Marine Research
of the National Academy of Marine Research
ISSN: 2709-6629 (Vol.3 Iss.2)
GPN: 2011200033

DOI: http://dx.doi.org/10.29677/MR.202312_3(2).0001
2023, 3(2), 1-17

Assessing Coastal Blue Carbon Sinks in Taiwan

Hsing-Juh Lin [1,2*] Kuan-Yu Chen [1] Yu-Chen Kao [1] Wei-Jen Lin [1,2]
Chiao-Wen Lin [3] Chuan-Wen Ho [1,2]

[1] Department of Life Sciences, National Chung Hsing University, Taichung City, Taiwan
[2] Innovation and Development Center of Sustainable Agriculture, National Chung Hsing University, Taichung City, Taiwan
[3] Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung City, Taiwan

ABSTRACT

Maintaining and enhancing blue carbon sinks have become an emerging priority to mitigate climate change. This study aims to assess the carbon sinks of coastal blue carbon ecosystems in Taiwan by collecting published journal papers, grey literature, and research reports to inventory the carbon sequestration and stock of the major coastal blue carbon ecosystems, including mangroves, seagrass beds, and salt marshes. The total area of salt marshes in Taiwan is 188 ha, of which the exotic species *Spartina alterniflora* in Kinmen accounts for 68% of the total. The largest area of coastal blue carbon systems in Taiwan is 5481 ha for seagrass beds, of which 5420 ha are distributed in Dongsha Island. Mangroves cover 681 ha. The carbon sequestration and stock of the representative species of salt marshes are 3.45~24.33 Mg C ha^{-1} yr^{-1} and 53.26~91.89 Mg C ha^{-1}, respectively. The carbon sequestration and stock of the representative species of dominant intertidal seagrasses are 2.93~6.22 Mg C ha^{-1} yr^{-1} and 8.91~10.50 Mg C ha^{-1}, respectively. The carbon sequestration and stock of subtidal seagrasses in Dongsha Island are 14.73 Mg C ha^{-1} yr^{-1} and 26.38 Mg C ha^{-1}. The carbon sequestration and stock of mangrove species are 12.81~25.07 Mg C ha^{-1} $yr^{-1}$and 134.50~292.23 Mg C ha^{-1}. Based on the distribution area of each species, the total carbon sequestration capacity is 3,661 Mg C yr^{-1} for salt marshes, 80,619 Mg C yr^{-1} for seagrass beds, and 11,183 Mg C yr-1 for mangroves. The total carbon stock is 16,000 Mg C for salt marshes, 144,444 Mg C for seagrass beds, and 181,560 Mg C for mangroves. Combining the three blue carbon ecosystems, the total carbon sequestration capacity and stock is 95,463 Mg C yr^{-1} or 350,030 Mg CO_2 yr^{-1} in Taiwan. Further actions are suggested to reduce the uncertainty in the carbon sinks of coastal blue carbon ecosystems in Taiwan.

Keywords: Carbon stock, Carbon sequestration, Mangroves, Salt marshes, Seagrass beds.

---

* Corresponding author, E-mail: hjlin@dragon.nchu.edu.tw

Received 29 July 2023, Accepted 16 September 2023.

1 INTRODUCTION

Carbon sink is defined as the continued separation of greenhouse gases (GHGs), mainly CO_2, CH_4 and N_2O, from the atmosphere or other emission units, which are then stored in trees, forests, soil, oceans or facilities. Natural ecosystems can absorb atmospheric CO_2 via photosynthesis, which is then fixed into plant tissue and soil. Natural carbon sinks can be qualified as Nationally Determined Contributions (NDCs) for the COP21 (the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change, UNFCCC), which is a national climate action plan to cut emissions and adapt to the impacts of climate change (https://unfccc.int/event/cop-21). Each party of the Paris Agreement (Article 4, paragraph 2) is required to establish NDCs and update them every five years. Natural carbon sinks can offset the GHG emissions and help countries reach their carbon neutrality goal (net zero emissions) by 2050, including Taiwan.

Oceans, soil, and forests are the main natural carbon sinks on Earth. Compared with the carbon sequestration of forests, the carbon sequestration of oceans and soil in Taiwan has received much less attention. Coastal blue carbon mainly refers to organic carbon stored in mangroves, tidal salt marshes, and seagrass beds (Mcleod et al., 2011). The sediment of coastal blue carbon systems is characterized by long-term anaerobic conditions, thereby slowing down the decomposition of soil organic carbon, which can result in substantial carbon storage (Chmura et al., 2003). In addition, the high productivity of coastal blue carbon vegetation results in a large number of dead leaves and roots buried in the soil (Mcleod et al., 2011), thus forming a huge carbon stock.

Mangroves refer to habitats of trees and shrubs that grow in the intertidal zone, where the environmental topography is generally above mean sea level. Salt marshes refer to salty water coastal areas that are regularly flooded by tides, where salt-tolerant plants densely grow, including herbaceous plants, meadows or low-lying shrubland. Seagrass beds are the habitats of submerged flowering plants, all belonging to the order Alismatales, which grow in a completely halophytic environment of the subtidal zone (Howard et al., 2014). Mangroves were mainly distributed in the tropics. Salt marshes are mainly distributed in temperate to polar zones. Seagrasses have the most extensive global distribution and area of the three, spanning tropical and temperate regions (Davidson et al., 2019).

Coastal blue carbon ecosystems are also well known hot spots of marine biodiversity. These systems can provide the ecosystem service of carbon sequestration, which can offer carbon credits for GHG emission allowance and offset projects (Kuwae et al., 2022). Conservation of blue carbon ecosystems is a win-win strategy for business and nature, which is a nature-based solution (NbS) to simultaneously protect biodiversity and mitigate GHG emissions advocated by the United Nations Biodiversity Conference (COP15) in 2022 (https://www.unep.org/un-biodiversity-conference-cop-15). The objectives of this study are to (1) compile the results of coastal blue carbon sequestration-related studies by searching for published journals and grey literature in Taiwan, (2) inventory the carbon sequestration data of coastal blue carbon ecosystems, and (3) put forward further work suggestions.

2 DATA COLLECTION METHOD

The data collection method for information related to the carbon sequestration in the coastal blue ecosystems of Taiwan involved searching information on the Web of Science database or using the Google Scholar search engine to find international SCI journal published research, accessing the Taiwan PhD and Master's Thesis Value-added System (https://ndltd.ncl.edu.tw/) to find master's and doctoral theses that have been published in major colleges and universities in Taiwan, using the Government Research Information System (https://www.grb.gov.tw/) to find research reports commissioned by central and local government agencies in the past, and compiling data on carbon sequestration and stock in Taiwan's coastal blue carbon systems such as mangroves, seagrass beds, and salt marshes.

