to monitor mangrove carbon sinks. Research shows that the comprehensive application of the above strategies can effectively enhance the carbon sink function of mangrove ecosystems and provide nature-based solutions to respond to climate change. Finally, looking forward to the future development direction of mangrove carbon sink management and research, we call for strengthening global cooperation and policy support to give full play to the key role of mangroves in carbon sink growth and coastal ecological protection.
Keywords Mangroves; Carbon sink; Ecological restoration; Carbon trading; Remote sensing monitoring

1 Introduction

Climate change has become a common challenge facing mankind. How to reduce the concentration of greenhouse gases in the atmosphere and enhance the carbon sink function of natural ecosystems is an important way to achieve climate stability. Carbon sink refers to the process of removing greenhouse gases such as carbon dioxide from the atmosphere and stored in ecosystems for a long time through biological action, including the absorption and storage of carbon by ecosystems such as forests and oceans. In the global carbon cycle, healthy ecological carbon sinks can offset some anthropogenic carbon emissions and slow down the trend of climate warming. Among them, coastal blue carbon ecosystems (such as mangroves, salt marshes, and seagrass beds) are considered to be the key natural solution to climate change due to their high carbon sequestration efficiency per unit area and long carbon storage time. Mangroves are woody wetland plant communities that grow in the intertidal zones of tropical and subtropical coasts. Although their global coverage is relatively small, they play a unique and important role in carbon storage and carbon sinks (Alongi, 2020).

The carbon sequestration capability of mangrove ecosystems is prominent in their high productivity and long-term burial of large amounts of organic carbon. Mangrove plants can grow rapidly in a salt marsh peat environment, fixing CO_2 in the atmosphere into biomass, and feeding carbon into the soil through the desolate and root systems to form a thick silt layer. These water-saturated peat soils have low oxygen content, which slows down the decomposition of organic matter and allows a large amount of carbon to be stored for a long time. Research shows that the annual carbon sequestration of mangroves per hectare is significantly higher than that of land forests, and their carbon sink rate per unit area can reach several times that of tropical rainforests. In addition, mangroves can also export part of organic carbon to offshore deposits through tides, thereby expanding the scope of their carbon sink influence. This unique “blue carbon” function makes mangroves play an indispensable role in the global carbon cycle (Cuenca-Ocay, 2024).

However, man-made interference and changes in the natural environment are putting mangrove ecosystems at serious threats. Since the mid-20th century, the global mangrove area has been greatly reduced due to factors such as coastal development, aquaculture, and timber harvesting. It is estimated that 30%~50% have been lost, and the resulting carbon emissions and ecological function degradation are worrying. In recent years, countries have gradually realized the importance of mangrove protection and restoration to carbon sinks and incorporated them into national strategies for mitigating and adapting to climate change (Ferreira and Lacerda, 2022). In this context, systematically studying the ecological basis of mangrove carbon sink function, identifying the causes of its decline in carbon sink function, and exploring effective recovery and management strategies are of great practical significance for improving mangrove carbon sink and serving the "dual carbon" goal. This article aims to review and analyze various strategies and practical experiences in enhancing carbon sinks through mangrove restoration and management, in order to provide scientific reference for coastal ecological protection and climate change response.

2 Ecological Basis of Mangrove Carbon Sink Function

2.1 Mangrove biomass and soil carbon storage mechanism

The reason why mangroves are known as an efficient carbon sink system is due to its unique biomass distribution and soil carbon burial mechanism. On the one hand, mangrove plants have developed root systems and high growth volumes, and can still accumulate a large amount of biomass in harsh intertidal environments. Mangroves are rich in carbon in their trunks, branches, leaves and roots, and their biomass per unit area is often higher than that of land forests of the same latitude. More importantly, the mangrove ecosystem distributes a considerable proportion of fixed carbon underground: a large number of pillar roots and lateral roots that support trees are deeply rooted in the mud, and carbon is continuously input into the soil (Zhang et al., 2022). With the fall of organic debris such as mangrove leaves and branches, these organic matter decomposes extremely slowly in long-term flooding and hypoxic peat environments, and gradually accumulates to form a thick carbon-rich deposit layer (Perera and Amarasinghe, 2021). This "underground carbon pump" mechanism makes mangrove soil a huge carbon reservoir, accounting for more than half of the total carbon reserves of mangrove ecosystems. Research shows that in mangrove peat soil, carbon can be stably buried for hundreds to thousands of years. Once mangroves are damaged, these carbons that were originally in the soil will be reexposed and released into the atmosphere in the form of CO_2 (Salmo et al., 2019). Therefore, maintaining the accumulation of mangrove biomass and sequestration of soil carbon is crucial to its carbon sink function.

