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Oceanic Blue Carbon in Seas around Taiwan

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ABSTRACT

In order to mitigate the impacts of climate change, achieving carbon neutrality has become paramount. Previously, the estimation of negative carbon emissions was primarily focused on green carbon and yellow carbon. However, the oceans constitute one of the major global carbon pools, absorbing approximately 25-30% of the carbon dioxide from the atmosphere. Taiwan is committed to achieving net-zero carbon emissions by 2050, and the contribution of carbon absorption by the surrounding water cannot be overlooked. Therefore, this study aims to comprehensively review research on oceanic blue carbon (carbon sequestration or particulate organic carbon (POC) flux entering the bottom of the euphotic zone) sinks in Taiwan's territorial waters and exclusive economic zone. The results indicated that the carbon sequestration within Taiwan's territorial waters was 4.0±0.7 Mt-CO_2 yr^{-1}. Within the exclusive economic zone (EEZ), the carbon sequestration in the East China Sea, the northern South China Sea, and the western North Pacific Ocean were 49.3±14.9, 19.9±4.5, and 26.4±7.8 Mt-CO_2 yr^{-1}, respectively. In other words, carbon sequestration by deep-sea blue carbon can account for about 33.5% of annual carbon emissions in Taiwan, suggesting that deep-sea blue carbon cannot be ignored in order to achieve net-zero carbon emissions. Estimation uncertainty of oceanic blue carbon in seas around Taiwan can be affected by overlapping EEZs, lateral carbon transport, typhoons, mesoscale eddies, and internal waves, but detailed spatio-temporal investigations in seas around Taiwan are still needed.

Keywords: Biological carbon pump, Particulate organic carbon, Net zero carbon emissions, POC flux, Carbon neutrality, East China Sea, South China Sea, Pacific.

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1 INTRODUCTION

Climate change is a major problem for humanity due to its massive environmental impacts. Global warming can lead to rising sea levels, melting of glaciers, massive flooding and heat waves, biodiversity loss, and acidification of the oceans (Hsieh et al., 2021; Weerathunga et al., 2023), among other catastrophes (Urban, 2015). The increase in the average global temperature has been proportional to the increase in atmospheric CO_2 concentration (Deutch, 2020). The CO_2 concentration of ~400 ppm in 2020, created a warming of about 1.1°C more than pre-industrial times. However, climate science indicates that limiting global warming is still possible provided that carbon emissions drop significantly by 2030 and ultimately reach net zero. Recognizing the urgency of this matter, the 2015 Paris Agreement adopted the 1.5 °C target as a basis for global emissions reductions. Many countries and businesses have shown a clear commitment to reducing their carbon emissions to reach net-zero emissions by 2050 (Alrawahi et al., 2023). Net-zero emissions will be achieved when all emissions released by human activities are counterbalanced by removing carbon from the atmosphere in a process known as carbon capture. Low carbon initiatives toward a net-zero target have been emphasized in different parts of the world such as renewable energies, electric vehicles (Bonsu, 2020), energy-efficient buildings (Alrezaei et al., 2016), net-zero carbon cities (Seto et al., 2021), carbon taxation and emissions trading (Parry et al., 2022), and nature-based climate solutions (Seddon, 2022). However, the crucial role of oceanic blue carbon in mitigating climate change is yet to be determined.

The oceans, land and forests, and the atmosphere are the three major active carbon pools. The oceans account for 93%, the terrestrial ecosystem for 5%, and the atmosphere for only 2% (Friedlingstein et al., 2022). The oceans are a crucial carbon sink, compared to land and forests, which are capable of sequestering carbon in the twilight zone (200 ~ 1,000 m), the midnight zone (below 1,000 m), and deep-sea sediments (Gruber et al., 2023). There are primarily two mechanisms in the ocean that allow it to store carbon in deep seas and bottom sediments. The first mechanism is the physical carbon pump (Lévy et al., 2013), which involves the dissolution of carbon dioxide from the atmosphere at the ocean-atmosphere interface, which dissolves into the surface seawater (Figure 1). This process occurs due to the difference in partial pressure of CO_2 between the atmosphere and the surface seawater. This dissolved carbon dioxide moves downward slowly, aided by global thermohaline circulation, spreading from polar and high-latitude regions to the deep sea. The second mechanism is known as the "Marine Biological Pump," which mainly occurs in the euphotic zone and the twilight zone (Figure 1). It involves the photosynthesis of phytoplankton, where dissolved CO_2 is converted to particulate organic carbon (POC) (Longhurst & Harrison, 1989). Through the marine food chain, POC is transported to the deep sea in the form of marine biological debris, marine organism excreta, or marine snow. The biological pump is also the primary mechanism responsible for governing deep blue carbon (or POC flux, marine biological pump, and carbon sequestration in oceans, Figure 2).