3 MANGROVES

Mangroves in a broad sense include true mangroves (salt-tolerant woody plants that grow in the intertidal zone of estuaries) and mangrove associates (salt-tolerant herbs, vines, and shrubs that grow on the edges of mangroves) (Rivera-Monroy et al., 2017). True mangroves can be subdivided into minor mangroves that cannot form pure forests in the intertidal zone, as well as major mangroves that are fully adapted to tidal inundation, such as with specialized salt secretion mechanisms, viviparous seedlings, and supporting roots (Polidoro et al., 2010). Due to differences in anaerobic conditions in habitats and the formation of pure forest ecosystems, blue carbon assessments are dominated by predominant mangrove forests (Howard et al., 2014). For academic purposes, this study refers to the main mangrove plant ecosystem as mangrove forests in the narrow sense.

Lin et al. (2019) surveyed the distribution area and species composition of major mangrove forests in Taiwan. Mangroves are the most widely distributed of the three major coastal blue carbon ecosystems in Taiwan, mainly found along the western coast, and the northernmost extends from the mouth of the Tamsui River to the south of Dapang Bay, Pingtung (Lin et al., 2019). The mangrove area is bounded by Da'an in Taichung, *Avicennia marina* in the south, *Kandelia obovata* in the north, and *Lumnitzera racemosa* and *Rhizophora stylosa* is sporadically distributed along the coast south of Chiayi. The area of mangrove forests in Taiwan increased from 178 ha to 586 ha between 1976 and 2011 (Wang et al., 2015), and Lin et al. (2019) noted that the total area is at least 681 ha. However, the increase in mangrove area in Taiwan is mostly caused by anthropogenic planting and the subsequent expansion (Wester & Lee, 1992); overgrown mangroves may lead to mosquito breeding and flooding (Shih et al., 2015), and even lead to reduction in carbon sequestration (Ho et al., 2017), biodiversity (Pan et al., 2021), and GHG emissions (Lin et al., 2021a). Therefore, the distribution area of mangroves in Taiwan will change with the expansion or deforestation of mangroves (Lin et al. 2019).

4 SEAGRASS BEDS

Seagrass is a submerged vascular plant living in shallow coastal waters, which can be divided into P-type (persistent species) with strong tissue toughness, larger plant size, and strong anti-interference ability, as well as C-type (colonizing species) with poor tissue toughness, smaller plant size, and strong resilience, and O-type (opportunistic species) according to the life history of seagrass species (Kilminster et al., 2015). In general, the P-type or persistent seagrass belongs to the species of late succession, whereas the C-type and O-type seagrasses are early succession species. According to Nordlund et al. (2016), seagrass species of the same genus or individual types may have similar ecological services and functions. Seagrass habitats can also be divided into two sediment types: sand and mud (Lin et al., 2019).

Seagrass beds occupy the largest area of Taiwan's three major coastal blue carbon ecosystems, but most of the area (99%) is located around Dongsha Island and Atoll. The rest are recorded on the islands of Taiwan but are small (< 1 ha) in area. At present, as many as 12 species of seagrass are known to exist in Taiwan (Ko, 2004; Lin et al., 2005; Liu et al., 2018), representing about 1/6 of the world's seagrass species. Lin & Chen (2019a) surveyed the distribution area and species composition of major seagrasses in Taiwan, including *Halophila beccarii, H. depcipiens, H. ovalis, H. major, Thalassia hemprichii, Cymodocea rotundata, C. serrulata, Syringodium isoetifolium, Thalassiodendron ciliatum, Halodule pinifolia, H. uninervis* and *Zostera japonica.* Taiwan's seagrass is mainly distributed in the mudflats or sand flats covered by shallow seawater on the west coast of Taiwan, Hengchun Peninsula, and neighboring islands (Lin & Chen, 2019a). The species in the islands of Taiwan are *H. beccarii, H. ovalis, T. hemprichii, H. pinifolia, H. uninervis* and *Z. japonica,* while others are subtidal seagrasses that are only distributed in Dongsha Island and Atoll or only occur at water depths below 1 m (Lin & Chen, 2019a). Among them, *H. beccarii* is a "vulnerable" species according to the International Union for Conservation of Nature (IUCN) that grows only in intertidal mudflats (Short et al., 2010).

5 SALT MARSHES

Salt marshes can be divided into tidal salt marshes and inland salt marshes depending on the extent of seawater exchange. The former are stable relative to inland salt marshes lacking tides due to periodic tidal incidence that can take away the accumulated salt in the surface soil (Jørgensen, 2009), which is the main coastal blue carbon system. According to the survey of marshes in Taiwan conducted by Ye (2005), there are 173 marsh species belonging to 50 families, most of which are Poaceae, Asteraceae, and Cyperaceae. *Paspalum vaginatum* and *Phragmites vallatoria* are the most dominant marsh species. Among them, however, there are not many tidal salt marsh species that meet the criteria of "can form a certain population in tidal affected areas and provide carbon sequestration capacity." According to Lin (2022), the most dominant species of tidal salt marshes in Taiwan are monocotyledonous herbs such as *Bolboschoenus planiculmis, Phragmites australis, Sporobolus virginicus* and *Spartina alterniflora.* Among them, the native species *Bolboschoenus planiculmis* is an important protected species in the Gaomei Wetlands in Taichung, while *Spartina alterniflora* is an invasive alien species drifting across the sea along the coast of China (Lin & Chen, 2019b).

6 ASSESSING COASTAL BLUE CARBON SINKS

The assessment of ecosystem carbon sinks can be carried out from two aspects: dynamic carbon fluxes and static carbon stocks. The former aims to subtract carbon output from net primary production and soil respiration (i.e., GHG emissions) to obtain carbon sequestration within the entire system, reflecting the rate of organic carbon accumulation in plants and soils; the latter measures the amount of organic carbon in plants and soils to quantify the existing carbon pool within ecosystems.