2.2 Regional differences in mangrove carbon sink capacity

The carbon sink capacity of mangroves varies significantly in different regions, and is affected by multiple factors such as climatic conditions, species composition and geographical environment. Mangroves in tropical regions (such as Southeast Asia) usually have the highest carbon storage and carbon sequestration rate due to their high temperature and high humidity throughout the year (Adame et al., 2020). Some studies compared the carbon storage of mangrove ecosystems on different continents and found that the total ecosystem carbon storage per hectare of mangroves in Southeast Asia and Oceania often exceeded 800~1 000 tons, while the carbon storage per hectare of mangroves in arid areas such as the Middle East may be less than 200 tons per hectare (Chatting et al., 2020). On the one hand, this difference is attributed to the tall and dense trees in tropical mangroves and deep soil deposits, which can accumulate more biomass and peat carbon; on the other hand, regional tidal and sedimentary environments also play a role. For example, in large deltas or estuaries, mangroves often benefit from adequate freshwater and sediment supply, and are more efficient in burying carbon. In contrast, mangroves in subtropical and temperate marginal areas have slower plant growth, short and sparse forests, and relatively low carbon sink capacity. In addition, the dominant tree species and community structure of mangroves in different regions will also bring about differences in carbon sink functions. For example, the dominant stands of mangrove families usually have higher xylem carbon content and underground root input, resulting in higher carbon reserves (Sigamani et al., 2023).

2.3 Effects of natural conditions on carbon sink function (tidal, salinity, etc.)

The function of mangrove carbon sinks is also regulated by local natural environmental conditions, among which tidal law and salinity are two key factors. Tides not only bring nutrients and sediments to mangroves, but also affect the soil flooding cycle, thus having a dual effect on carbon sinks. Moderate tidal flooding helps bury organic carbon: as the tide rises and falls, suspended organic matter and sediment are deposited on the mangrove subsoil to form a new carbon layer; at the same time, frequent flooding creates an oxygen-deficient environment and slows down the decomposition of organic carbon in the soil. However, overly strong currents may also wash away the yet-stable organic debris, reducing carbon retention (Yong et al., 2024). Therefore, there are differences in the carbon sink effect of mangroves under different tidal amplitudes and frequencies. Generally speaking, silt environments such as the estuary delta are more conducive to mangrove carbon deposition than the scattered coast (Fu et al., 2025). Salinity indirectly regulates carbon sink function by affecting the activity of mangrove plants and soil microbial activities. In mangrove environments with lower salinity or freshwater input, trees grow faster and produce more biomass, which is conducive to carbon accumulation; but freshwater erosion may increase the rate of organic matter decomposition. In addition to tides and salinity, factors such as temperature, rainfall, and nutritional levels will also affect the growth and carbon dynamics of mangroves. For example, high temperatures can prolong mangrove growth period and increase photosynthesis intensity, but extreme high temperatures or droughts may lead to mangrove stress and even death, thereby releasing carbon reserves (Rodda et al., 2022).

3 Analysis of the Causes of Mangrove Degradation and Decline in Carbon Sink Function

3.1 Coastal development, breeding and deforestation pressure

Human activities are the main reason for the accelerated degradation of mangroves and the decline in carbon sink functions in modern times. Large-scale development in coastal areas directly leads to the loss of mangrove habitats. When ports, urban infrastructure and tourism facilities are built in coastal areas in many countries, large-scale land reclamation has been reclaimed, destroying the original mangrove wetlands. At the same time, the emission of industrial and urban domestic sewage causes the deterioration of coastal water quality, further affecting the growth and survival of mangroves (Passos et al., 2022). Secondly, the expansion of aquaculture industry has put great pressure on mangrove ecology. Since the 1970s and 1980s, a prawn farming boom has emerged around the world, especially in Southeast Asia, and a large number of mangrove swamps have been cleared and dug into shrimp ponds and fish ponds (Mitra and Sikder, 2023). According to statistics, during this period, mangrove losses caused by aquaculture development accounted for 30%~50% of the total losses. Once mangroves are replaced by breeding ponds, they not only lose the carbon fixation capacity of live trunks, but also the carbon accumulated in the original soil is also rapidly oxidized due to excavation and exposure, and converted into CO_2 and discharged into the atmosphere. Again, excessive cutting and timber collection are also important human factors in mangrove degradation. In some underdeveloped coastal areas, mangroves have been cut down by local residents for fuel, wood and charcoal, exceeding the forest's own regeneration capacity, resulting in forest land degradation or even complete disappearance (Gowda et al., 2025). In addition, coastal agricultural reclamation, salt field development, etc. also occupy a large amount of mangrove habitat.

3.2 The impact of invasive species and natural disasters

In addition to direct man-made destruction, ecological invasions and natural disasters can also lead to mangrove degradation, which in turn affects its carbon sink function. In some mangrove areas, invasive alien species are changing the structure and function of local ecosystems. For example, some invasive plants (such as saline herbs such as serrata) spread in mangrove habitats, which may compete with young mangrove plants for space and nutrients, hindering the natural renewal of mangrove forests. In addition, invasive herbivores or insects (such as some mangrove-eating beetle larvae) will also cause damage to mangroves and reduce stand density and vitality when they reproduce in large quantities. These ecological invasions are often the result of unintentional introduction of human activities, but they pose a long-term threat to the health of mangroves, which in turn weakens their carbon sink capacity. Tropical storms, hurricanes and typhoons often rage mangrove areas, and strong storm surges can destroy large areas of mangroves in a short period of time. Taking the tropical cyclone "Nargis" that attacked Myanmar in 2008 as an example, it caused more than 35% of mangroves in the Irrawaddy Delta to be destroyed, and the carbon stocks accumulated over decades were released. Gradually induced environmental pressures such as sea level rise, extreme high temperatures and droughts, etc., are also seen as potential threats to mangroves (Liu et al., 2024). For example, sea level rise increases the risk of mangroves being submerged. If the siltation rate does not match the Shanghai plane rise rate, the mangroves may retreat or even die out, and the stored soil carbon is reexposed.

