INNSPUB

Journal of Biodiversity and Environmental Sciences | JBES
ISSN: 2220-6663 (Print); 2222-3045 (Online)
Website: https://www.innspub.net
E-mail contact: info@innspub.net
Vol. 27, Issue: 2, p. 46-57, 2025

RESEARCH PAPER

OPEN ACCESS

Overemphasis on blue carbon leads to biodiversity loss: A case study on subsidence coastal wetlands in southwest Taiwan

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Key words: *Avicennia marina*, Carbon sink, Biodiversity, Land subsidence, Reservoir desilting

DOI: https://dx.doi.org/10.12692/jbes/27.2.46-57 [Published: August 10, 2025]

ABSTRACT

This paper presents a methodology that accounts for biodiversity in calculating the carbon storage of bio-carbon sinks. The feasibility of this approach is demonstrated in the coastal wetlands of Tainan City. The wetland profiles adopted for this calculation method include information on local mangroves, such as *Avicennia marina*, *Lumnitzera racemose*, *Kandelia obovat,* and *Excoecaria formosan*. In the study area, wetlands, mangroves, windbreak forests, and biodiversity habitats collectively cover an area of 7,789, 202, 240, and 1447 ha and have a carbon storage of 581,820, 53,222, 92,794, and 67,159 tons, respectively. This approach demonstrates that while maintaining the biodiversity of the original intertidal zone, mudflat or salt marsh ecosystem, better biodiversity and carbon sequestration can be achieved through mangrove planting and mosaic habitat management during the implementation of carbon sequestration projects, highlighting the key role of biodiversity in carbon sequestration projects. In particular, the findings indicate that dredging and sand removal in Tainan's Zengwen Reservoir has substantially prevented coastal erosion and restored the ecology of the Zengwen Estuary Delt. Finally, *A. marina* mangroves should not be planted on salt pans with land subsidence, such as closed hydrological systems.

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INTRODUCTION

In response to the Kunming-Montreal Global Biodiversity Framework (KM-GBF), which calls for reducing the loss of mangroves, seagrasses and salt marshes, more experts recommend planting more mangroves and seagrasses to mitigate the global biodiversity and climate crisis (Fu *et al.*, 2024). Taiwan enacted the Climate Change Response Act in February 2024 to reduce long-term greenhouse gas emissions, aiming to achieve net-zero emissions by 2050 (Ministry of Environment, 2023). Emission reduction strategies can incorporate local blue carbon ecosystems, which typically include coastal vegetative ecosystems, such as mangroves, seagrass beds, and salt marshes. In addition to their carbon sequestration potential, these ecosystems provide essential environmental functions. Emission reduction efforts often also involve carbon sinks, weights, and allowances; for example, trees may be planted to offset carbon emissions and renew forests.

Crucial wetlands surrounding highly urbanized areas often face a loss of ecological integrity and diversity (Jiang *et al.*, 2015; Yang and Ueng, 2011), and their protection during large-scale human activity, such as construction, remains challenging. Carbon sequestration, biodiversity-weighting, and carbon quotas are key components of protection efforts, which typically involve tree planting to regenerate forests and offset carbon emissions. Several researchers have advocated for thinning old trees and replacing them with young trees to increase the sequestration capacity of carbon sinks.

From 2013 to 2014, part of the mangroves was removed from Fangyuan beach, Changhua County. The Changhua Wild Bird Society commissioned Dr. Ueng to assist in supervision and conducted 7 collections, collecting a total of 1,635 specimens belonging to 60 species (Ueng, 2014).

The dominant species in the dense forest sample area (site A) and the site where the sea cucumber was removed in the previous year (site B) were: crebs *Parasesarma bidens*, *P. pictum* (Sesarmidae), and *Macrophthalmus banzai* (Macrophthalmidae), mollusca *Onchidium verruculatum* (Onchidiidae) and *Littoraria undulata* (Littorinidae), respectively. The dominant species in the adjacent open mudflats (sites C and D) were: crebs *Mictyris brevidactylus* (Mictyridae), *M. banzai*, *Austruca perplexa* and *Gelasimus borealis* (Ocypodidae), and *Lingula anatine* (Lingulidae), respectively. Further analysis by SIMPER 6 SIMPER showed that the average dissimilarity between the two habitat types A+B and C+D was 92.5% (Ueng, 2014).