The carbon budgets of mangroves and seagrass beds (Li et al., 2018; Huang et al., 2015; Zou et al. 2021) were integrated into the conceptual model of carbon budgets for the three major coastal blue carbon systems (Figure 1). The net carbon uptake by blue-carbon vegetation through photosynthesis is allocated to aboveground and belowground production, which is generally the main source for carbon sinks (Li et al., 2018; Huang et al., 2015). In terms of carbon output, GHG emissions have a direct impact on the atmosphere. Static carbon stocks can directly reflect the existing organic carbon pool within blue carbon systems, so plant tissues and soil carbon pools are also included in these carbon budgets.

The absorption of carbon dioxide via plant photosynthesis and GHG emissions by the soil or through plants are the pathways through which carbon is directly exchanged with the atmosphere. Other carbon inputs or outputs are considered as lateral transport (Li et al., 2018; Huang et al., 2015). Laterally transported carbon include litter, debris, particulate organic carbon (POC) and dissolved organic (DOC) and inorganic carbon (DIC), which are closely related to hydrological conditions. Some of the imported carbon is decomposed and converted into GHGs by microorganisms, some is deposited into the soil as carbon burial, and the rest is expored with tides or currents.

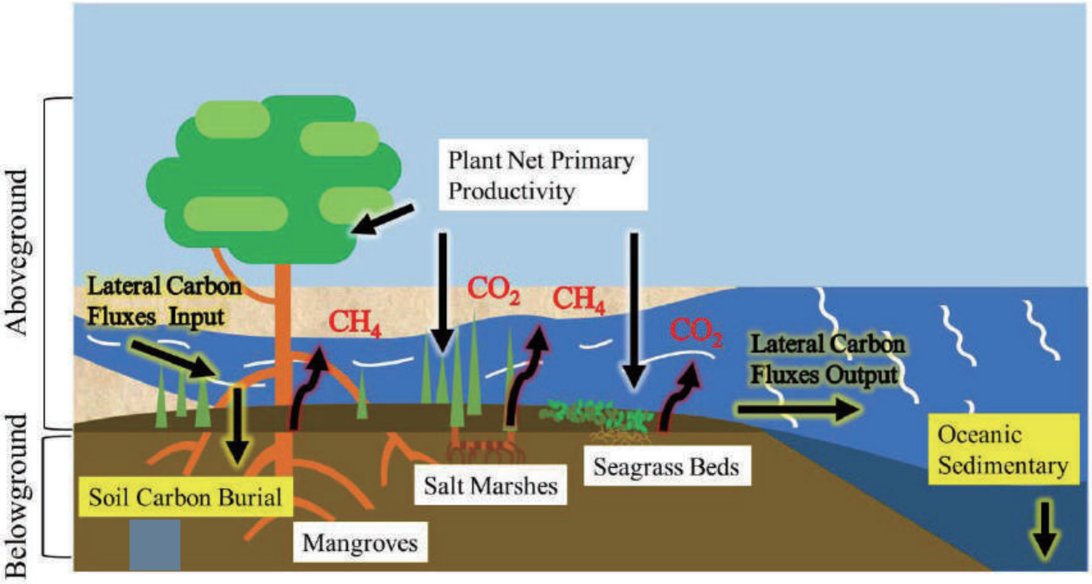

Figure 1. Conceptual model of carbon gain and loss in coastal blue carbon ecosystems.

According to the 2013 Supplement to the IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC, 2014), the accuracy level of carbon sink estimation is divided from low to high, i.e., Tier 1: using the emission factors preset by the IPCC for estimation; Tier 2: country-specific key factor parameters and the use of country-specific or location-specific data; Tier 3: obtained through direct measurements in the field or model estimation. Detailed verification, timed replicates or model calculations of major carbon pools are frequently used to assess the changes in carbon pool and flux in a region. In this study, the quantification of carbon sequestration capacity of the coastal blue ecosystems in Taiwan can be divided into two steps: (1) researching relevant literature to establish the emission factors of the representative species of three blue carbon ecosystems in Taiwan. The accuracy of the carbon emission factors belongs to Tier 2 or Tier 3; (2) assessing the total carbon sequestration capacity of the coastal blue carbon systems by multiplying the emission factors of the representative species with the distribution area or activity data of each blue carbon system. The accuracy of the activity data belongs to Tier 2.

The calculation methods of carbon sequestration can be divided into three types: (1) the carbon pool difference method, where the carbon stock at two different time points is determined and the change is supposed to result from carbon loss such as GHG emissions, which is a Tier 3 estimate; (2) the gain and loss method, which is based on the emission factors of scientific literature or country-specific data, resulting in Tier 1 or Tier 2 data; and (3) the flux method, where an estimate is derived from direct measurements or modeling of the GHG emissions between soil and vegetation or atmosphere and water bodies, which can obtain Tier 2 or Tier 3 data. In this study, the methods used for different blue carbon ecosystems are as follows: applying the carbon pool difference method to estimate vegetation carbon sequestration and soil carbon burial for salt marshes and seagrass beds, and integrating the flux method and gain and loss method to estimate mangrove vegetation carbon sequestration and decomposition in the soil carbon pool, respectively.

The carbon sequestration capacity of coastal blue carbon systems was estimated by summing the vegetation carbon sequestration (Mg C ha^{-1} yr^{-1}) and soil carbon burial rate (Mg C ha^{-1} yr^{-1}) (Equation 1). The soil carbon burial rate is a direct measurement of the change of soil carbon stock or the contribution of decomposed plant litter and dead roots to the soil carbon pool, which covers the results of autogenous carbon input and decomposition carbon loss (e.g., GHG emissions). This can better represent the carbon sequestration capacity on a long-time scale. The soil carbon burial rate in salt marshes and seagrass beds was estimated by the change of soil carbon stock in the top 30 cm layer (Huang et al., 2015; Chen & Lin, 2022) because the soil carbon pool below 30 cm is generally less affected by the autogenous carbon input. The soil carbon burial rate in mangroves was estimated by the contribution of decomposed aboveground and belowground litter to the soil carbon pool (Li et al., 2018; Chou et al., 2022). In terms of carbon storage (Mg C ha^{-1}), the carbon stock of the aboveground and belowground parts of the plant tissue, as well as the soil carbon stock, was added as shown in Equation (2) (3). Then, the carbon sequestration capacity and carbon stock of the representation species were multiplied by their distribution area and then added up to obtain the carbon sequestration rate (Mg C yr^{-1}) and carbon stock (Mg C) of the coastal blue carbon ecosystems in Taiwan, as detailed in Equation (4) and (5).