3.3 Large-scale shrimp farming in Southeast Asia leads to mangrove degradation and carbon loss

Large-scale shrimp farming in Southeast Asia is one of the most representative cases of mangrove degradation and carbon loss. Since the 1970s, a craze for shrimp exports has been set off in coastal areas such as Thailand, Vietnam, and Indonesia. Large areas of mangrove forests have been cut down and ponds have been dug for construction of shrimp fields (Hashim et al., 2021). It is reported that between the 1970s and 1990s, about one-third of mangrove losses in Southeast Asia could be attributed to the expansion of the shrimp farming industry. This industrial-driven land use change has severely damaged the function of mangrove carbon sinks: first, the original mangrove vegetation was completely removed, and a large amount of carbon stored in the trees was immediately lost; more hidden but far-reaching, the excavation of shrimp ponds exposed the mangrove peat soil layer to the air, and the organic carbon accumulated in the soil that has been accumulated for hundreds of years is quickly decomposed by microorganisms and released into CO_2 and methane. According to research estimates, every hectare of mature mangroves clearance can cause soil and vegetation carbon reservoirs to release hundreds of tons of carbon dioxide equivalent to the atmosphere. If the disturbances to soil and periodic drainage during shrimp pond operation are taken into account, carbon emissions will be further increased. Not only that, many shrimp farming ponds were abandoned after several years of operation due to diseases or deterioration of water quality, leaving behind bare ground and salinized mud bottoms that are difficult to recover. These degraded lands often cannot grow back into mangroves for many years, which means that carbon sink function is lost for a long time and may even be converted into a net carbon source. The lessons of the large-scale replacement of mangroves in Southeast Asia by shrimp ponds are profound: short-term economic benefits cause huge ecological costs and destroy valuable blue carbon pools (Rahman et al., 2024). In recent years, with the global re-understanding of the value of blue carbon, some Southeast Asian countries have begun to take measures to curb the further transformation of mangroves into breeding ponds. Vietnam and Thailand have introduced coastal land use control policies, prohibiting new shrimp farms in key mangrove areas, and encouraging ecological restoration of abandoned shrimp ponds (Figure 1) (McSherry et al., 2023). However, restoring lost carbon reserves is not easy and takes decades of effort. The case in Southeast Asia shows that anthropogenic land use changes can significantly regress the function of mangrove carbon sinks in a short period of time, emphasizing the importance of strengthening coastal planning management and preventing blind aquaculture expansion. This is also the lessons that must be learned from promoting the protection and restoration of mangroves and achieving carbon sink improvement.

4 Strategies and Technologies for Mangrove Restoration

4.1 Comparison of natural recovery and artificial assisted recovery technology

For the recovery of degraded mangroves, two technical paths can be adopted: natural recovery and artificial assisted recovery, each with its advantages and disadvantages and applicable conditions. Natural recovery refers to restoring stands by relieving stressors and improving environmental conditions, relying on the natural diffusion and renewal capabilities of mangroves themselves. For example, stop interference and restore tidal channels, so that the seeds and combrots adjacent to healthy mangroves spread to the degraded areas with the flow of water, and naturally germinate into forests. This method is low in cost and has less manual intervention, and the recovered communities are often more ecologically adaptable and diverse. In areas with a highly degraded and isolated from mangrove mother sources, it may be difficult to re-establish mangrove vegetation by relying solely on natural transmission (Wongprom et al., 2023). At this time, manual assisted recovery technology is needed to intervene. Artificial recovery usually includes the links of seedling cultivation, planting and post-management, that is, artificially cultivating mangrove plant seedlings or collecting combsyls, and then planting them into the target recovery area. Artificial afforestation can accurately control species selection and planting density, and rebuild trees with a certain coverage in a short period of time, which is the main means to achieve rapid expansion of mangrove area. In the past few decades, the coastal areas of Guangdong and Guangxi in China have grown mangrove forests again through large-scale artificial planting of mangrove seedlings such as autumn eggplant and olive.