Because the two distinct ecosystems—the enclosed, shady mangrove forest and the open, sun-soaked intertidal zone—follow planting or removal, their succession patterns shift in different directions. This means that the species communities and similarities here are constantly changing (Bordin *et al.*, 2023). Salt pans with tidal inflows grow *Enteromorpha* algaes, providing habitat for mollusks such as *Elysia chilkensis* and *Ecomania boodleae* (Ueng and Wang, 2001; Ueng *et al.*, 2001). The value of salt pan wetlands cannot be ignored due to unfamiliarity with species classification.

Variations in carbon sequestration rates across habitats at different successional stages within carbon sinks warrant further investigation (Bordin *et al.*, 2023). In this study, we introduce a biodiversity-weighted model to assess how biodiversity can enhance the capacity of carbon sinks. Our findings indicate that mangrove planting does not harm the biodiversity of exposed beach land but can improve carbon sequestration and restore the habitat's biodiversity.

Historical records indicate that indigenous communities in Taiwan engaged in mangrove bark trade with outsiders during the 17th century, including immigrants from Fujian and Guangdong who settled in Taiwan before 1662. Spanish priest Jacinto Esquive (1632) described how residents collected bark from mangroves near the Senae community on the north bank of the Tamsui Estuary (Taipei), which was then dried and sold to customers in China (Hsu, 2023).

Since the Last Glacial Maximum (c. 20,000 years BP), the Zengwen River has discharged directly into the sea after traversing now the Danei District of Tainan City. It was not until around 4000 years ago that the geomorphological emergence of Tainan Island altered the river's terminus, diverting its flow into the proto-Taijiang Lagoon (Chen *et al.*, 2005). In its early phases, the Zengwen River lacked a stabilized channel, contributing to the dynamic sedimentary and hydrological evolution of the evolving coastal plain. Over subsequent millennia, the Taijiang Lagoon underwent substantial transformations driven by alluvial deposition, overbank flooding, and anthropogenic modifications such as channelization and land reclamation. These processed collectively contributed to the formation of the modern Zengwen Estuary Delta, a complex deltaic landscape consisting of multiple distributaries and coastal wetlands. The present drainage system includes watercourses such as the Jiangjyun River, Cigu Creek, Luermen Creek, Yanshuei River, and Erren River.

Before the 18th century, the coast of Tainan in southern Taiwan was an inner bay lined with lagoons and sandbars. The oldest map of this area is included in the Kangxi Taiwan Map, which is preserved in the National Taiwan Museum. The primary fish species in this area included Mugilidae, Sciaenidae, and Engraulinae, which historically served as essential food source for spoonbills (*Platalea minor*) (Ueng, 2007b) and dolphins (*Sousa chinensis taiwanensis*) (Wang *et al.*, 2015), as well as sustaining the livelihood of local Siraya indigenous communities (Lin *et al.*, 2022). Due to heavy rain in 1823, the Taijian Lagoon filled with silt and became a shoal, and approximately 300 km² of the lagoon's area disappeared. The land was then reclaimed into salt pans, agricultural lands and fishponds, and mangroves grew in the tidal gullies (Huang, 1735; Vingboons, 1636). Environmental changes driven by human activity have led to the endangerment of several species, including *Geloina erosa* and *Fronsella taiwanicae*, while others, such as *Terebralia sulcata*, *Telescopium telescopium*, and *Parafossarulus manchouric*, are gradually extinction (Fig. 1).

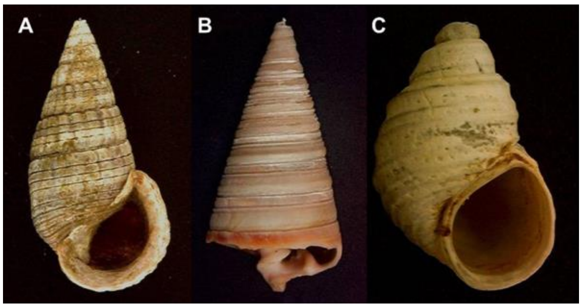

Fig. 1. Three species of shellfish have become extinct from Taijiang Lagoon. A. *Terebralia sulcata*, B. *Telescopium telescopium*, C. *Parafossarulus manchouric*

Accordingly, Weiskopf *et al.* emphasize the close relationship between biodiversity, habitat and environment, and the sequestration capacity of carbon sinks (Weiskopf *et al.*, 2024).