Carbon sequestration capacity (Mg C ha^{-1} yr^{-1}) (1)

= Carbon sequestration rate in plant tissue + Carbon burial rate in soil

= Change in the carbon stock of aboveground and belowground parts + Change in soil carbon stock

Carbon stock of species (Mg C ha^{-1}) (2)

= [Aboveground biomass(g DW m^{-2}) × Aboveground carbon content (C %) + Belowground biomass (g DW m^{-2}) × Belowground carbon content (C %) + Soil organic carbon stock (g C m^{-2})] × 10^4(m^2 ha^{-1})×10^{-6}(Mg g^{-1})

Soil organic carbon stock(Mg C ha^{-1}) in a meter deep (3)

= Σ Soil organic carbon stock in different layers (e.g.,0-10 cm,10-20 cm and 20-30 cm deep) (g C m^{-2})×10^4(m^2 ha^{-1})×10^{-6}(Mg g^{-1})

Carbon sequestration capacity of coastal blue carbon ecosystems in Taiwan (Mg C yr^{-1}) (4)

= Σ Carbon sequestration capacity of each representative species of coastal blue carbon ecosystems (Mg C ha^{-1} yr^{-1}) × the area of each species in Taiwan (ha)

Carbon stock of coastal blue carbon ecosystems in Taiwan (Mg C yr^{-1}) (5)

= Σ Carbon stock of each representative species of coastal blue carbon ecosystems (Mg C ha^{-1} yr^{-1}) × the area of each species in Taiwan (ha)

7 DISTRIBUTION OF COASTAL BLUE CARBON ECOSYSTEMS IN TAIWAN

The distribution area of coastal blue carbon ecosystems in Taiwan was integrated, and the largest area is 5,481 ha for seagrass beds, of which 5,420 ha are distributed in Dongsha Island and 25 ha are distributed in Taiping Island in the South China Sea (Shao et al., 2014) (Figure 2). In the islands of Taiwan, the mangrove area is the largest (681 ha), followed by tidal salt marshes (188 ha) and seagrass beds (36 ha). In terms of counties and cities, the distribution area of mangroves is 226 ha in Tainan City, and the distribution area of tidal salt marshes is 127 ha in Kinmen County (Tables 1, 2, and 3).

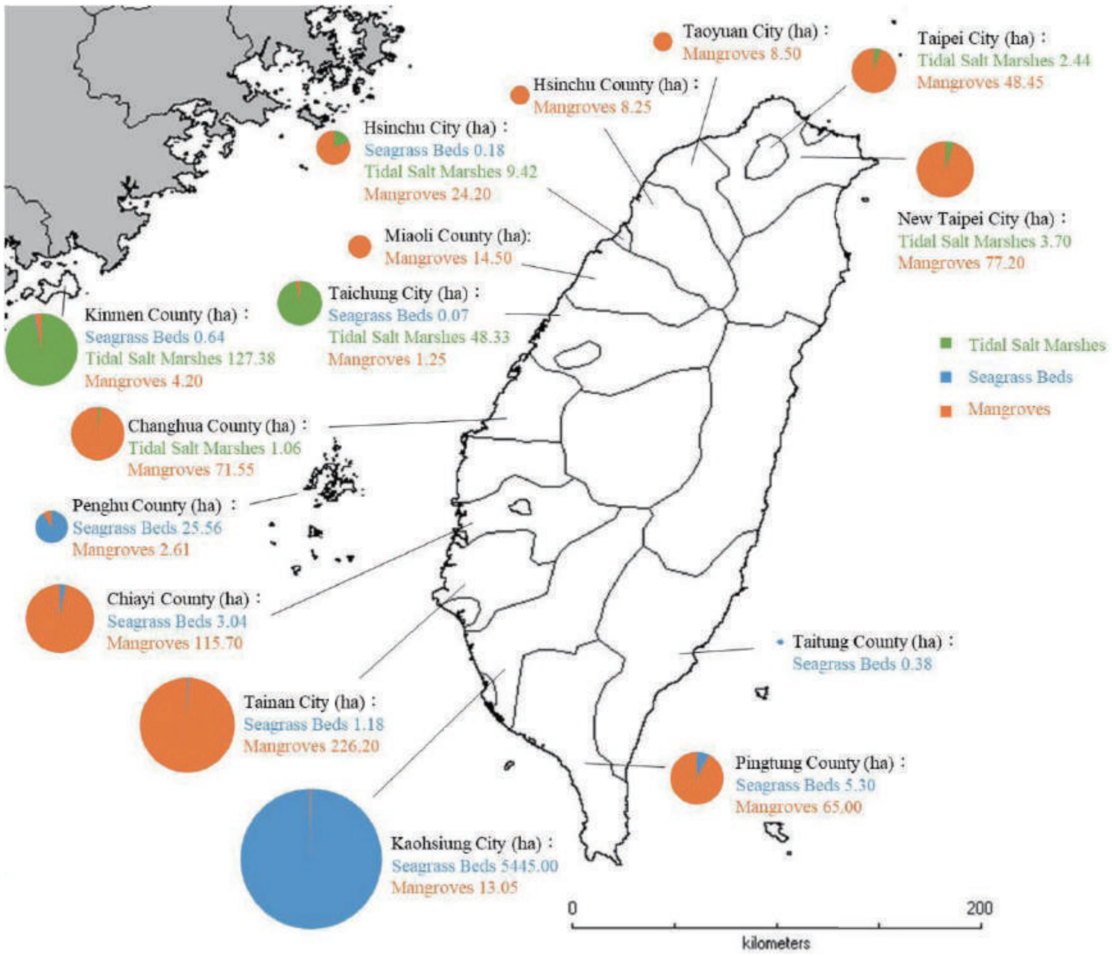

Figure 2. Distribution area of coastal blue carbon ecosystems in Taiwan.

