Chapter 11
CO_2 Uptake in the Shallow Coastal Ecosystems Affected by Anthropogenic Impacts

Tomohiro Kuwae, Jota Kanda, Atsushi Kubo, Fumiyuki Nakajima, Hiroshi Ogawa, Akio Sohma, and Masahiro Suzumura

Abstract Shallow coastal ecosystems (SCEs) are generally recognized as not only significant organic carbon reservoirs but also as sources for CO_2 emission to the atmosphere, thus posing a dilemma regarding their role in climate change mitigation measures. However, we argue that SCEs can act as sinks for atmospheric CO_2 under a given set of biogeochemical and socioeconomic conditions. The key properties of SCEs that show net uptake of atmospheric CO_2 are often characteristic of human-dominated systems, that is, high nutrient inputs from terrestrial systems, input of treated wastewater in which labile carbon has been mostly removed, and the presence of hypoxic waters. We propose a new perspective on the potential of human-dominated SCEs to contribute to climate change mitigation, both serving as

T. Kuwae (✉)
Coastal and Estuarine Environment Research Group, Port and Airport Research Institute, Yokosuka, Japan
e-mail: kuwae@p.mpat.go.jp

J. Kanda
Department of Ocean Sciences, Tokyo University of Marine Science and Technology, Minato-ku, Tokyo, Japan

A. Kubo
Department of Geoscience, Shizuoka University, Suruga-ku, Shizuoka-Shi, Shizuoka-Ken, Japan

F. Nakajima
Department of Urban Engineering, The University of Tokyo, Bunkyo-ku, Tokyo, Japan

H. Ogawa
Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwanoha, Kashiwa-shi, Chiba, Japan

A. Sohma
Graduate School of Engineering, Osaka City University, Sugimoto, Sumiyoshi-ku, Osaka, Japan

M. Suzumura
National Institute of Advanced Industrial Science and Technology, AIST Tsukuba West, Tsukuba, Japan

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carbon reservoirs and providing direct net uptake of atmospheric CO_2, in light of human systems–ecosystem interactions. Namely, if we view the land and a SCE as an integrated system, with appropriate management of both wastewater treatment and SCE, we will be able to not only suppress CO_2 release but also capture and store carbon.

11.1 Introduction

Recent research has demonstrated that the sediment of shallow coastal ecosystems (SCEs), such as mangroves, salt marshes, tidal flats, seagrass meadows, estuaries, and embayment, is important as a marine carbon reservoir (e.g., Nellemann et al. 2009; McLeod et al. 2011; Fourqurean et al. 2012; Duarte et al. 2013; Miyajima et al. 2015, 2017; Endo and Otani 2018; Inoue 2018; Miyajima and Hamaguchi 2018). Moreover, coastal ecosystems with high primary productivity, such as seagrass meadows, can serve as net sinks for atmospheric CO_2 (i.e., total CO_2 uptake minus total CO_2 release is positive; Smith 1981; Tokoro et al. 2014).

From the viewpoint of mitigating climate change, the net uptake of atmospheric CO_2 through the exchange of CO_2 at the air–water interface is a direct process, whereas the suppression of CO_2 emission to the atmosphere by carbon storage in the marine ecosystem is an indirect process (Fig. 11.1). Although these are two completely different processes, both are effective for mitigating climate change. There is controversy as to which is more important, but ecosystems that show both net uptake of atmospheric CO_2 and long-term storage of carbon are desirable.

However, because ecosystems are dynamic natural systems characterized by complex fluctuations in biological communities and environmental conditions, atmospheric CO_2 uptake and carbon storage do not occur at constant rates. The CO_2 gas exchange at the air–water interface fluctuates through absorption and emission phases and the amount of carbon stored in the ecosystem increases and decreases over time (Tokoro et al. 2014, 2018). Therefore, in considering the effectiveness of ecosystem-based technology measures such as mitigation of climate change through the use of blue carbon ecosystems, setting a specified time and space of interest in advance is important to judge whether atmospheric CO_2 is taken up or whether carbon is stored. As the temporal and spatial scales of the processes increase, the measure becomes more effective and more reliable.