Fig. 2. Distribution of sandbars and lagoons along the coast of Tainan in the 18th century

Several place names in southern Taiwan originate from coastal fauna and flora, including Hai-ueng-sand (whale), Kun-shen (whale), Han-xi (*Thryssa* *hamiltonii*), Kang-lang (*Phoenix hanceana*), and Lu-cao (*Broussonetia papyrifera*). Over the past 6,000 to 300 years, land-use patterns and ecological environment within this 300 km^2 region—featuring waters ranging from −70 to −20 m deep—have undergone significant transformation0s (Huang, 1735; Vingboons, 1636) (Fig. 2). Numerous migratory Sciaenidae otoliths have been excavated from cultural relics near the lagoon (Lin *et al.*, 2022). We therefore hypothesize that from 6,000 to 300 years ago, the Taijiang Lagoon, which is protected by Tainan Island and a series of sandbars to the west, functioned as a breeding habitat for the Taiwan's white dolphin (Fig. 3).

Fig. 3. Taiwan's white dolphin family (photo by Yu-Chun Chien)

Since the construction of Zengwen Reservoir was completed in October 1973, the intertidal zone of Tainan's coast has experienced erosion. This study evaluated the effects of recent reservoir sands discharge and dredging on the restoration of coastal intertidal zones.

Current policies in Taiwan focus primarily on short-term ecological change through carbon sequestration incentives and engineering approaches but ignore ecological diversity. We propose that the biodiversity within these habitats can be strategically utilized to enhance the sequestration capacity of carbon sink; this means that enterprises that contribute to comprises biodiversity should have their carbon quotas or taxes offset accordingly.

MATERIALS AND METHODS

Study area within Tainan city

The study area encompasses the southwest coast of Tainan City, extending from Jiangjun River in the north to Sihkunshen Ditch in the south (Fig. 4). This region includes the coastal sites, estuaries, and lagoons of Taijiang National Park.

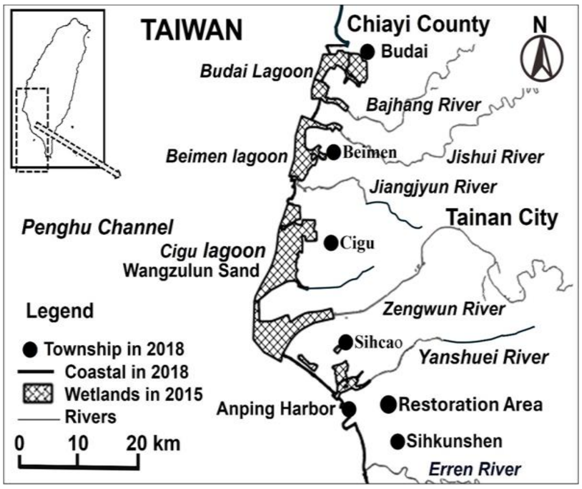

Fig. 4. Map of the study area within Tainan city, Taiwan

Estimation of mangrove, windbreak, and sand areas

For area estimation, we selected images collected at the Center for Space and Remote Sensing Research, National Central University, Taiwan, by satellites SPORT 7 on March 22, 2017; SPORT 6 on November 19, 2023; and SPORT 6 on February 22, 2025 (Center for Space and Remote Sensing Research, 2025). The primary purpose of this study was to estimate the land area covered by mangroves, windbreaks, and sand within the study site.

Estimation was conducted using the normalized difference vegetation index and unsupervised classification in ArcGIS Pro and Google Earth Pro images or through onsite comparison with Google Earth Pro (Center for Space and Remote Sensing Research, 2025; Chen *et al.*,2020).