Table 1. Distribution and covered area of tidal salt marshes and dominant species in Taiwan. (Lin, 2022)

Location	County/City	GPS	Dominant Species	Area (ha)
Tamsui River	Taipei City & New Taipei City	25.086778 N, 121.497236 E	*Phragmites australis*	6.14
Xiangshan	Hsinchu City	24.777600 N, 120.913006 E	*Bolboschoenus planiculmis*	5.42
Da'an	Taichung City	24.368969 N, 120.581328 E	*P. australis*	10.09
Gaomei	Taichung City	24.312222 N, 120.548728 E	*P. australis*	38.25
Shengang	Changhua County	24.165239 N, 120.459617 E	*B. planiculmis*	0.87
Wanggong	Changhua County	23.966389 N, 120.320903 E	*Spartina alterniflora*	0.19
Kinmen	Kinmen County	24.470872 N, 118.384008 E	*S. alterniflora*	127.38
Total				188.33

Table 2. Distribution and covered area of seagrass beds and dominant species in Taiwan. (Lin & Chen, 2019a)

Location	County/City	GPS	Dominant Species	Area (ha)
Xiangshan	Hsinchu City	24.77661 N, 120.91288 E	*Zostera japonica*	0.18
Gaomei	Taichung City	24.31592 N, 120.54793 E	*Z. japonica*	0.07
Baishuihu	Chiayi County	23.42872 N, 120.14747 E	*Halophila beccarii*	1.56
Haomeiliao	Chiayi County	23.36236 N, 120.13205 E	*H. beccarii*	1.48
Qigu	Tainan City	23.12378 N, 120.08476 E	*Halophila ovalis*, *Halophila decipiens*	1.18
Liuqiu	Pingtung County	22.33371 N, 120.35927 E	*Thalassia hemprichii*, *Halodule uninervis*	0.10
Haikou	Pingtung County	22.08779 N, 120.7082 E	*Halodule pinifolia*, *T. hemprichii*	4.38
Wanliton	Pingtung County	21.9956 N, 120.70546 E 21.99779 N, 120.70134 E	*T. hemprichii*	0.02
Dakwan	Pingtung County	21.95155 N, 120.74992 E	*T. hemprichii*, *H. uninervis*	0.56
Nanwan	Pingtung County	21.95712 N, 120.76763 E	*T. hemprichii*, *H. uninervis*	0.25
Green Island	Taitung County	22.65353 N, 121.47361 E	*T. hemprichii*	0.38
Zhenhai	Penghu County	23.6479 N, 119.60488 E	*H. ovalis*, *H. uninervis*	25.30
Shagang	Penghu County	23.60822 N, 119.62084 E	*H. ovalis*	0.25
Chongguang	Penghu County	23.58656 N, 119.57273 E	*H. uninervis*	0.02
Wujiang River Estuary	Kinmen County	24.43173 N, 118.30891 E	*Z. japonica*	0.47
Cihu, South Hill	Kinmen County	24.46450 N, 118.29668 E	*Z. japonica* *H. ovalis*	0.07
Shanglin, Zhongdun	Kinmen County	24.42668 N, 118.22215 E	*Z. japonica*, *H. ovalis*	0.10
Dongsha Atoll	Kaohsiung City	20.70410 N, 116.72146 E	*T. hemprichii*, *H. ovalis*	5,420.00
Taiping Island	Kaohsiung City	10°22'38"N 114°21'59"E	*T. hemprichii*, *H. uninervis*	25.00
Total				5,481.35

Table 3. Distribution and covered area of mangroves and dominant species in Taiwan. (lin et al., 2019)

Location	County/City	GPS	Dominant Species	Area (ha)
Waziwei	New Taipei City	25.16612 N, 121.41697 E	*Kandelia obovata*	9.90
Zhuwei	New Taipei City	25.15621 N, 121.4566 E	*K. obovata*	47.1
Guandu	Taipei City	25.11557 N, 121.4642 E	*K. obovata*	41.8
Shezi Daotou	Taipei City	25.10928 N, 121.46556 E	*K. obovata*	6.65
Luzhou	New Taipei City	25.09947 N, 121.47283 E	*K. obovata*	20.2
Xinwu	Taoyuan City	25.01732 N, 121.03526 E	*K. obovata*	8.50
Xinfeng	Hsinchu County	24.90842 N, 120.97225 E	*K. obovata*, *Avicennia marina*	8.25
Xiangshan	Hsinchu City	24.80885 N, 120.91348 E	*K. obovata*, *A. marina*	24.2
Zhunan	Miaoli County	24.66725 N, 120.84216 E	*K. obovata*	14.5
Da'an	Taichung City	24.37497 N, 120.58296 E	*K. obovata*	1.25
Yuanlin Canal	Changhua County	24.05736 N, 120.40658 E	*A. marina*	13.5
Fubao	Changhua County	24.03673 N, 120.37352 E	*A. marina*	5.25
Hanbao	Changhua County	23.99224 N, 120.35514 E	*A. marina*	8.25
Wanggong	Changhua County	23.96738 N, 120.34095 E	*A. marina*	9.05
Fangyuan	Changhua County	23.93156 N, 120.31477 E	*A. marina*, *K. obovata*	35.5
Aogu	Chiayi County	23.5138 N, 120.12843 E	*Lumnitzera racemosa*, *A. marina*	15.0
Puzi River Mouth	Chiayi County	23.45833 N, 120.17639 E	*A. marina*	68.0
Haomeiliao	Chiayi County	23.36234 N, 120.13122 E	*A. marina*, *Rhizophora stylosa*	19.5
Bazhang River Mouth	Chiayi County	23.33476 N, 120.126 E	*A. marina*	13.2
Shuangchun	Tainan City	23.31278 N, 120.11544 E	*A. marina*, *R. stylosa*	25.5
Beimen, Xuejia	Tainan City	23.29426 N, 120.11337 E	*A. marina*, *L. racemosa*	97.5
Jiangjun River Estuary	Tainan City	23.22617 N, 120.08489 E	*A. marina*, *L. racemosa*	6.00
Qigu	Tainan City	23.11833 N, 120.08963 E	*A. marina*	5.20
Sicao	Tainan City	23.00312 N, 120.15007 E	*A. marina*, *L. racemosa*	87.0
Sikunshen	Tainan City	22.96021 N, 120.18139 E	*A. marina*	5.00

Location	County/City	GPS	Dominant Species	Area (ha)
Qieding	Kaohsiung City	22.91727 N, 120.18402 E	*A. marina,* *L. racemosa*	1.05
Yong'an	Kaohsiung City	22.83649 N, 120.20789 E	*A. marina*	4.00
Yuanzhonggang	Kaohsiung City	22.7227 N, 120.26112 E	*A. marina*	4.75
Jhongdous	Kaohsiung City	22.64651 N, 120.2866 E	*A. marina,* *L. racemosa*	2.25
Linyuan	Kaohsiung City	22.49187 N, 120.38524 E	*A. marina*	1.00
Dapeng Bay	Pingtung County	22.44072 N, 120.48978 E	*A. marina,* *R. stylosa*	65.0
Qingluo	Penghu County	23.59801 N, 119.64755 E	*A. marina,* *L. racemosa*	2.61
Wujiang River Estuary	Kinmen County	24.42858 N, 118.31485 E	*A. marina,* *K. obovata*	4.20
Total				680.70