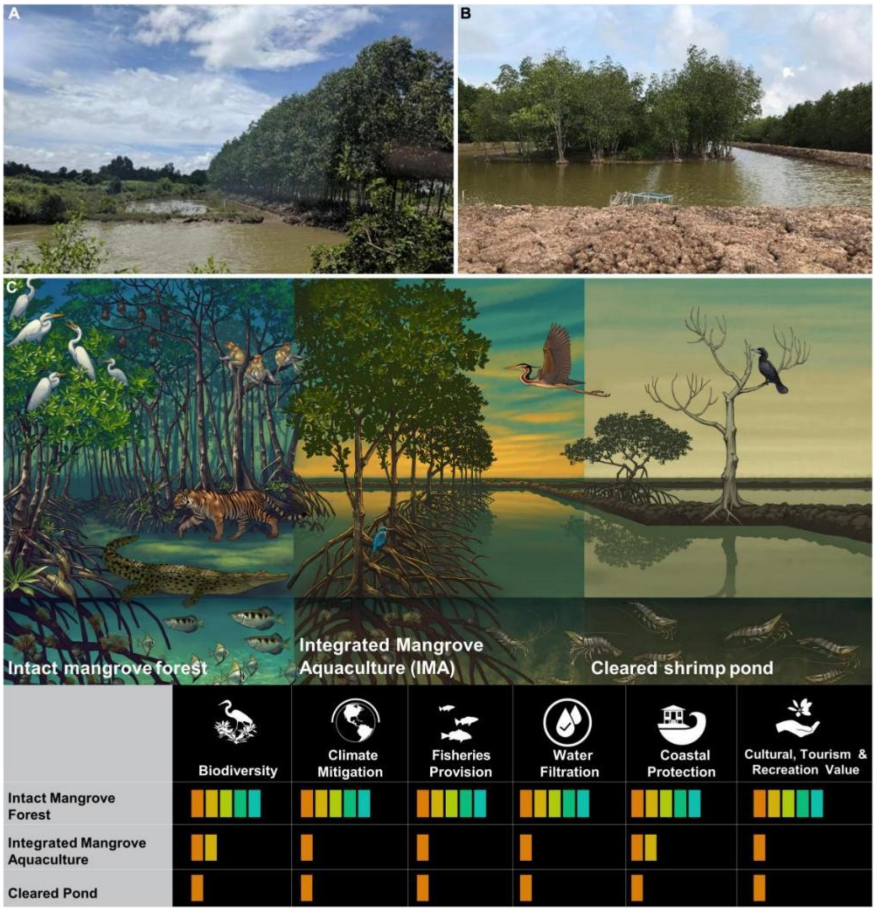

Figure 1 Common layouts for integrated mangrove aquaculture and their benefits for biodiversity and ecosystem service provision (Adopted from McSherry et al., 2023)

Image caption: Integrated mangrove aquaculture shrimp systems showing: (A) Mmangroves directly adjacent to the pond on the pond walls, and (B) mangroves within the pond as a central mass. (C) Stylized differences between intact mangrove forests, integrated mangrove aquaculture, and cleared shrimp ponds and their value for biodiversity and ecosystem service provision (Adopted from McSherry et al., 2023)

4.2 Plant selection and community structure optimization

During the recovery of mangroves, the selection of plant species and the optimization of community structure play an important role in improving carbon sink function. Different mangrove species have differences in growth rate, maximum tree height, wood density and root system structure, which affect their carbon sequestration ability and ecological adaptability. In restoration practice, local native mangrove species should be selected as much as possible, and reasonable matching should be made according to the height of the tidal beach and environmental conditions. In the low tide beach area near the sea, pioneer species such as *Avicennia marina* or *Rhizophora stylosa*, which are flood-resistant and have developed root systems can be planted first. These species are resistant to salt and surges, and can quickly stabilize mud and sand after survival, creating conditions for subsequent species (Chowdhury et al., 2023); in the middle and high tide areas, species with weak flood-resistant but large density such as *Bruguiera gymnorhiza* and *Kandelia obovata* can be introduced to form a multi-layered forest structure. Through this species configuration with complementary advantages, the recovery area can quickly develop into a structurally stable mangrove community. Plantations with single tree species often have growth bottlenecks, are susceptible to pests or extreme weather, and their carbon sink function is unstable. Because mixed-planted mangroves contain plants of different functional types, the ecological niche is more comprehensive, and the overall productivity and stress resistance are higher. Some studies have pointed out that the carbon reserves of mixed mangrove forests in multi-tree species are significantly higher than those in pure forests (Wang et al., 2021).

4.3 Case analysis: results of the mangrove restoration project in the mekong delta of vietnam

The mangrove restoration project in the Mekong Delta region of Vietnam is one of the successful examples of large-scale mangrove ecological restoration in Southeast Asia in recent years. The coastal areas of the Mekong Delta experienced severe mangrove destruction in the late last century, and a large number of forests were consumed by herbicide destruction during the Vietnam War and subsequent expansion of the shrimp farming industry, and the coastal protection and carbon sink function declined sharply. To reverse this situation, the Vietnamese government has worked with international organizations and local communities to implement a large-scale mangrove restoration project between 2015 and 2020 (Tinh et al., 2022). In this project, the managers comprehensively adopted engineering and biological measures: on the one hand, they built permeable embankments and sediment promotion devices to guide sediment on the coast to provide a matrix for mangrove reconstruction; on the other hand, they artificially planted mangrove seedlings on a large area, and at the same time, they rely on natural germination of adjacent stands for natural recovery in some areas (Figure 2).