We then analyzed the ecological impacts of dredging, beach maintenance, and Water Resources Agency management activities in the study area within the past seven years (2017–2024) on spatiotemporal satellite images (Chen, 2014; Chen *et al.*, 2020). Our analysis focused on the effects of heavy rains associated with Typhoon Gaemi (July 2024) and of sand removal and dredging during the flood discharge of the Zengwen Reservoir, containing approximately 2.58 million cubic meters of sand discharge (Southern Region Water Resources Branch, WRA, 2024).

Benthic organisms, crustaceans, and waterbirds inhabit the intertidal zone across five habitat types: forests, grasslands, dry sand dunes, wet sand beaches, and shallow water areas (0–20 cm or up to 30 cm). The wet beach is a crucial foraging area for the Kentish Plover (*Charadrius alexandrinus*) (Chen *et al.*, 2015), serving as the eastern boundary of our study area, which is marked by roads and embankments.

These habitats can be divided into eight types: aqueous habitats (with water depths of >90, 90–60, 60–30, or 30–0 cm); wetlands; forests; dry sand dunes; and highly reflective surfaces (Chen *et al.*, 2020; Chen, 2014). The wet beach area has been preserved to ensure foraging opportunities for the Kentish Plover population, and roads and embankment serve as the eastern boundary of the study site (Chen *et al.*, 2015). The SIMPER program in Primer 7 was used to analyze differences in characteristics between both satellite images, including habitat composition (Krebs, 1999).

Carbon sink

According to Lin (2024), blue carbon ecosystems in Taiwan include mangroves (938.8 ha), seagrass beds (7,818 ha), and salt marshes (188.3 ha) (Lin, 2024). Although the land area of salt marshes is small, this habitat is crucial for aquatic insect larvae and snails, including Dolichopodidae, Ephydridae, Stenothyridae, and Stratiomyidae, respectively (Ueng *et al.*, 2009; Ueng, 2013; Ueng and Wang, 2003; Wang *et al.*, 2007). These larvae play a key role in the food chain of waterbirds. The carbon stock for mangroves, seagrass beds, and salt marshes within the study area is approximately 263.5, 26.4, and 85.0 t C/ha, respectively (Lin, 2024; Ueng *et al.*, 2021).

Organic matter of coastal sand dunes and intertidal zone

Qrganic matter (OM) in coastal sand dunes, beaches, and intertidal zones serves as a major carbon sink. A study by Ueng *et al.* (2021) analyzing soil samples from the southwest coast of Taiwan reported the following average OM concentrations: 24.3, 21.9, and 7.7 g/kg in the Sinfulun sand dune, Zengwun Estuary sand dune (Fig. 5), and Cigu intertidal zone sites, respectively (Ueng *et al.*, 2021).

Fig. 5. On April 8, 2025, the Sinfulun Sand dune at the Zengwen Estuary was reformed into a small lagoon where oysters can be cultured

Carbon sink biodiversity-weighting

The Shannon-Wiener diversity index H' (log base e) was used as our biodiversity index (H') (Parker and Pianka, 1975; Krebs, 1999). The Jhuoshuei Estuary in western Taiwan has an H' of 1.20, 2.79, and 1.80 in benthic, fish, and crustacean species, respectively (Chen *et al.*, 2016). The H' for fish species in Cigu Lagoon is 1.90 (Chen *et al.*, 2005), and the H' for bird species in Cigu Salt Pan is 2.67 (Chen *et al.*, 2020). Additionally, the H' for mangrove spider species is 1.21 and 1.69 in the Jishuixi and Puzixi estuaries, respectively (Chen, 2012). The H' for fry fish families is 2.02 in the Cigu Wetland (Chen, 2012). The rough average estimate of these H' values is approximately 2.01 ± 0.56. We recommend increasing the carbon allowance of these wetlands by 10% - 15% of their carbon sequestration for their contribution to biodiversity.

Given these values and the scope of administrative discretion of government agencies, we recommend increasing the carbon quota of each wetland or subhabitat by 1–15% of their carbon sequestration as an incentive to ensure that carbon sequestration is promoted without sacrificing biodiversity (Ueng *et al.*, 2025). For the prediction of mangrove carbon sink in the land subsidence area, It is recommended to adjust the k value by the formula $Y(t) = -k(t - a)^2 + b$, where k is the decline rate of annual radius growth and should be reduce, t and a is years, and (a, b) is the maximum sequestration capacity of the carbon sink within that habitat.