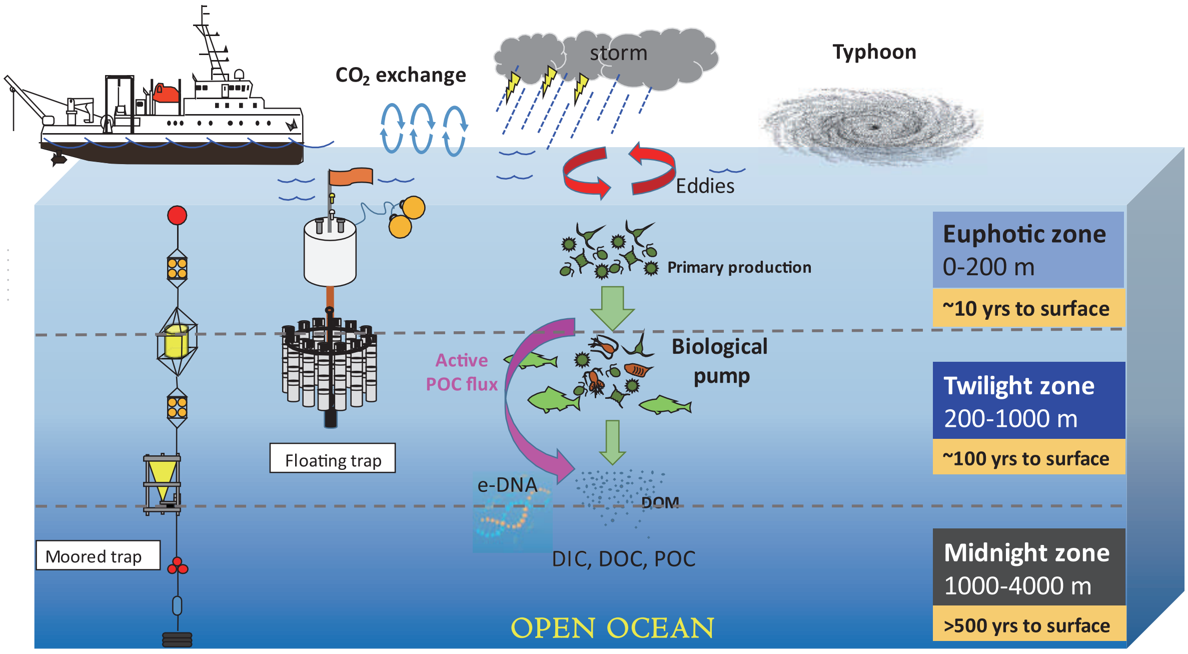

Figure 1. Schematic diagram showing the particulate organic carbon flux measured by floating sediment traps (left) deployed at the bottom of the euphotic zone (about 150 m) for at least 24 hours.

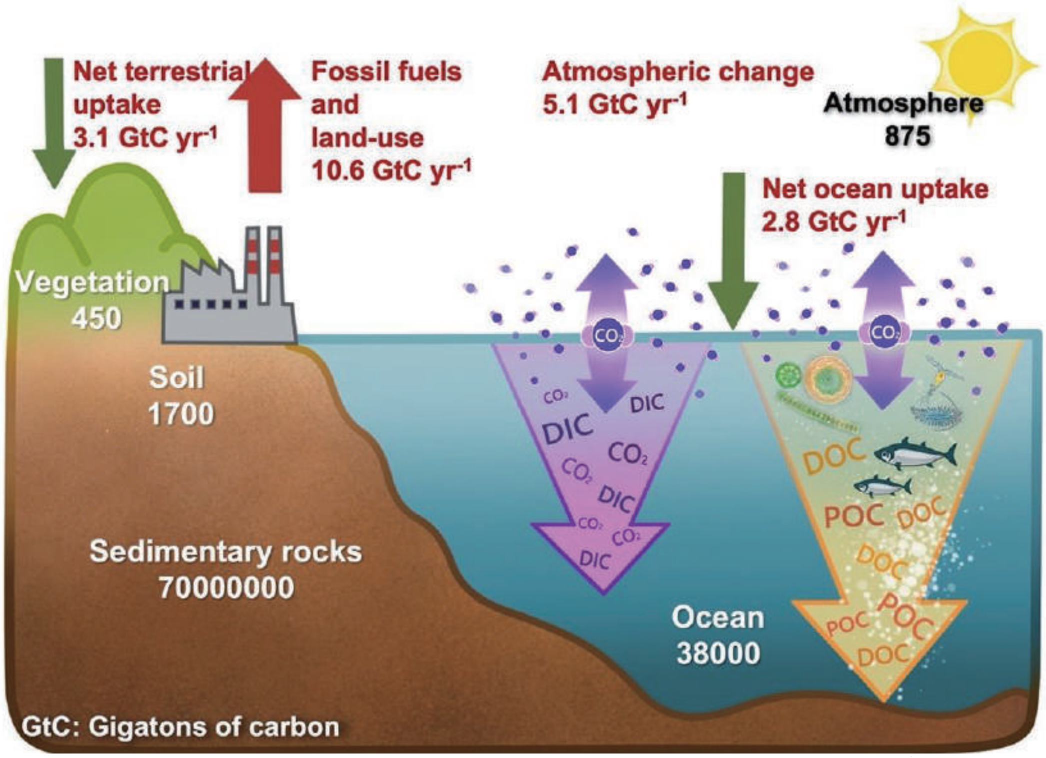

Figure 2. Global annual carbon emissions and carbon fluxes (red arrows) and reservoirs within land, atmosphere, and oceans. Carbon uptake by the oceans occurs primarily through biological pumps (yellow arrow) and physical pumps (purple arrow). The image was quoted from the CTCI Foundation, August 2022, and the datasets were from Friedlingstein et al., 2022.