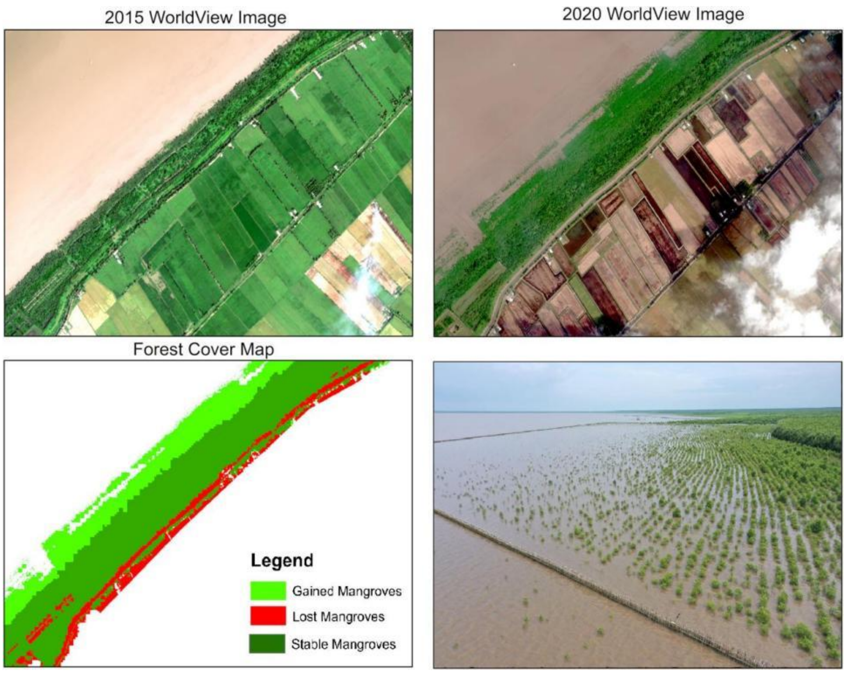

Figure 2 Mangroves are successfully restored to the sea and attributed to high sediment deposition and land creation that occurs along these shorelines (Adopted from Tinh et al., 2022)

According to statistics, a total of about 27 000 hectares of newly planted and naturally restored mangroves in the Mekong Delta region within five years, offsetting the losses of about 16 000 hectares caused by aquaculture and coastal erosion during the same period, and achieving a net increase of about 11 000 hectares of mangrove area. This has increased the mangrove coverage in the area by about 14%, reconnecting many broken forest patches. More importantly, the recovery project significantly improves the ecosystem's carbon sink capacity. Monitoring results show that newly recovered mangroves have grown well in just a few years, with average tree height and breast diameter increasing year by year, and the carbon reserves in forest land have steadily increased. The soil surface carbon content at some demonstration sites increased by more than 20% within three years of recovery, showing a strong carbon sink rate. In addition, the recovery of mangroves has brought about disaster reduction and livelihood benefits.

This case shows that through large-scale recovery actions combined with government-led, community participation and scientific guidance, the trend of mangrove degradation can be reversed in a short period of time and rebuilding the ecological carbon pool. The success of the Mekong Delta mangrove restoration project has provided valuable experience for other coastal areas around the world. The model of "engineering measures + ecological restoration + social participation" can be used as a reference for future mangrove carbon sink improvement projects.

5 Innovation in Mangrove Management Model

5.1 Community co-management and benefit sharing mechanism

Traditionally, mangroves are often centrally managed by government forestry or marine departments, but practice has proved that it is difficult to protect mangroves in a timely and effective manner on the vast coastline by relying solely on official supervision. In recent years, a mangrove management model with community co-management as the core has emerged in many countries, emphasizing the inclusion of local communities into the management system, sharing the responsibility for mangrove protection and management with the government, and sharing the resulting benefits (Adenan, 2018). Under this mechanism, fishermen and villagers living near mangroves are no longer regarded as mere resource users, but are empowered to become guardians of resources. At the same time, the introduction of a benefit-sharing mechanism allows communities to directly benefit from mangrove protection, thus forming positive incentives (Karpowicz et al., 2024). There are many specific ways to share benefits, including sustainable use of mangrove resources (such as regularly and limitedly collecting dead branches of firewood, honey, aquatic products, etc.), and sharing of income from participation in ecological tourism. In some mangrove ecological tourism areas in Thailand, community members participate in tour guides and management. Part of the tourism income is used for community development and the other part is used for mangrove maintenance. Villagers gain tangible economic benefits from it, so they support protection work more. Under the community co-management model, the traditional "government management and people's use" has transformed into "government guidance and people's protection", which has greatly alleviated the problem of insufficient supervision of manpower and reduced conflicts. Facts have proved that with the in-depth participation of the community, the illegal logging and encroachment of mangroves have been significantly reduced, and forest restoration and carbon sink improvement have been smoother.