RESULTS

Carbon sink

Based on satellite images of the coastal areas surrounding Tainan City, taken by SPORT7 on March 22, 2017, and SPORT 6 on November 19, 2023, the total area of the four nationally important wetlands from Jianqjyun Estuary to Sikunshen Ditch was 7,788.8 ha in 2023, with a yellow carbon storage capacity of 581,826 tons. We calculated the total mangrove area as 202.0 ha and the total area within the national wetland as 150.2 ha, which is 35.6 ha more than the national wetland area in 2017. The area outside the national wetlands was 51.8 ha in 2023, which is 20.4 ha more than in 2017. The windbreak habitats in 2023 were approximately 240.4 ha, which is 16.3 ha less than in 2017, with a carbon stock of 92,794 tons (Table 1, Fig. 6).

The Water Resources Agency (2024) reported that the cumulative dredging volume of the Zengwen Reservoir reached 138.7 million m^3 between 2017 and 2024, with an annual average of 6.3 ± 3.2 million m^3/yr. This exceeds the annual average sand volume (5.6 million m^3/yr) recorded from 2002 to 2023. Consequently, the Zengwen Estuary Delta is on the cusp of full restoration, and the yellow carbon along the Tainan coast can be included in carbon sink calculations (Fig. 6).

Table 1. Characteristics of carbon sinks within the study area

Sample sites	Area of 2017 (ha)	Area of 2023 (ha)	+/−(ha)	Stock (t C/ha)	Total carbon stock (t C)
Wetland (n= 4)	7,395.0	7,788.8	393.8	74.7	581,826
Mangroves in wetlands (n= 4)	114.6	150.2	35.6	263.5	39,578
Mangrove outside the wetland (n= 6)	31.4	51.8	20.4	263.5	13,644
Windbreak forest (n= 3)	256.7	240.4	−16.3	386.0	92,794
Biodiversity weighting (n= 8)		1,447.4		46.4	67,159
Total		8,231.2	433.5		795,002

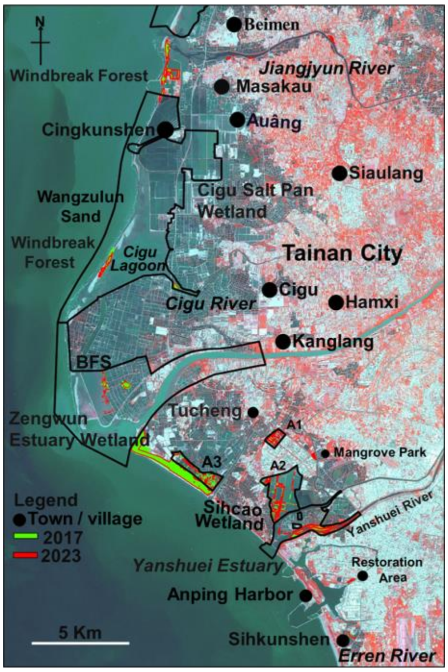

Fig. 6. Distribution of mangrove and windbreak forests from the Jiangjun Estuary to the Sikunshen Ditch, Tainan City, in 2017 and 2023. BFS: Black-faced Spoonbill Reserve, A1-A3: zoning of Sihcao Wetland, the green ones are the mangroves and windbreaks in 2017, and the red ones are the new additions in 2023

Based on satellite images of the coastal areas surrounding Tainan City, captured by SPORT 7 on March 22, 2017, and by SPORT 6 on February 22, 2025, the total mangrove area within the Zengwun Estuary Wetland (including BFS and EFP), and Cigu West Campus of National University of Tainan (WCT) was 57.3 ha in 2023, and 62.6 ha in 2025, reflecting an overall increase of 5.3 ha. This change was primarily attributed to a 21.2 ha expansion of BFS (from 4.1 ha to 25.2 ha), a 19.4 ha reduction in EFP (from 32.7 ha to 13.3 ha), and 3.5 ha increase in WCT (from 20.8 ha to 24.1 ha). The spatial similarity between the two periods was only 22.6% (Figs. 7 and 8).