8 CARBON SEQUESTRATION CAPACITY AND STOCK OF COASTAL BLUE CARBON SYSTEMS IN TAIWAN

In general, mangroves show the highest areal values of carbon stock among the three coastal blue carbon ecosystems, followed by salt marshes and seagrass beds (Table 4). While the carbon sequestration rates of mangroves are also higher than those of other two blue carbon plants, the carbon sequestration rates of salt marsh plants and seagrasses are comparable. The carbon sequestration rate and stock of the invasive alien species *S. alterniflora* is much higher than those of other three salt marsh plants (Table 4). The carbon sequestration capacity of intertidal seagrasses is comparable to that of salt marsh plants. However, the carbon sequestration capacity of subtidal seagrasses is 2-3 times higher than that of intertidal seagrasses. The carbon stock of salt marshes is approximately 7-10 times higher than that of seagrass beds, particularly in the soil. The carbon sequestration rate of mangroves is approximately 3-5 times higher than that of salt marsh plants or seagrasses. The carbon stock of mangroves is 4 times higher than that of salt marshes and 30-40 times that of seagrass beds.

In Taiwan, tidal salt marshes cover a total area of 188 ha, with an annual carbon sequestration capacity of 3,661 mg C yr^{-1} and an existing carbon stock of 16,000 Mg C (Table 5). Seagrass beds (including intertidal and subtidal zones) have a total area of 5,481 ha, an annual carbon sequestration capacity of 80,619 mg C yr^{-1}, and an existing carbon stock of 144,444 mg C. According to the distribution area of mangroves in Taiwan inventoried by Lin et al. (2019), the carbon sequestration rate of mangroves in Taiwan is 11,183 mg C yr^{-1} and an existing carbon stock of 181,560 mg C.

The combined carbon sequestration capacity of the three coastal blue carbon ecosystems in Taiwan is 95,463 Mg C yr^{-1} or 350,030 Mg CO_2 yr^{-1}, and the existing carbon stock is 342,004 Mg C. If the invasive alien species *S. alterniflora* is removed from the habitats, the salt marsh carbon sequestration rate will be reduced by 3,617 Mg C yr^{-1} (3.8% reduction).

Table 4. Carbon sequestration rate and stock of major plant species and the soil of the three coastal blue carbon ecosystems in Taiwan.

Ecosystems	**Species**	**(a) Plant Carbon Sequestration Rate (Mg C ha^{-1} yr^{-1})**	**(b) Soil Carbon Burial Rate (Mg C ha^{-1} yr^{-1})**	**(c) Plant Carbon Stock (Mg C ha^{-1})**	**(d) Soil Carbon Stock (Mg C ha^{-1})**	**(e) Carbon Sequestration Rate (Mg C ha^{-1} yr^{-1}) =(a)+(b)**	**(f) Carbon Stock (Mg C ha^{-1}) =(c)+(d)**	**Sources**
Salt marshes	*Bolboschoenus planiculmis*	1.15	2.30	1.14	58.24	3.45	59.38	Lin, 2022
	Sporobolus virginicus	2.61	3.97	5.92	47.34	6.58	53.26	
	Phragmites australis	7.95	-2.15	11.05	65.27	5.80	76.32	
	Spartina alterniflora	16.20	8.13	13.04	78.85	24.33	91.89	
Intertidal seagrass beds	*Thalassia hemprichii* (late succession on sandy sediment)	2.84	0.09	1.16	8.52	2.93	9.69	Lin, 2022
	Halodule uninervis (early succession on sandy sediment)	5.06	0.09	0.39	8.52	5.15	8.91	
	Zostera japonica (early succession on mud sediment)	1.21	5.01	0.15	10.35	6.22	10.50	Lin, 2022; Zou et al., 2021
	Halophila beccarii (early succession on mud sediment)	5.16	-0.38	0.20	14.89	4.78	15.09	Lin, 2022
Subtidal seagrass beds	Dongsha subtidal seagrasses	13.43	1.30	2.90	23.49	14.73	26.38	Huang et al., 2015; Zou et al., 2021

Ecosystems	**Species**	**(a) Plant Carbon Sequestration Rate (Mg C ha^{-1} yr^{-1})**	**(b) Soil Carbon Burial Rate (Mg C ha^{-1} yr^{-1})**	**(c) Plant Carbon Stock (Mg C ha^{-1})**	**(d) Soil Carbon Stock (Mg C ha^{-1})**	**(e) Carbon Sequestration Rate (Mg C ha^{-1} yr^{-1}) =(a)+(b)**	**(f) Carbon Stock (Mg C ha^{-1}) =(c)+(d)**	**Sources**
Mangroves	*Kandelia obovata*	23.96	1.11	63.46	194.13	25.07	257.59	Lin, 2022; Li et al., 2018; Chou et al., 2022
	Avicennia marina	11.62	1.20	56.08	236.15	12.81	292.23	Lin, 2022; Li et al., 2018; Chou et al., 2022
	Lumnitzera racemosa	15.75	1.70	62.96	71.54	17.45	134.50	Lin, 2022
	Rhizophora stylosa	12.35	1.01	45.33	166.60	13.37	211.93	

(a)(b)(e) Positive values indicate a gain and negative values indicate a loss.

(d) The depth of soil carbon stock: salt marshes: 1 m, intertidal seagrass beds: 0.30 m, subtidal seagrass beds: 1 m, mangroves: 1 m.

Table 5. Carbon sequestration rate and stock of the coastal blue carbon ecosystems in Taiwan.

	Total Area (ha)	**Total Carbon Sequestration Rate (Mg C yr^{-1})**	**Total Carbon Stock (Mg C)**
Tidal salt marshes	188	3,661	16,000
Intertidal seagrass beds	11	53	129
Subtidal seagrass beds	5,470	80,566	144,315
Mangroves	681	11,183	181,560
Total	6,350	95,463	342,004

9 SUGGESTIONS FOR COASTAL BLUE CARBON SINKS IN TAIWAN

To mitigate global warming and achieve net zero emissions by 2050 in Taiwan, it is essential to increase the carbon sequestration and storage capacity of natural ecosystems. Coastal blue carbon systems are critical venues that sequester and store carbon. They not only help mitigate climate change, but may also provide numerous ecosystem services, such as coastal protection, water purification, nutrient cycling, fishing, and biodiversity enhancement (Lin et al., 2020b). The following improvement actions are suggested to reduce the uncertainty of coastal blue carbon sinks in Taiwan.