The marine biological pump is an essential pathway for removing particulate carbon and nutrients from shallow marine waters. During the sinking process, these particles are decomposed by bacteria and recycled back to the surface water (Schlitzer, 2002). Approximately less than 10% of POC can be exported to the deep sea (depth greater than 1,000 meters), and only less than 1% of particles can truly settle to the seabed and be stored in sediments (Ducklow et al., 2001; Lutz et al., 2002). If the marine biological pump were to cease functioning, it is estimated that atmospheric carbon dioxide concentrations would increase by 50% approximately. Conversely, when the biological pump operates at its maximum efficiency, atmospheric carbon dioxide levels could potentially decrease by 50% (Buesseler et al., 2008; Sarmiento & Toggweiler, 1984; Parekh et al., 2006) (Figure 2). Therefore, the biological pump is considered to play a crucial role in marine blue carbon, and accurately estimating the export flux of marine blue carbon (i.e., POC export flux) has become an important issue (Hung et al., 2012). Currently, marine scientists primarily use sediment traps and natural radioactive tracers such as Th-234/U-238 disequilibrium methods to measure the carbon sink of marine blue carbon (POC flux) (Chen et al., 1986; Buesseler et al., 2000; Hung et al., 2010) (Figure 1).

Taiwan and many countries have claimed to be able to reach net carbon-zero emissions by 2050; however, it is a big challenge and difficult mission for many countries to reach carbon neutrality based on current carbon emissions and energy policy. Although lots of green energy, solar power, offshore wind power, green hydrogen energy, etc., have been proposed to be used or promoted globally, net-zero emissions are still not possible to reach based on current scientific carbon sources and sinks (Friedlingstein et al., 2022). Therefore, scientists have proposed many negative carbon sink approaches to reduce atmospheric CO_2 concentrations (Jiao et al., 2020), but these approaches need a long time to be tested or must provide evidence to run a large-scale experiment. Currently, the most important issue is to quantitatively estimate the natural baseline of carbon sinks on land, forests, and oceans for each country. Carbon sequestration by forests in Taiwan has been reported to be 21 million tons of CO_2 annually (EPA). A few investigations have been conducted on POC fluxes in the East China Sea (ECS), the South China Sea (SCS), the Kuroshio current, and the western North Pacific, but the open ocean blue carbon in seas around Taiwan remains unclear. This study aims to review POC fluxes (e.g., open ocean blue carbon) in seas around Taiwan and discuss their role in net-zero carbon emissions. Moreover, the study compared open ocean blue carbon to coastal blue carbon and green carbon by forests in Taiwan.

2 MATERIALS AND METHODS

2.1 Carbon sink datasets from exclusive economic zone (EEZ)

This review study focuses on the blue carbon sink in Taiwan's EEZ, including its territorial seas. The most reviewed POC flux dataset comes from the bottom of the euphotic zone because the deep sea serves as a natural "warehouse" and is the most effective "natural therapy" for mitigating climate change. Taiwan is located in the subtropical region surrounded by the Taiwan Strait, the ECS, the SCS, and the Northwest Pacific (Figure 3). The waters surrounding Taiwan, except for the shallow areas near the Taiwan Strait and the ECS along China, are generally deep, providing excellent conditions for large-scale natural carbon sinks in the ocean.