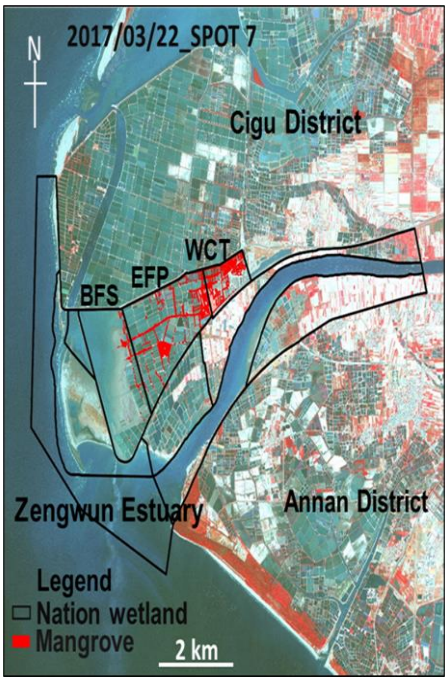

Fig. 7. The mangrove area in Zengwun Estuary Wetland on March 22, 2017. BFS: Black-faced Spoonbill Reserve, EFP: East Fish-pond site, WCT: Cigu West Campus site of Tainan University

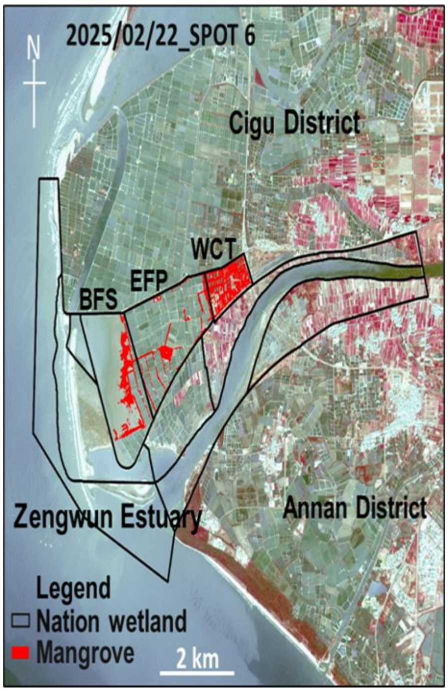

Fig. 8. The mangrove area in Zengwun Estuary Wetland on February 22, 2025. BFS: Black-faced Spoonbill Reserve, EFP: East Fish-pond site, WCT: Cigu West Campus site of Tainan University

Reservoir sand removal and dredging

Analysis of satellite images from March 22, 2017, and February 22, 2025, revealed that water areas with a depth of >90 cm and 90–60 cm decreased by 4,015.4 ha, whereas water areas with a depth of 60–30 or 30–0 cm and wetlands increased by 3,902.2 ha, totaling 7,917.6 ha (Table 2), indicating large storage capacity for yellow carbon.

The SIMPER program in Primer 7 was used to analyze satellite images and divided the total intertidal zone of the Zengwen Estuary Delta (6,477 ha) into two sample areas: Cigu Salt Pan Wetland (Cigu S.P.) and Zengwen Estuary Wetland (Zengwen E.), , all bounded by the west seawal. Each sample area was further divided into eight ecological habitats. Following sand removal from the reservoir and tidal transport between 2017 and 2024, the average dissimilarity of habitat classifications between both satellite images was 61.4% (Table 2). Discrepancies were primarily observed between areas with a water depth of 60–30 cm (34.3%), >90 cm (30.7%), and 90–60 cm (19.1%).

Separate calculation for the northern and southern areas within the study site revealed that the average similarity of the west side of the seawall in the Cigu Salt Pan Wetland over both years was 56.5%, primarily comprising areas with a water depth of 0–60 cm (41.7% of the similarity), >90 cm (29.7%), and 30–0 cm (15.6%) and wetland areas (7.5%), accounting for 94.53% of the observed similarity. The average similarity of the west side of the Zengwen Estuary seawall over both years was 85.5%, primarily comprising areas with a water depth of 30–0 cm (44.6% of the similarity) and 60–30 cm (43.0%) and wetland areas (5.2%), totaling 92.8% of the observed similarity. These findings indicate that the replenishment of sand sources from upstream decreased the area with a water depth of >60 cm and increased the area with a water depth of 60–30 and 30–0 cm and wetland areas, forming an intertidal ecosystem suitable for *Scopimera longidactyla* and *Mictyris brevidactylus* crabs and shore birds (Figs. 9 and 10).