5.2 Introduction of ecological compensation and carbon trading mechanism

In order to increase the enthusiasm for mangrove protection and restoration, many regions have begun to explore economic means, such as ecological compensation and carbon trading, to convert the ecological service value of mangroves into actual benefits and feedback to protectors. The ecological compensation mechanism is usually led by the government. In addition to government compensation, ecological compensation for development projects is also one of the important means. Under the strict environmental impact assessment system, if mangroves are occupied due to necessary infrastructure construction, the use of the local area must pay funds to restore at least the same area of mangroves in other places, or directly implement replanting in designated areas to achieve "one to one, one, one, and one to the best." This internalizes the cost of the developer, prompting it to minimize the occupation of mangroves (Rasowo et al., 2024). The carbon trading mechanism provides a platform for an efficient carbon sink ecosystem like mangroves to enter the market. As the international community's awareness of "blue carbon" increases, more and more carbon trading systems and voluntary carbon markets have included mangrove carbon sinks in the accounting and trading scope. A typical case is Kenya’s “Mikoko Pamoja” project, the world’s first mangrove carbon credit project. Local communities receive carbon credit income every year for protecting mangroves, which is used for community development and reinvestment in ecological protection (Chisika and Yeom, 2023). This model has been replicated in many countries, such as Indonesia, Madagascar and other places, and has launched pilot projects for mangrove carbon trading. Carbon trading provides a continuous source of funding for mangrove conservation, making it a reality that "makes trees stand more valuable than cut down".

5.3 Case analysis: mangrove management model in indonesia's blue carbon project

Indonesia is one of the countries with the richest mangrove resources, and in recent years, the country's innovative practices in the field of blue carbon have attracted much attention. Among them, a blue carbon demonstration project carried out in Southeast Sulawesi Province vividly interprets the innovation of mangrove management models. The project aims to restore approximately 1 700 hectares of degraded mangrove forests (mainly abandoned shrimp pond land) along Sulawesi coast and to achieve sustainable financing through carbon trading (Cameron et al., 2019). Unlike traditional projects led by government or company, this project adopts a compound management model of community-led + policy support + market operation. In terms of community-led development, 35 coastal villages in the project site jointly established a cooperative organization to jointly participate in the planning and implementation of mangrove restoration. They sell or rent abandoned breeding land as a restoration area based on villages and undertake daily seedling cultivation, planting and forest protection. The project trains ecological monitors for each village to ensure that the community has full knowledge and management of the resource recovery process. Secondly, in terms of policy support, the Indonesian government promulgated the Forest Carbon Management Regulations in 2023, including the restoration of mangrove and other vegetation in the official carbon management scope (Sidik et al., 2023). The project became one of the first batch of blue carbon projects registered under the new regulations, and the government has opened a green channel in terms of land transfer, approval and carbon rights confirmation. This reflects the government's role in escorting innovative models at the institutional level. In terms of market operations, the project has received the launch support of the "Blue Carbon Accelerator Fund" (BCAF) and plans to sell future carbon emission reductions to obtain long-term funds through carbon certification that meets international standards (VCS, etc.).

6 Comprehensive Measures to Improve Carbon Sink Capacity

6.1 Restoring mangrove area and improving ecological quality

To enhance the carbon sink capacity of mangroves, we must focus on both "quantity" and "quality", that is, on the one hand, expand the coverage area of mangroves, and on the other hand, improve the health and carbon density of mangrove ecosystems. In terms of area restoration, scientific mangrove expansion plans are formulated, and areas where mangroves are distributed in history but degraded by human activities are preferred, such as shallow tidal flats, abandoned salt fields and breeding ponds are restored by gradually renovating these areas (Gowda et al., 2025). This practice of "retrieving ponds to forests" and "retrieving nurseries to wet" can avoid fierce conflicts with existing land use and can restore the original ecological function to the greatest extent. At the same time, laws and regulations should be improved, new mangrove occupation and damage should be strictly controlled, and the trend of area reduction should be curbed from the source. On this basis, we need to focus on improving the ecological quality of mangroves. Quality improvement includes improving the species diversity, structural complexity and stress resistance of stands (Li et al., 2025). In addition, improving water quality and soil environment is also an important part of quality improvement. If the pollution load of rivers around mangroves is too high, the eutrophication of water bodies will affect the growth of mangroves. Basin pollution control should be strengthened to ensure that mangroves are supplied by clean fresh water and the soil salt and pH are maintained within the appropriate range. Some studies have pointed out that the carbon storage per hectare of healthy and mature mangroves can be several times higher than that of degraded sparse forest land, so the carbon sink gain obtained by ecological restoration (such as sealing, replanting, and diversity restoration) in existing forest land cannot be ignored.

6.2 Linkage with the ecological network of wetland systems such as seagrass beds and salt marshes

Mangroves are not isolated ecological units. They often form a coastal wetland ecological network with adjacent seagrass beds, coastal salt marshes, etc. From the perspective of carbon sinks, mangroves have close connections with seagrass beds and salt marshes in the exchange and storage of carbon elements. As an upstream system, mangroves not only bury carbon itself, but also transport some organic debris and dissolve organic carbon to nearshore water bodies through tides. A considerable portion of these organic matter settles in adjacent seagrass beds and tidal flats, and continues to be buried (Yuan et al., 2022). Therefore, protecting mangroves helps maintain an organic carbon supply to downstream seagrass beds and mudflats. In addition, different wetlands are also complementary in the time scale of carbon sequestration: mangroves fast carbon sequestration rates and soil carbon turnover are relatively fast, seagrass bed carbon sequestration rates are slightly lower, but the carbon reservoir formed is more stable. The combination of the two can improve the stability of carbon sinks throughout the region (Wang and Liu, 2024). Therefore, in practice, linkage recovery has become an important strategy. Seagrass bed restoration is mostly carried out in appropriate water depths outside the mangrove forest. By transplanting seagrass algae clusters, conditions are created for mangrove forests to filter water quality and accumulate sedimentation. During the pilot projects in Florida, the United States and Guangdong, China, after mangroves, salt marshes and seaweeds in the same bay were restored at the same time, the carbon sink effect of the overall ecosystem was significantly improved. In addition to carbon sinks, this measure also brings synergistic gains in ecosystem services: the connected wetland network provides a "life corridor" throughout mangrove-seagrass-coral reefs for wild animals such as fish and shrimp, which is conducive to biodiversity; at the same time, the existence of multiple ecological barriers also enhances the protection function of coastline against storms and erosion (Saavedra-Hortua et al., 2023).