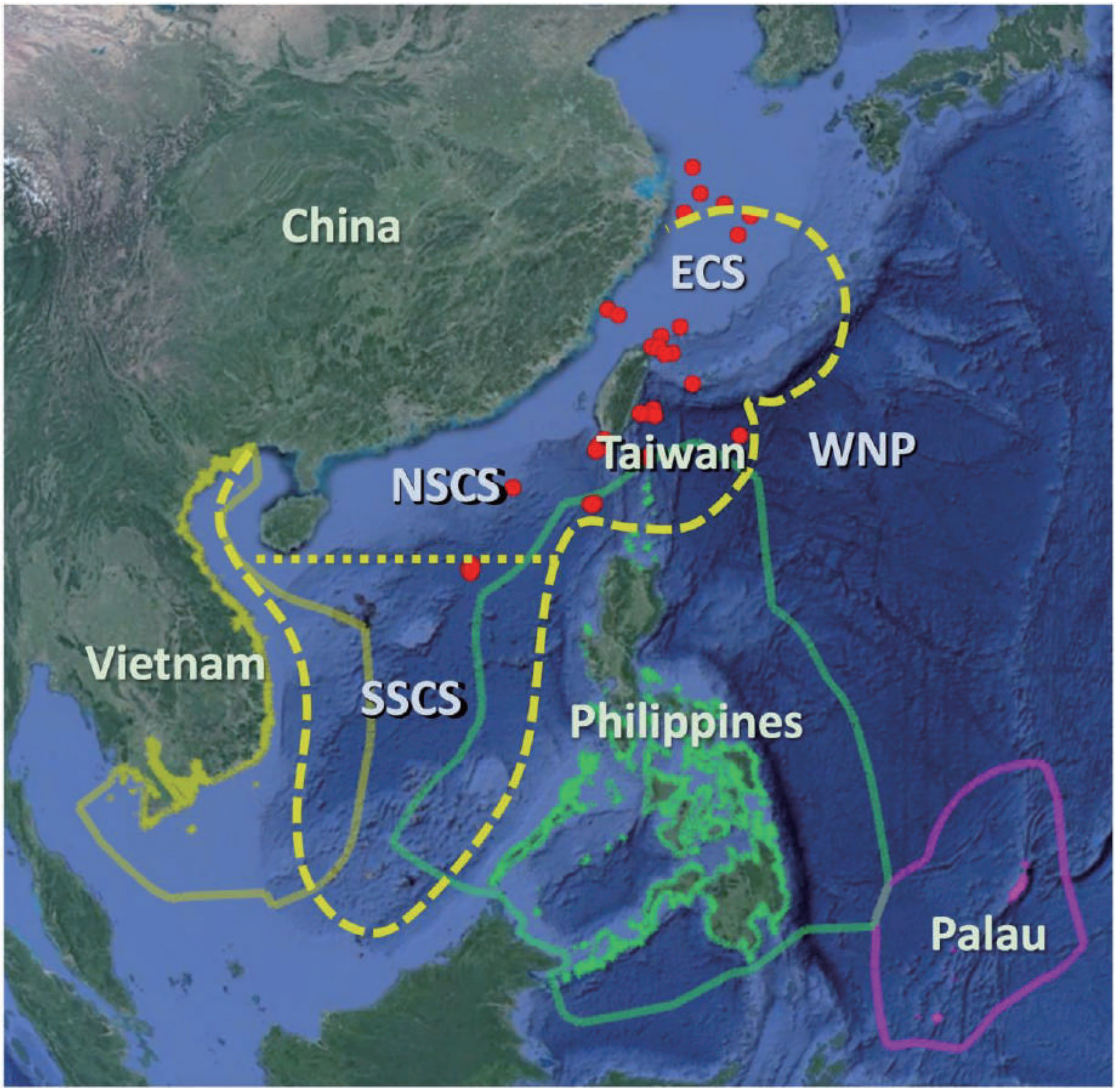

Figure 3. Marine biological pump sampling locations (red dots) within Taiwan's Exclusive Economic Zone (East China Sea (excluding Japan territorial waters in Okinawa islands), South China Sea, Western North Pacific Ocean) and Taiwan's territorial waters. Solid yellow, green, and pink lines represent the EEZ in Vietnam, Philippines and Palau, respectively. The dashed yellow line represents the EEZ of Taiwan.

Although the oceanic biological pump has been measured in Taiwan's territorial waters and EEZ for a long time, studying the marine biological pump is costly and time-consuming. As a result, POC fluxes in the past several decades are limited. Moreover, the overlapping maritime boundaries with neighboring countries and frequent typhoons passing through Taiwan's waters hinder data collection on the marine biological pump. Therefore, available data is used to compile and estimate the facts.

Previous literature reports on the biological pump data in the ECS, SCS, and Northwest Pacific were mainly measured using sediment traps. However, due to the vast extents of these three major regions and the inherent spatial and temporal variations of the biological pump, not every monitoring station has year-round data for all seasons. We should be aware of this and consider it as an area for further investigation.

3 RESULTS AND DISCUSSION

3.1 East China Sea

The ECS is a region with relatively high nutrient levels, leading to diverse marine ecosystems and abundant fishing grounds. The average marine biological pump in this area during spring, summer, autumn, and winter is estimated to be 77 ± 53, 80 ± 57, 148 ± 77, and 148 ± 83 mg-C m^{-2} d^{-1}, respectively (Hung et al., 2009, 2010, 2012, 2013; Chen et al., 2013; Hung and Gong, 2011) (Figure 4). Taiwan's territorial waters and EEZ in the ECS cover areas of 1.9×10^{10} and 3.3×10^{11} m^2, respectively.

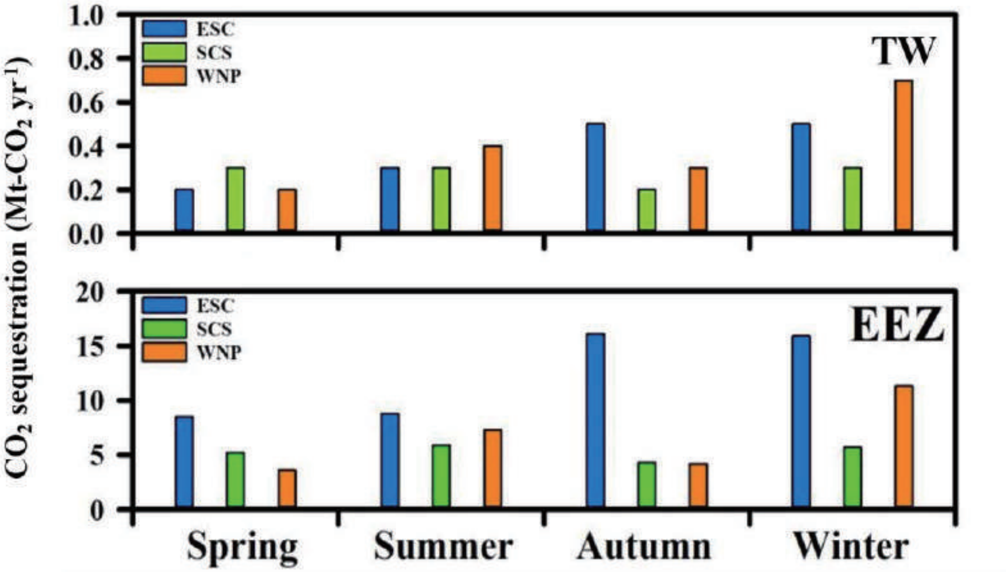

Figure 4. Seasonal CO_2 sequestration in Taiwan's territorial waters (TW) and EEZ in the Western North Pacific Ocean (WNP), East China Sea (ECS), South China Sea (SCS).