Table 2. Impact of sand discharge and dredging of Zengwen reservoir on different types of habitats at the Zengwen Estuary Delta. (ha)

Water deep and land	2017		2025		Variation from 2017 to 2025
	Cigu S.P.	Zengwen E.	Cigu S.P.	Zengwen E.	
> 90 cm	544.1	2293	26.7	294.6	−2515.8
90–60 cm	928.0	762.1	121.2	69.4	−1499.5
60–30 cm	57.4	97.2	1191.3	1694.6	2731.2
30–0 cme	1117.1	286.1	1236.7	1296.3	1129.8
Wetland	136.9	138.7	142.8	174.1	41.2
Green plant	9.4	27.5	8.3	21.6	−6.9
No grass land	25.4	33.4	85.0	84.2	110.5
High reflection	13.0	7.8	19.4	11.0	9.6
Total	2831.3	3645.7	2831.3	3645.7	

Zengwen E. was Zengwen Estuary Wetland, and Cigu S.P. was Cigu Salt Pan. Wetland

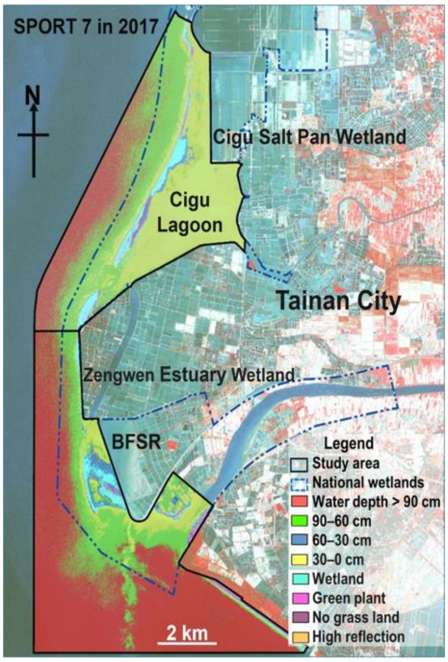

Fig. 9. Landscape classification of the Zengwen Estuary was performed using SPORT 7 satellite images (March 22, 2017) and processed with ENVI 4.8 software. BFSR: Black-faced Spoonbill Reserve

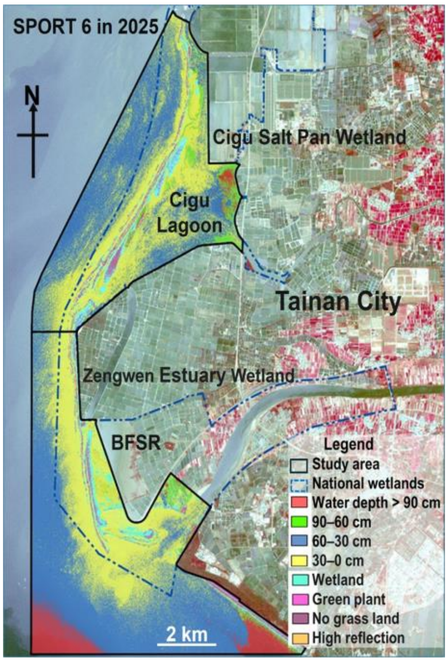

Fig. 10. Landscape classification of the Zengwen Estuary was performed using SPORT 6 satellite images (February 22, 2025) and processed with ENVI 4.8 software. BFSR: black-faced Spoonbill Reserve

Biodiversity weighting

We recommend increasing the carbon allowance of the wetlands in the study area by 10% to 15% of their carbon stock based on their contribution to biodiversity. This process would increase the carbon stock by biodiversity weighting 67,168.89 tons (approximately 9.2% of the original carbon sink). The carbon stock allowances identified within the study area were 795,002 tons.