The effect of human activity cannot be ignored at longer time scales. The geophysical setting of SCEs is often at the boundary between land and sea, making them socioeconomically important features. As a result, the carbon cycle of many SCEs has changed significantly over time due to the load of nutrients and organic matter (green carbon), freshwater use, and topographic modification (Bauer et al. 2013; Regnier et al. 2013). In particular, because nutrient loading and wastewater

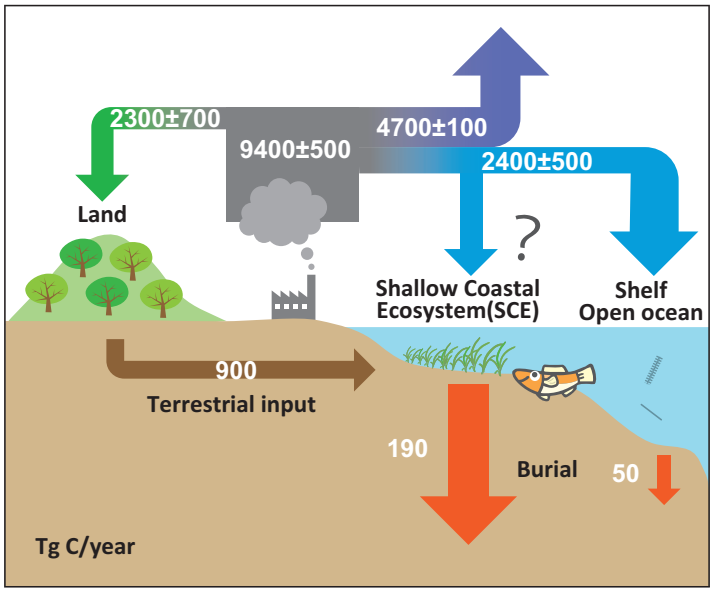

Fig. 11.1 Global carbon cycling. See Le Quéré et al. (2018) for atmosphere data (mean ± SD for 2007–2016), Nellemann et al. (2009) for the sedimentary accumulation rate, and IPCC (2013) for terrestrial input. SCE sediments accumulate 190 million tonnes of carbon (Tg C) every year, much faster than sediments in shelves and the open ocean

treatment have large impacts on the cycling of biogeochemical elements (e.g., carbon, nitrogen, and phosphorus) in the ecosystem (McIntyre et al. 2000), they may also have an impact on the uptake of atmospheric CO_2 and carbon storage within the ecosystem.

In comparison with the open ocean and shelves, SCEs are hotspots with a high rate of carbon accumulation to the sediment, although few measurements of CO_2 exchange at the air–water interface have been conducted, highlighting SCEs as largely unexplored places (but see Borges et al. 2005; Cai 2011; Chen et al. 2013; Laruelle et al. 2013; Regnier et al. 2013; Akhand et al. 2018; Otani and Endo 2018; Tokoro et al. 2018; Watanabe and Nakamura 2018). SCEs are characterized by diverse biogeochemical cycles and biota. Their complexity reflects their position at the boundaries between air and water, water and sediment, and atmosphere and sediment, with very different physical properties (such those of fresh water and salt water) and with rapid exchange rates at the interfaces. Thus, the estimation of carbon stock and flow in SCEs is highly uncertain compared to that in other ecosystems. In this chapter, we discuss the potential for climate change mitigation by SCEs that have been strongly affected by human impacts for a long time.

11.2 CO_2 Uptake and Carbon Storage in SCEs

11.2.1 Relationship Between Carbon Storage and CO_2 Uptake

The essential functions required when considering mitigating climate change by utilizing blue carbon ecosystems are storing carbon (Miyajima and Hamaguchi 2018) and subsequently suppressing CO_2 emission to the atmosphere, net direct atmospheric CO_2 uptake (Tokoro et al. 2018), or both. However, SCEs are generally recognized to be net emitters of CO_2 to the atmosphere (Borges and Abril 2011), due to the fact that the water generally contains a large amount of CO_2 and organic green carbon inflowing from terrestrial sources (Laruelle et al. 2013; Regnier et al. 2013) (Fig. 11.2). Indeed, when summarized based on salinity, it is clear that those SCEs more influenced by fresh water and with lower salinity are greater sources of CO_2 (Fig. 11.3).