The estimated annual biological pump in Taiwan's territorial waters and EEZ of the ECS is approximately 2.8 ± 0.9 and 49.3 ± 14.9 Mt-CO_2 yr^{-1}, respectively. (Figure 4, 5) On the other hand, model-based estimates for carbon accumulation in the East China Sea shelf sediment suggest a yearly amount of about 7 - 10 Mt-C yr^{-1} (equivalent to 25.2 - 30 Mt-CO_2 yr^{-1}, Chen & Wang, 1999). Chou et al. (2009; 2011) estimated that CO_2 fluxes in the whole ECS in summer and winter were approximately 1.6~2.7 x 10^5 t-CO_2 and 8.7 x 10^5 t-CO_2 $month^{-1}$ in July and November using carbon chemistry parameters and the gas-exchange model. In other words, the model-based carbon sequestration in the ECS is approximately 20 Mt-CO_2 yr^{-1} lower than the average value obtained from our field measurements in Taiwan's EEZ (49.3 Mt-CO_2 yr^{-1}). Possible reasons for this discrepancy are (1) strong lateral carbon transport in the ECS, which carries organic carbon away from the shelf area to the open ocean, as reported by many researchers (Rosa, 1985; Bonnin et al., 2002; Heussner et al., 2006; Guo et al., 2010, Hung et al., 2013; 2016); (2) limited seasonal data from the middle shelf area of the ECS, despite our measurements covering seasonal variations in some regimes mainly on the southern ECS; and (3) constraints on surveying larger areas or hotspots due to practical issues, such as potential disputes with fishing vessels over the deployment of sediment traps.

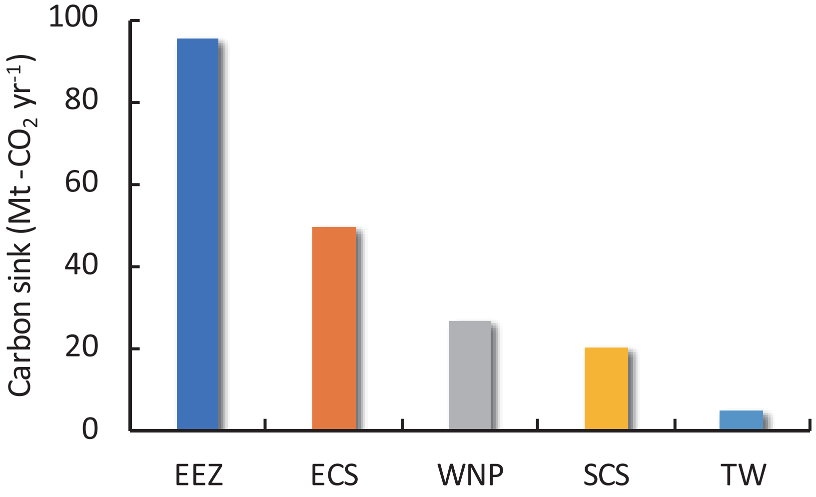

Figure 5. Carbon sink in Taiwan's territorial waters (TW), Western North Pacific Ocean (WNP), East China Sea (ECS), South China Sea (SCS) and the Total EEZ.

Moreover, the ECS is a typhoon-prone region, and summer and autumn expeditions are sometimes disrupted by typhoons, making data collection a challenge. In the future, frequent surveys and hiring fishing vessels to provide 24-hour supervision for floating sediment traps may be necessary in this high fishery activity area. Additionally, deploying short-term moored sediment traps might be considered a solution to the practical challenges during research in this region.

3.2 South China Sea

The South China Sea (SCS) is one of the largest oligotrophic marginal seas, with a maximum depth of below 3,000 meters. The average marine biological pump in this region during spring, summer, autumn, and winter is estimated to be 43 ± 20, 49 ± 28, 26 ± 24, and 48 ± 9 mg-C m^{-2} d^{-1}, respectively (Chen et al., 1998; Hung and Gong, 2010; Li et al., 2018; Shih et al., 2019, 2020a, 2020b; Wei et al., 2011; Zhou et al., 2013) (Figure 4). Taiwan's territorial waters and EEZ in the northern part of the SCS cover areas of 1.7×10^{10} m^2 and 3.6×10^{11} m^2, respectively. The estimated annual biological pump in the territorial waters and EEZ of the northern South China Sea (NSCS) is approximately 1.1 ± 0.2 and 19.9 ± 4.5 Mt-CO_2 yr^{-1} (Figure 5). This result clearly indicates that the biological pump in the NSCS is significantly lower than that in the ECS.

However, it is worth noting that the northern part of the SCS experiences large-scale internal waves from April to October each year, as reported by Li et al. (2018). These internal waves induce extensive algae blooms and greatly enhance the biological pump in the region. Additionally, Shih et al. (2020a) and other scholars have pointed out the presence of numerous mesoscale eddies in the NSCS. They found that these mesoscale eddies act as hotspots for the marine biological pump. Future research on the impact of mesoscale eddies and internal waves on the biological pump is worth exploring.

Regarding the exclusion of the southern part of the SCS in this data compilation, several reasons were considered: (1) The waters around Taiping Island in the southern South China Sea (SSCS) have numerous reefs, and different countries claim sovereignty over various islands, which could lead to diplomatic disputes if sediment traps drift into the waters claimed by other countries. (2) Some areas in this region have shallow water, and consideration was given to the safety of research vessel operations. (3) Sediment traps have fixed deployment depths, and after 24 hours at sea, they may drift from deep to shallow water, leading to the loss of the entire set of sediment traps. Overall, data on the biological pump in the SSCS is indeed very scarce, and the overlapping EEZs in this region are more complex compared to the ECS, making it impractical to include them in the calculations. Moreover, some areas of the SSCS have overlapped with the Philippines, Vietnam and other countries. Adequate judgment will be essential to address this intricate political problem in the future.