(1) More accurate estimation: At present, the data of blue carbon ecosystem inventories are limited by the accuracy of inventories of large areas, the investigation of subtidal seagrasses, the mixing growth of species, and the seasonal growth and decline of herbaceous plants (seagrass and salt marsh), which may have a greater impact on the area. When adopting GPS positioning and measuring the habitat of blue carbon ecosystems in the field, satellite imagery or drones can be used as a supplement due to the lack of access or large distribution area to obtain more accurate local distribution area and species composition status information. More real-time and accurate data from technologies such as satellite imagery or drones are also more suitable to assess the seasonal growth and decline of coastal vegetation.

(2) Subtidal zone survey: The research of subtidal seagrass carbon sinks is mainly limited by boat availability, diving operation technology, and instruments for GHG emissions. For example, when performing seagrass productivity labeling experiments in the Dongsha Atoll, boats may not be able to retrieve the marked seagrass plants at the same point every other week, hindering such experiments, so the seagrass productivity of Dongsha is considered a rough estimation (Lin & Hsiao, 2010). However, 99% of the seagrass beds in Taiwan are in the subtidal zone. The carbon sequestration rate and stock of subtidal seagrasses are also much higher than those of intertidal seagrasses.

(3) Greenhouse gas flux variation: Variation in GHG fluxes from the habitats of coastal blue carbon systems is often large (Li et al., 2018; Lin et al., 2020a; Yang & Yuan, 2019); however, mitigating GHG emissions can be a critical management strategy (Lin et al., 2021b). Feasible management methods can start from sewage prevention and control; organic sewage loading (particularly freshwater) should be avoided as much as possible from being flushing into coastal blue carbon ecosystems, so as to avoid the reduction of salinity in the organic-rich substrate, which might result in a large amount of carbon dioxide and methane emissions.

(4) Contribution of lateral transport and total alkalinity to carbon sinks: future inclusion of less studied lateral transport will be one of the focuses of more accurate estimates for blue carbon sinks, including the transport of particulate organic carbon (POC) and dissolved organic (DOC) and inorganic carbon (DIC) (Li et al., 2018). Tropical seagrass beds may have substrates with high calcium carbonate content (Zou et al., 2021). When acids released by seagrass roots dissolve the calcium carbonate in the substrate, total alkalinity is also exported (Chou et al., 2021). Therefore, based on the potential contribution of DIC and total alkalinity to seagrass carbon sinks, it is speculated that the carbon sink capacity of coastal blue carbon ecosystems in Taiwan is underestimated.

ACKNOWLEDGEMENTS

This study was financially supported by the "Innovation and Development Center of Sustainable Agriculture" from the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan.

REFERENCES

Chen, K. Y., & Lin, H. J. (2022). High-resolution mapping of seagrass biomass dynamics suggests differential response of seagrasses to fluctuating environments. *Diversity, 14*(11), 999. https://doi.org/10.3390/d14110999

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., & Lynch, J. C. (2003). Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles, 17*(4), 1111. https://doi.org/10.1029/2002GB001917

Chou, M. Q., Lin, W. J., Lin, C. W., Wu, H. H., & Lin, H. J. (2022). Allometric equations may underestimate the contribution of fine roots to mangrove carbon sequestration. *Science of The Total Environment, 833,* 155032. https://doi.org/10.1016/j.scitotenv.2022.155032

Chou, W. C., Fan, L. F., Yang, C. C., Chen, Y. H., Hung, C. C., Huang, W. J., Shih, Y. Y., Soong, K. Y., Tseng, H. C., Gong, G. C., Chen, H. Y., & Su, C. K. (2021). A Unique Diel Pattern in Carbonate Chemistry in the Seagrass Meadows of Dongsha Island: The Enhancement of Metabolic Carbonate Dissolution in a Semienclosed Lagoon. *Frontiers in Marine Science, 8,* 717685. https://doi.org/10.3389/fmars.2021.717685

Davidson, N. C., & Finlayson, C. M. (2019). Updating global coastal wetland areas presented in Davidson and Finlayson (2018). *Marine and Freshwater Research, 70*(8), 1195-1200. https://doi.org/10.1071/MF19010

Ho, C. W., Huang, J. S., & Lin, H. J. (2017). Effects of tree thinning on carbon sequestration in mangroves. *Marine and Freshwater Research, 69*(5), 741-750. https://doi.org/10.1071/MF17151

Howard, J., Hoyt, S., Isensee, K., Telszewski, M., & Pidgeon, E. (2014). Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. *International Union for Conservation of Nature (IUCN).*

Huang, Y. H., Lee, C. L., Chung, C. Y., Hsiao, S. C., & Lin, H. J. (2015). Carbon budgets of multispecies seagrass beds at Dongsha Island in the South China Sea. *Marine Environmental Research, 106,* 92-102. https://doi.org/10.1016/j.marenvres.2015.03.004

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., & Troxler, T. G. (eds.) (2014). 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. *Intergovernmental Panel on Climate Change (IPCC).*

Jørgensen, S. E. (Ed.). (2009). Ecosystem Ecology. First Edition, Academic Press.

Kilminster, K., McMahon, K., Waycott, M., Kendrick, G. A., Scanes, P., McKenzie, L., O'Brien, K. R., Lyons, M., Ferguson, A., Maxwell, P., Glasby, T., & Udy, J. (2015). Unravelling complexity in seagrass systems for management: Australia as a microcosm. *Science of the Total Environment, 534,* 97-109. https://doi.org/10.1016/j.scitotenv.2015.04.061

Ko, C. J. (2004). *A Taxonomic and Distributional Study of Seagrass in Taiwan.* [Master thesis, National Sun Yat-sen University], National Digital Library of Theses and Dissertations in Taiwan.

Kuwae, T., Watanabe, A., Yoshihara, S., Suehiro, F., & Sugimura, Y. (2022). Implementation of blue carbon offset crediting for seagrass meadows, macroalgal beds, and macroalgae farming in Japan. *Marine Policy, 138,* 104996. https://doi.org/10.1016/j.marpol.2022.104996.