In any case, if we look at this carbon flow from the viewpoint of climate change mitigation, we note that SCEs have a positive function of storing organic carbon and a negative function of being a net source of CO_2 to the atmosphere. The dilemma of

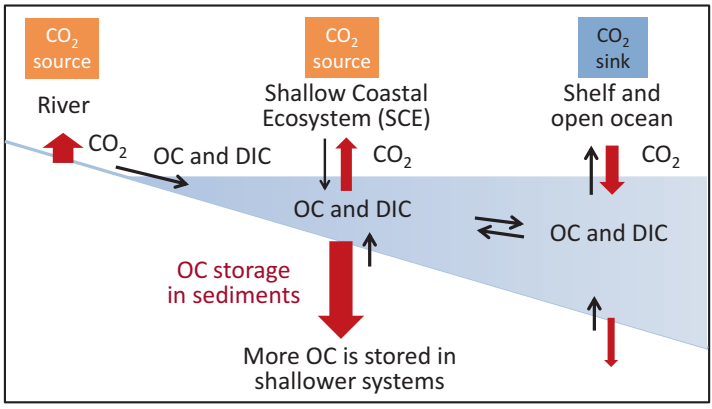

Fig. 11.2 Conventional findings on air–water CO_2 exchange and carbon storage in each marine geographic region. *OC* organic carbon, *DIC* dissolved inorganic carbon

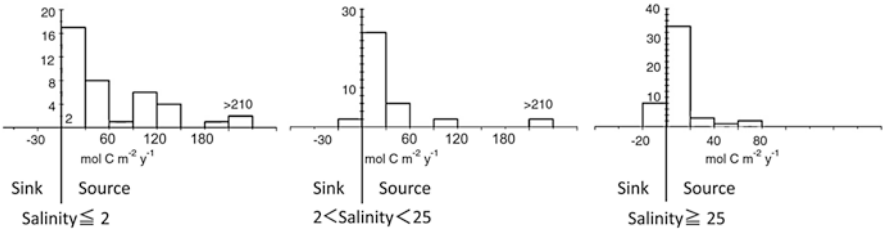

Fig. 11.3 Relationship between salinity and air–water CO_2 exchange in SCEs. Those SCEs with lower salinity emit more CO_2. (Modified from Chen et al. 2012)

"storing carbon but emitting CO_2" occurs because water intervenes between the sediment (the main pool of carbon) and the atmosphere. Similarly, this dilemma can also occur in inland waters such as lakes and rivers (Cole et al. 2007). In turn, in a forest or grassland ecosystem not interrupted by water, the same amount of carbon taken up from the atmosphere is stored in organisms and/or in the soil, assuming a closed system. Because of this, the dilemma has not been specifically discussed in terrestrial ecosystems. In reality, however, terrestrial ecosystems are also open systems, as large amounts of green carbon flow out of these ecosystems through rivers and into the sea (Fig. 11.1). Therefore, in forest and grassland ecosystems, the amount of net CO_2 uptake is larger than the amount of organic carbon stored.

11.2.2 Carbon Storage in SCEs

Among the various processes that influence carbon storage in SCEs, the major ones supporting the high accumulation of organic carbon in the sediment include (1) large supplies of autochthonous organic matter (i.e., blue carbon formed within SCEs) and/or allochthonous organic matter (green carbon flowing in from terrestrial sources and/or blue carbon flowing from outside the SCE); (2) a large supply of mineral particles, which are the main component of the sediment (Sholkovitz 1976); and (3) aggregation of the mineral particles and organic matter to promote sedimentation (Kennedy et al. 2010; Zonneveld et al. 2010).