3.3 Western North Pacific Ocean

The western North Pacific is an oligotrophic open ocean, with a maximum depth exceeding 5,000 meters. The presence of the Kuroshio current, with ocean currents reaching 1-2 m s^{-1}, makes it challenging to deploy and retrieve sediment traps. Additionally, in the eastern offshore region of the Kuroshio current, the surface water is characterized by low chlorophyll concentrations, which may not be the focus of scientific interest. Expeditions in this region are less frequent, except during the summer typhoon season, when oceanographers or meteorologists are drawn to study the effects of typhoons on the marine environment. Consequently, data on the biological pump in this area is relatively limited (Figure 3), and there are few year-round datasets from a fixed location.

The marine biological pump in the western North Pacific during spring, summer, autumn, and winter is estimated to be 32 ± 5, 65 ± 68, 38 ± 0, and 103 ± 11 mg-C m^{-2} d^{-1}, respectively (Hung and Gong, 2007; Chuang, 2010; Hung et al., 2012; Chen et al., 2013; Shih et al., 2015) (Figure 4). Using the same approach as above, assuming these data represent seasonal variations, and considering Taiwan's territorial waters and EEZ in the western North Pacific, covering areas of 1.1×10^{10} m^2 and 3.3×10^{11} m^2, respectively, the estimated annual biological pump is approximately 0.8 ± 0.2 and 26.4 ± 7.8 Mt-CO_2 yr^{-1} (Figure 5).

Several points need to be emphasized: (1) The euphotic zone depth and nitracline depth in the western North Pacific are deeper than those in the ECS and the SCS, resulting in lower biological pump values per unit area during non-winter seasons. (2) The region is impacted by strong northeasterly monsoons after autumn, which leads to a shallower nutrient jump layer depth and favorable conditions for algae blooms, increasing the biological pump. However, stormy winter weather hinders data collection and exploration at sea. (3) According to Shih et al., this broad area contains significant mesoscale eddies, which are already known as hotspots for the marine biological pump (Shih et al., 2015). (4) Summer and autumn are active typhoon seasons in the western North Pacific, and typhoons significantly increase the marine biological pump (Hung et al., 2010; Shih et al., 2013). Therefore, the western North Pacific is another hotspot of interest for the biological pump. However, due to the challenges of sampling and the risks posed by adverse weather conditions, sediment trap deployments in this area need to utilize moored sediment traps. These traps can be deployed in mild weather from April to May and retrieved in September to October of the same year, with a new set of moored sediment traps simultaneously deployed to deal with rough sea conditions.

3.4 Carbon sequestration in Taiwan's EEZ

Due to data limitations and the inability to cover all important sampling sites in Taiwan's EEZ (including the ECS, the SCS, and the Northwest Pacific region) (Chen et al., 1998; Chen et al., 2013; Chuang et al., 2010; Hung & Gong, 2007, 2010, 2011; Hung et al., 2009, 2010, 2012, 2013; Li et al., 2018; Shih et al., 2015, 2019, 2020a, 2020b), based on the currently available data from the three major regions in the three seas, we estimated that Taiwan's EEZ's natural carbon sink is approximately 95.6 ± 31.3 Mt-CO_2 yr^{-1} (Figure 5). We did not have oceanic carbon flux values in adjacent countries such as the Philippines, Vietnam, and Palau. Herein, we adapted the mean POC flux (18.4 = (21.7+15.1)/2) ton-C km^{-2} yr^{-1}) in the WNP and NSCS representing the Philippines. We used the average POC flux (28.2 = (41.3+15.1)/2) in the NSCS (15.1 ton-C km^{-2} yr^{-1}) and the ECS (41.3 ton-C km^{-2} yr^{-1}) representing Vietnam. We adapted POC flux in the oligotrophic water in the WNP (7.3 ton-C km^{-2} yr^{-1}) representing Palau. As a consequence, the oceanic POC fluxes in the EEZs of the Philippines (1.97 x10^{6} km^{2}), Vietnam (0.75 x10^{6} km^{2}), and Palau (0.61 x10^{6} km^{2}), are 36.2, 21.1 and 4.5 M-ton C yr^{-1}, respectively. In other words, the CO_2 sequestration in the Philippines, Vietnam, and Palau will be 133, 78 and 16.5 Mt-CO_2 yr^{-1}. It is noted that Tuvalu (territory area ~25 km^{2}) is located in the South Pacific Ocean and its EEZ is approximately 0.75 x10^{6} km^{2}. If we use POC flux in the WNP (7.3 ton-C km^{-2} yr^{-1}) representing Tuvalu, the oceanic blue carbon in Tuvalu will be 20.3 Mt-CO_2 yr^{-1}. However, the EEZs of these countries have remarkably overlapped (except for Palau and Tuvalu), but this indeed suggests that oceanic blue carbon is quite important for most island countries or countries with huge EEZs. Nevertheless, these oceanic blue carbon values in these countries are urgent to be investigated in the future.

This estimation is primarily influenced by two sources of uncertainty. Firstly, the biological pump in the three seas may exhibit significant spatial and temporal variations due to natural phenomena such as typhoons, mesoscale eddies, phytoplankton nitrogen fixation, and internal waves. Secondly, the determination of EEZ boundaries involves complex issues of overlapping with neighboring countries. In this estimation, we have set aside the political and overlapping zone issues and defined the boundaries based on Taiwan's territorial waters' 200-nautical-mile zone, subtracting the territories and territorial waters of other countries within Taiwan's EEZ. As a result, the estimated EEZ area (10.2×10^{11} m^{2}) is larger than the provisional enforcement zone (1.8×10^{11} m^{2}).