Li, S. B., Chen, P. H., Huang, J. S., Hsueh, M. L., Hsieh, L. Y., Lee, C. L., & Lin, H. J. (2018). Factors regulating carbon sinks in mangrove ecosystems. *Global Change Biology, 24*(9), 4195-4210. https://doi.org/10.1111/gcb.14322

Lin, C. W., Kao, Y. C., Chou, M. C., Wu, H. H., Ho, C. W., & Lin, H. J. (2020a). Methane emissions from subtropical and tropical mangrove ecosystems in Taiwan. *Forests, 11*(4), 470. https://doi.org/10.3390/f11040470

Lin, C. W., Kao, Y. C., Lin, W. J., Ho, C. W., & Lin, H. J. (2021a). Effects of Pneumatophore Density on Methane Emissions in Mangroves. *Forests, 12*(3), 314. https://doi.org/10.3390/f12030314

Lin, H. J., Hsieh, L. Y., & Liu, P. J. (2005). Seagrasses of Tongsha Island, with descriptions of four new records to Taiwan. *Botanical Bulletin of Academia Sinica, 46*(2), 163-168. https://doi.org/10.7016/BBAS.200504.0163

Lin, W. J., Chiu, M. C., Lin, C. W., & Lin, H. J. (2021b). Effects of sediment characteristics on carbon dioxide fluxes based on interacting factors in unvegetated tidal flats. *Frontiers in Marine Science, 8.* https://doi.org/10.3389/fmars.2021.670180

Lin, H. J., & Hsiao, S. C. (2010). Investigation of macroalgae biomass, seagrass phenology and productivity in the Dongsha area. *Marine National Park Headquarters.*

Lin, H. J., Ho, C. W., & Chen, T. Y. (2019). Surveys on Mangrove Ecosystems. *Ocean Conservation Administration, Ocean Affairs Council.*

Lin, H. J., & Chen, T. Y. (2019a). Surveys on Seagrass Beds. *Ocean Conservation Administration, Ocean Affairs Council.*

Lin, H. J., & Chen, T. Y. (2019b). Report on the Impacts of Global Warming on Taiwan's Blue Carbon Ecosystems and Carbon Sinks. *Greenpeace.*

Lin, H. J. (2022). Surveys and Assessment of Important Coastal Carbon Sink Ecosystems in Taiwan. *Ocean Conservation Administration, Ocean Affairs Council.*

Lin, W. J., Wu, J., & Lin, H. J. (2020b). Contribution of unvegetated tidal flats to coastal carbon flux. *Global Change Biology, 26*(6), 3443-3454. https://doi.org/10.1111/gcb.15107

Liu, P. J., Lin, H. J., & Yang, M. D. (2018). Investigation of Seagrass Ecological Assemblage in Dongsha Atoll. *Marine National Park Headquarters.*

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Frontiers in Ecology and the Environment, 9*(10), 552-560. https://doi.org/10.1890/110004

Nordlund, L., Koch, E. W., Barbier, E. B., & Creed, J. C. (2016). Seagrass ecosystem services and their variability across genera and geographical regions. *PLoS One, 11*(10), e0163091. https://doi.org/10.1371%2Fjournal.pone.0163091

Pan, S. H., Ho, C. W., Lin, C. W., Huang, S. C., & Lin, H. J. (2021). Differential Response of Macrobenthic Abundance and Community Composition to Mangrove Vegetation. *Forests, 12*(10), 1403. https://doi.org/10.3390/f12101403

Polidoro, B. A., Carpenter, K. E., Collins, L., Duke, N. C., Ellison, A. M., Ellison, J. C., Farnsworth, E. J., Fernando, E. S., Kathiresan, K., Koedam, N. E., Livingstone, S. R., Miyagi, T., Moore, G. E., Nam, V. N., Ong, J. E., Primavera, J. H., Salmo III, S. G., Sanciangco, J. C., Sukardjo, S., Wang, Y., & Yong, J. W. H. (2010). The loss of species: mangrove extinction risk and geographic areas of global concern. *PLoS ONE, 5*(4), e10095. https://doi.org/10.1371/journal.pone.0010095

Rivera-Monroy, V. H., Lee, S. Y., Kristensen, E., & Twilley, R. R. (2017). Mangrove Ecosystems: A Global Biogeographic Perspective. Springer International Publishing AG, Switzerland.

Shao, G. J., Lin, H. J., Peng, J. Y., Jhang, S. W., Syu, Y. C., Luo, W. Z., Jhang, G. S., Fan, T. Y., Chen, T. R., Ciou, Y. W., Song, K. Y., & Cheng, Y. J. (2014). Surveys on Biodiversity of Taiping Island in the Spratly Islands of the South China Sea. *National Parks Division, Construction and Planning Agency, Ministry of the Interior.*

Short, F. T., Coles, R., Waycott, M., Bujang, J. S., Fortes, M., Prathep, A., Kamal, A. H. M., Jagtap, T. G., Bandeira, S., Freeman, A., Erftemeijer, P., La Nafie, Y. A., Vergara, S., Calumpong, H. P., & Makm, I. (2010). Halophila beccarii. *The IUCN Red List of Threatened Species 2010,* e. T173342A6995080.

Shih, S. S., Hsieh, H. L., Chen, P. H., Chen, C. P., & Lin, H. J. (2015). Tradeoffs between reducing flood risks and storing carbon stocks in mangroves. *Ocean & Coastal Management, 105,* 116-126. https://doi.org/10.1016/j.ocecoaman.2015.01.001

Wang, S. H., Fu, S. W., Deng, G. J., Hong, S. J., & Liao, S. Y. (2015). Changes in area and species composition of mangrove forests in Taiwan. *Taiwan Forestry, 41,* 47-51.

Wester, L., & Lee, C. T. (1992). Mangroves in Taiwan: Distribution management and values. *Geoforum, 23*(4), 507-519. https://doi.org/10.1016/0016-7185(92)90007-Q

Yang, L., & Yuan, C. S. (2019). Analysis of carbon sink effects for saline constructed wetlands vegetated with mangroves to treat mariculture wastewater and sewage. *Water Science and Technology, 79*(8), 1474-1483. https://doi.org/10.2166/wst.2019.145

Ye, C. Y. (2005). *Ecological study on salt marsh community on the coast of Taiwan.* [Master thesis, National Sun Yat-sen University].

Zou, Y. F., Chen, K. Y., & Lin, H. J. (2021). Significance of belowground production to the long-term carbon sequestration of intertidal seagrass beds. *Science of The Total Environment, 800,* 149579. https://doi.org/10.1016/j.scitotenv.2021.149579