6.3 Case analysis: construction of the mangrove ecological corridor in Beihai, Guangxi, China

In Beihai City, Guangxi, China, an ecological restoration practice combining mangroves with other wetland systems provides an example for comprehensively improving carbon sink capacity. The Beihai is located along the Beibu Gulf coast and has a variety of wetland ecosystems such as mangroves, seagrass beds and coastal tidal flats. In the past, due to urban development and pollution, mangroves in some shore sections of the North Sea fell and deteriorated, the Yintan shoreline was broken and not connected, and the ecological function of wetlands was significantly reduced. To reverse the situation, Beihai City has implemented a large-scale "land-sea coordination" ecological restoration project since 2017. One of the core measures is to build a mangrove ecological corridor and connect urban rivers, wetland parks and coastal mangroves into one (Sun et al., 2025). At the same time, the restoration project also carried out the restoration of Yintan beach shoreline and the protection of seagrass beds, ultimately realizing ecological connectivity between rivers and forests and beaches (Figure 3). After several years of hard work, Beihai City has restored about 370 mu of mangrove forests and artificially replanted 270 mu of mangrove seedlings, connecting the once broken mangrove areas into a nearly 4.5-kilometer-long coastal shelterbelt (Wu et al., 2022). After the ecological corridor is opened, the carbon sink function of the system is significantly enhanced. On the one hand, the overall health of continuous mangroves has improved: due to the reduction of freshwater runoff pollution and clearer water quality, mangrove growth has become more vigorous, and the survival rate of artificially planted mangroves in some areas has increased from less than 20% to more than 50%. The forest soil gradually returned to its silt state, and the newly deposited peat layer steadily increased the soil carbon content per unit area. On the other hand, biodiversity has increased significantly and mangrove ecosystems have become stable. Monitoring shows that the number of bird species recorded in the project area increased from 136 in 2017 to 171 in 2020. Most of the new species were wadering birds and shorebirds, including critically endangered spoon-billed sandpipers and other migratory birds. The success of the construction of Beihai mangrove ecological corridor lies in the fact that it coordinates urban pollution control, mangrove restoration and coastline improvement. Through the coordinated restoration of multiple ecosystems, it has achieved the goal of "clear water, rich forests and beautiful beaches".

7 Construction of Monitoring and Evaluation System

7.1 Application of satellite remote sensing and drone monitoring technology

To effectively enhance and maintain the carbon sink function of mangroves, a complete monitoring and evaluation system must be established to track the scope changes, growth status and carbon reserves of mangrove ecosystems for a long time. The development of modern remote sensing technology provides a powerful tool for large-scale and high-frequency mangrove monitoring. Among them, satellite remote sensing has been widely used in mangrove resource surveys and dynamic monitoring (Pillodar et al., 2023). Medium- and high-resolution satellite images can clearly identify the spectral differences between mangroves and other land cover types, accurately map the spatial distribution of mangroves. Researchers have also developed vegetation index and classification algorithms for mangroves, such as the mangrove vegetation index (MVI) based on Sentinel-2 data, which can quickly extract mangrove information. Through comparative analysis of images at different periods, the changing trend of mangrove area and the specific areas where losses or growth occur can be quantitatively evaluated. On a global scale, NASA and other institutions have jointly launched the Global Mangrove Watch platform, integrating multi-source satellite data to monitor annual changes in global mangrove forests, and providing macro decision-making support to countries. In addition to area changes, satellite remote sensing can also be used to monitor the biomass and health of mangroves. Some studies have also tried to measure the height and crown width of individual trees using drones' LiDAR or structured light technology to more accurately calculate carbon storage.