Recently, Weerakkody et al. (2022) reported the biological pump in Taiwan's waters to be in the range of 59-130 Mt-CO_2 yr^{-1}, which is comparable to our estimated data of the biological pump in the three major seas (95.6 ± 31.3 Mt-CO_2 yr^{-1}). When comparing Taiwan's EEZ carbon sink with Taiwan's forest carbon sink (21.4 Mt-CO_2 yr^{-1}) and coastal blue carbon sink (0.34 Mt-CO_2 yr^{-1}), the EEZ's carbon sink is significantly larger. As mentioned in the introduction, the oceans are the largest active carbon reservoir in the Earth system, and this result is not surprising due to Taiwan's EEZ's larger area compared to its forest and coastal wetland areas.

While the status of deep-sea carbon sinks as "tradable carbon" is still debated, and a consensus on their precise definition has not yet been reached, a recent study by British scientists Barange et al. (2017) assessed the North Atlantic's biological carbon pump and estimated that its carbon sequestration and associated carbon cost would decrease due to ocean warming (Barange et al., 2017).

Combining all of Taiwan's forest carbon sink (21.4 Mt-CO_2 yr^{-1}), coastal blue carbon sink (0.34 Mt-CO_2 yr^{-1}) (Lin et al., 2023, this issue), Taiwan's territorial waters carbon sink (4.7 Mt-CO_2 yr^{-1}), and Taiwan's entire EEZ carbon sink (95.6 Mt-CO_2 yr^{-1}), the current total natural carbon sink for Taiwan is approximately 117.3 Mt-CO_2 yr^{-1} (Figure 6). Currently, Taiwan's carbon emissions are around 280-290 Mt-CO_2 yr^{-1}. In summary, for Taiwan to achieve carbon neutrality by 2050, without changing existing energy policies and effectively reducing carbon emissions from gasoline and diesel vehicles, and implementing other mitigation actions, Taiwan would need to increase its carbon sink by 172.7 Mt-CO_2 yr^{-1} to balance the current carbon emissions.

Besides spatiotemporal variation of POC flux and EEZ's areas, oceanic blue carbon (POC flux in open ocean) at a depth of 500 m has been used as a potential depth to estimate carbon sequestration (Jin et al., 2020) because these exported carbon can be sequestered in deeper water (> 500 m) for hundreds of years or more (Primeau, 2005; Palevsky and Doney, 2018). As a consequence, POC flux (>500 m) in seas around Taiwan may not reach 95 Mt-CO_2 yr^{-1} and it needs more studies in the future.

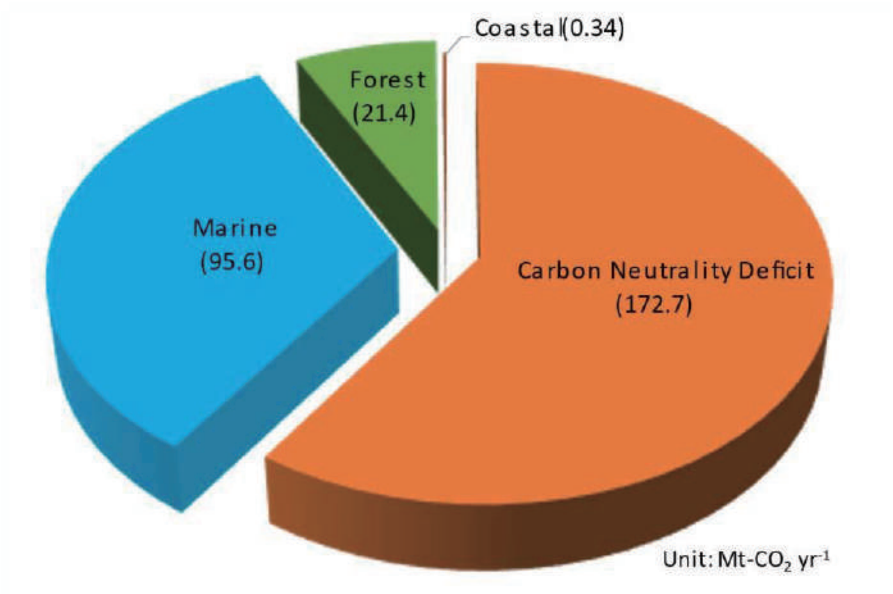

Figure 6. Schematic representation of Taiwan's carbon sink potential (Marine Blue Carbon Sink, Forest Carbon Sink, Coastal Blue Carbon Sink: 95.6, 21.4, and 0.34 Mt-CO$_2$ yr^{-1}, respectively) and Carbon Neutrality Deficit (172.7 Mt-CO$_2$ yr^{-1}).

3.5 Prospects of Taiwan's EEZ Carbon Sink

There is no doubt that Taiwan's EEZ has the largest carbon sink compared to coastal blue carbon (0.34 Mt yr^{-1}) (Lin et al., 2023) and forests (22.5 Mt yr^{-1}) in Taiwan (National Development Council, Taiwan, 2022; CTCI Foundation, 2022). Although there is more comprehensive data available for the ECS and SCS, the biological pump in these regions may have spatiotemporal variations and be influenced by natural phenomena such as typhoons, mesoscale eddies, and internal waves. Investigating the biological pump in these regions is crucial for future research. Moreover, it is urgent to know how much carbon can be stored in sediments in Taiwan's EEZ in the future.