DISCUSSION

Entities that maintain biodiversity by planting or cutting down trees should be compensated accordingly in the form of carbon sink rights, as indicated by the proposed diversity-weighted carbon sink model. This model allows for a nuanced understanding of the necessity of biodiversity beyond species counts. A promising method for biodiversity weighting is the creation of gaps in mangrove forests for greater biodiversity, as indicated by the index H'. Applications for carbon sink rights must first be accompanied by at least four ecological field surveys.

Between 2017 and 2024, mangrove coverage within the study site expanded naturally by Estuarine interactions play a crucial role in carbon storage (Water Resources Agency, MOEA, 2024). At the Zengwen, Zhuoshui, and Wu (Dadu) estuaries along Taiwan's west coast, extensive mudflats have formed due to the accumulation of drifting sediment. Given that *Avicennia marina* seeds disperse via seawater, the species can rapidly establish expansive mangrove forests, extending into tidal gullies and drainage channels, thereby impeding water flow and compromising flood management. However, along Taiwan's western coastline, intertidal mudflats biodiversity need not be sacrificed to enhance carbon storage; targeted *A. marina* mangrove planting can achieve carbon sink objectives while preserving ecological integrity.

On May 12, 2025, Taiwan's Ministry of Environment held a meeting to review the reduction of greenhouse gas through mangrove planting. Scholars and experts suggested limiting planting areas to idle salt pans, fishponds, and abandoned ponds instead of coastal areas, somewhat resolving existing disputes. However, the salt pans along the southwest coast of Taiwan are located in areas with severe land subsidence: by 2024, land subsidence was −233.6, −179.4, −153.3 and −50.2 cm in Dongshi, Budai, Beimen, and Cigu, respectively Water Resources Agency, MOEA, 2024). During the annual rainy season, the salt pan habitat, which is dominated by aquatic plants (*Ruppia maritima*) and aquatic insects (*Berosus tayouanus, Tendipus tainanus, Ochthera sauteri*), serves as a breeding ground for the Black-winged Stilt (*Himantopus himantopus*), an indicator species within salt pan ecosystems. Salt pan ecosystems provide 17 orders, 39 families, and 48 species of animal food for stilt chicks (Ueng *et al.*, 2009). However, to prevent flooding, residents and gate managers have closed all water diversion and drainage gates around the salt pans in the study area. Consequently, nutrients in the habitat have gradually dried up, decreasing the biodiversity of benthic animals, fish, and shrimp (Water Resources Agency, MOEA, 2024; Ueng, 2007a). Forestry Bureau aerial photographs from 1984 show that these fishponds, which block tidal and sediment-laden currents, did not exist before this time (Ueng and Kuo, 1992; Forestry Bureau Aerial, 1984; Tainan County Government,1992). A lack of tidal exchange restricts both the growth of mangroves and the anticipated carbon sequestration effect (< 15 tC/ha per year).

Fossil evidence of *Stenotyra tainanica* in the Tainan Formation (4500- 8400 YBP), together with the contemporary presence of *S. chilkaensis* and *S. orissaensis* in southwest Taiwan's brackish wetlands, and the other new species *Odontomyia halophila* (Stratiomyidae) was described from salt marshes of western Taiwan (Wang *et al.*, 2007). These salt marsh wetlands are shaped by long-term successional dynamics and exhibit inherently slow species turnover due to hypersaline conditions and hydrological constraints. Afforestation or removed mangroves may increase carbon sinks or flood control (Huang, 2021; Wu, 2023), but this is accompanied by the emergence of new and different biological communities, which will also affect the assembly, diversity and species similarity percentage of its organisms (Ueng, 2014).

Uninformed afforestation with *A. marina*—disregarding these ecological parameters—risks disrupting established assemblages and eroding native biodiversity. Such losses not only impair ecosystem integrity but also diminish carbon sequestration capacity, a pattern increasingly evident in global terrestrial carbon systems (Ueng, 2014; Weiskopf *et al.*, 2024; Li, 2016; Liu *et al.*, 2021).

ACKNOWLEDGEMENTS

We are grateful to Mr. Po-Ling Deng, Mr. Yu-Chun Chien, Mr. Ching-Lung Liu, and Mr. Chih-Hao Liao. This study was supported by Ocean Conservation Administration, OAC, and Tainan City Government.

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