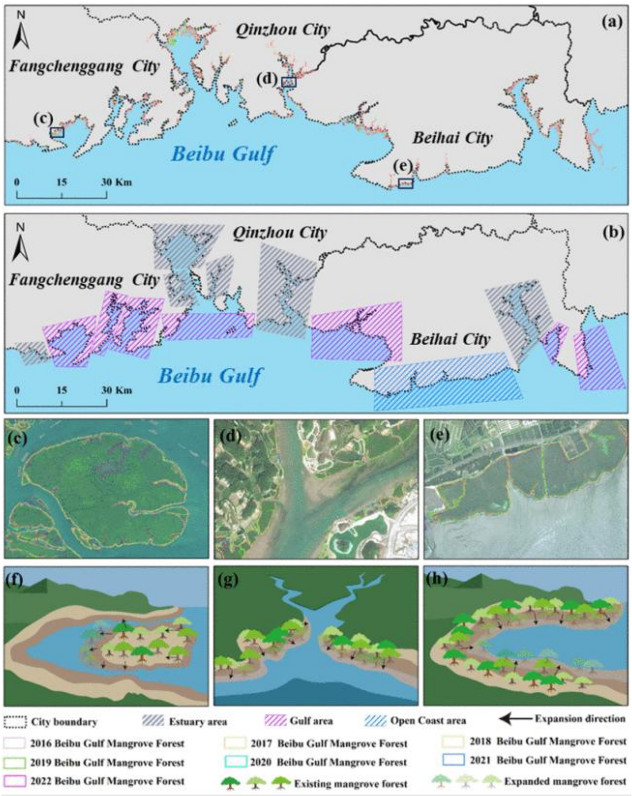

Figure 3 Schematic sketch of patterns of mangrove rapid expansion in Guangxi Beibu Gulf (Adopted from Sun et al., 2025)

Image caption: (a) Spatial distribution of mangrove forests in Guangxi Beibu Gulf from 2016 to 2022. (b) Classification of three different coastal mangrove forest types in Guangxi. (c)-(e) Examples of RGB satellite images of Google maps showing the expansion patterns of three different coastal zones types in Guangxi. (f)-(h) Schematic sketch of expansion patterns of three different coastal mangrove types in Guangxi Beibu Gulf (Adopted from Sun et al., 2025)

7.2 Soil carbon storage and biomass dynamic monitoring index system

Mangrove carbon sink monitoring should not only focus on the area and health of the forest, but also directly measure its carbon storage and changes. To this end, it is necessary to establish a dynamic monitoring index system covering soil carbon and vegetation biomass to quantitatively evaluate the changing trends of mangrove carbon sink function. In terms of soil carbon storage, monitoring indicators include soil organic carbon content, carbon density, and carbon burial rate. It is usually practiced to set up fixed monitoring sample sites in typical mangrove forests, collect soil profile samples regularly (such as every 5 years), and determine the organic carbon content and dry bulk weight at different depths, thereby calculating soil carbon storage per hectare (Alimbon and Mansegugiao, 2021).

In terms of vegetation biomass, indicators include the breast diameter, plant height, growth amount of trees, and the biomass carbon contained in xylem and roots per unit area. The commonly used method is to conduct forest inventory every year or every few years in a fixed sample, record the growth of a certain number of standard wood, and estimate the living carbon storage of the entire forest land through the biomass equation. For ecosystems such as mangroves where a large amount of carbon is distributed underground, both above-ground and underground biomass should be included in the monitoring system.

Finally, in order to make monitoring comparable and popular, unified technical standards and specifications should be followed. There are already some blue carbon monitoring guidelines internationally, which divide carbon storage monitoring into different levels (Tier 1/2/3), and encourage the gradual improvement of accuracy based on capabilities. A complete mangrove carbon sink monitoring index system will provide scientific basis for the certification of carbon trading projects, the compilation of national greenhouse gas inventory, etc., and is also an important tool for evaluating the effectiveness of management measures and adjusting strategies in a timely manner.

7.3 The Philippines' remote sensing-based mangrove carbon sink monitoring system

The Philippines has a vast mangrove coast and is actively committed to the assessment and improvement of its carbon sink capacity. In order to efficiently monitor the country's mangrove carbon sink monitoring system, the Philippines has built a mangrove carbon sink monitoring system based on remote sensing technology in recent years. The system was developed by the Philippine Space Agency (PhilSA) and a university research organization. It integrates satellite remote sensing, geographic information systems and artificial intelligence analysis to dynamically monitor the area changes and carbon reserves of mangroves across the country. In terms of data acquisition, the system makes full use of free images of Sentinel series satellites and data of domestic micro-nano satellites to achieve regular coverage of mangroves in more than 7 000 islands in the Philippines. Through machine learning algorithms, the project team has developed a mangrove classification model suitable for diverse environments in the Philippines, which can not only quickly identify mangrove distribution, but also determine whether mangrove forests are in a healthy, growing or degenerate state (Magalona et al., 2023). In terms of carbon storage estimation, the monitoring system combines remote sensing and ground survey data. The researchers selected representative mangrove sample sites from different regions, measured the stand structure and carbon content, and established a correlation model with satellite image characteristics. Based on the model, the system can calculate the changes in biomass carbon storage and soil carbon storage of mangroves in various places based on the latest remote sensing data. At the global level, the Philippines is also actively sharing its experience with other Southeast Asian countries to promote the construction of regional blue carbon monitoring networks. This case shows that using modern remote sensing and information technology can build an efficient mangrove carbon sink monitoring and evaluation system on a national scale, thereby supporting the needs of refined management and international carbon emission reduction reporting, and escorting the continuous improvement of mangrove carbon sink functions.

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Conflict of Interest Disclosure

The authors confirm that the study was conducted without any commercial or financial relationships and could be interpreted as a potential conflict of interest.

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