To achieve carbon neutrality by 2050, Taiwan needs to increase its carbon sink capacity by at least 172.7 Mt-CO$_2$ yr^{-1} to balance the current carbon emissions. While the adoption of electric and hydrogen-powered vehicles and hydropower will reduce carbon emissions, there will still be a gap in electricity generation that cannot be solely filled by solar and wind power. Although shutting down coal-fired power plants can reduce some carbon emissions, natural gas power generation will still result in substantial carbon emissions. Various approaches such as ocean fertilization, artificial upwelling, alkalinity enhancement, and cultivating marine seaweeds can be employed to enhance oceanic carbon sequestration capacity (Figure 7), besides cutting carbon emissions in Taiwan via using electric cars, green energy such as solar power, offshore wind power, hydrogen gas and multiple industrially reducing carbon emission strategies (National Development Council, Taiwan, 2022; CTCI Foundation, 2022). The increase and decrease of these carbon emissions need to be carefully evaluated. Additionally, the extension or extended service of nuclear power plants (mainly concerning nuclear waste storage) is also a topic worthy of rational discussion, because it is able to reduce carbon emissions largely.

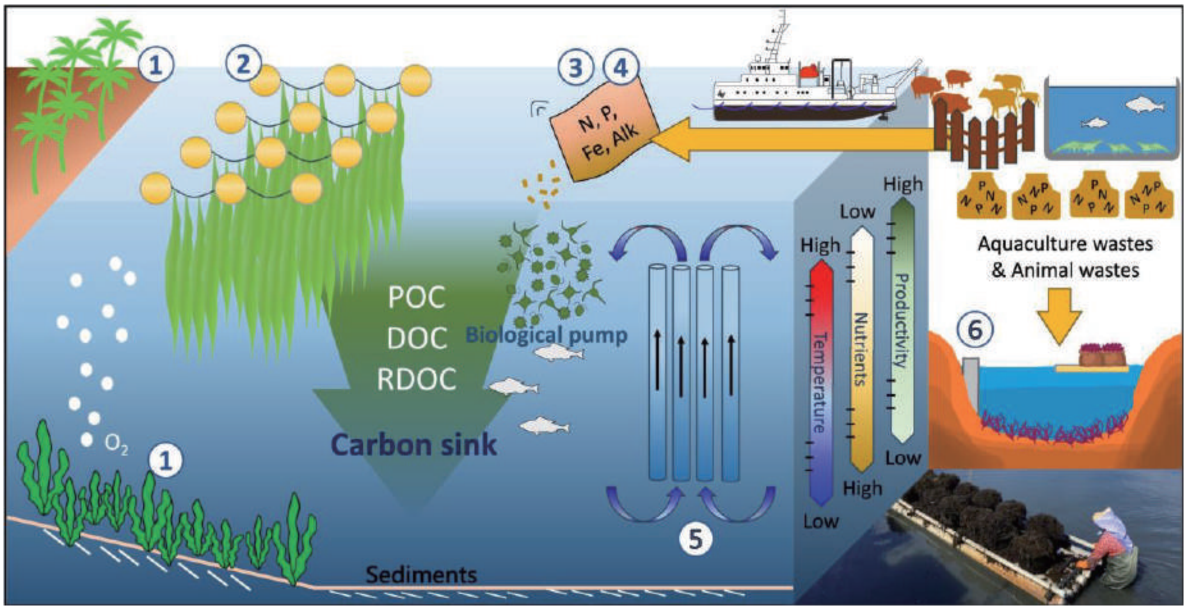

Figure 7. Potential marine carbon sequestration strategies. (1) Restoring coastal ecosystems, (2) marine macroalgae cultivation, (3) marine fertilization including sewage, aquaculture, and animal waste, etc., (4) alkalinity addition, (5) artificial upwelling, and (6) land-based macroalgae culture (redrawn from the CTCI foundation, August 2022). DOC: Dissolved organic carbon; RDOC: Refractory dissolved organic carbon.

Furthermore, recent research indicates that wild seaweed beds may play an important role in carbon sinks likely transporting POC and DOC to deep waters (Duarte, 2017, Watanabe et al., 2020). In fact, Weerakkody et al. (2022) conducted red seaweed, *Sarcodia suae,* experiments in six-ton FRP tanks in southern Taiwan, and found that the carbon capture rate of *Sarcodia suae* is double that of Da'an Forest Park in Taipei. This suggests that if suitable native large-scale seaweed species can be developed in Taiwan's waters, combined efforts from industry, government, and academia can result in large-scale aquaculture in coastal and nearshore areas or off-island areas, providing an opportunity for significant carbon sequestration (Figure 7). The sources of growth nutrients (mainly nitrogen and phosphorous) can be considered to use sewage treatment plants, aquaculture and swine wastewaters since Taiwan has an intensive aquaculture industry and 5~6 million hog heads every year (Tsai, 2018).

4 CONCLUSIONS

The estimated carbon sink in Taiwan's EEZ is a nature-based carbon sink. These preliminary assessment datasets provide the public with an understanding of Taiwan's current carbon sink potential in seas around Taiwan. It shows that Taiwan has significant space and resources for utilizing the ocean to increase carbon sequestration. Urgent action is needed to systematically evaluate the baseline of oceanic carbon sinks in seas around Taiwan and other countries. In addition, Taiwan has an abundance of ocean territorial waters that are suitable for conducting local seaweed farming in different seasons and alkalinity additions in some coastal regions in Taiwan. In some nearshore waters, nutrient supply for large-scale seaweed farming can be provided by sewage treatment plants, aquaculture, and swine wastewater in Taiwan.

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