The seabed of SCEs where carbon is deposited is also dynamic. Due to external forcing by waves and currents, the sediment surface layer is disturbed, its thickness varies, and the seabed topography changes. For example, erosion at the sea bottom implies outflow of sedimentary mineral particles and carbon from the sediment surface. In turn, when the waves and currents near the seabed are calm, the sediment and carbon accumulation rates increase. Furthermore, in such calm physical conditions, fine sediment particles are more easily deposited and organic matter adsorbs to the fine particles, often resulting in the formation of muddy sediments where much carbon is stored.

Decomposition of organic matter becomes slower after deposition on the sea bottom. This is related to the anoxic environment of the sediment except for its vast surface layer (e.g., about the top several millimeters in a muddy sediment). Because terrestrial soil is aerobically decomposed by exposure to oxygen from the air, its decomposition proceeds on a scale of decades, whereas in the anaerobic environment of the seabed, organic matter is decomposed and mineralized over thousands of years (Chambers et al. 2001). This suppression of the decomposition rate promotes accumulation of organic matter at the seabed (Miyajima and Hamaguchi 2018).

Vegetated SCEs such as mangroves, salt marshes, and seagrass meadows have among the fastest rates of carbon storage to their sediments, with average values ranging from 138 to 226 g C/m^2/year (range: 18–1713 g C/m^2/year); the rates are at least 1000 times greater than that in the open ocean (0.018 g C/m^2/year)

(Nellemann et al. 2009; McLeod et al. 2011). This difference cannot be explained solely by the difference in the production rate of blue carbon (SCE: 1044–2784 g C/m^2/year, open ocean: 120 g C/m^2/year; Gattuso et al. 1998). Rather, the existence of vegetation slows water currents and promotes the trapping and sedimentation of suspended particulate organic matter, causing an increase in the carbon accumulation rate (Hendriks et al. 2007; Kennedy et al. 2010).

Other factors also influence the carbon storage rate in SCEs, as explained in Chap. 2 (Miyajima and Hamaguchi 2018). These include chemical factors such as the quality (e.g., whether it is easy or difficult to decompose) of organic matter supplied and degradation enzyme activity; geophysical factors such as temperature, water depth, and the grain size and surface area of the sediment (Miyajima et al. 2017); and biological factors such as bioturbation (Zonneveld et al. 2010; Koho et al. 2013).

11.2.3 Requirements for a SCE Becoming a Net Sink of Atmospheric CO_2

As we explained, the carbon storage rate in aquatic ecosystems is not equal to the net atmospheric carbon uptake rate because these are open systems in which water intervenes between the sediment and atmosphere. In addition, the inorganic–organic conversion in the water column is complex. As a result, the amount of material exchanged at the air–water interface and that exchanged at the water–sediment interface generally do not balance.

Gas exchange between the atmosphere and the ocean occurs at the air–water interface. If the concentration of CO_2 in seawater is lower than that in air, then atmospheric CO_2 will be absorbed into the sea (Wanninkhof 1992). Currently, the atmospheric CO_2 concentration fluctuates from about 350 to 450 ppm; in turn, the CO_2 concentration in SCE surface waters ranges from about 20 ppm to more than 3000 ppm. Thus, the actual gas exchange rate and direction of the flux (i.e., whether the ecosystem is a sink or a source of CO_2) are dependent on the CO_2 concentration in the surface water.

The CO_2 concentration in the surface water becomes undersaturated and atmospheric CO_2 is taken up (1) if the CO_2 concentration in the influent water from outside the target area is lower than that of the atmosphere, or (2) if the concentration decreases below the atmospheric concentration due to the occurrence of processes lowering the CO_2 concentration in the surface water. Rivers are major CO_2 influents from outside SCEs, and their CO_2 concentrations are high. The partial pressure of CO_2 in more than 95% of global inland waters is higher than that in the air, with a median value of about 3100 μatm (Raymond et al. 2013). Thus, in order for the surface water of SCEs to be undersaturated, it is necessary to have a process that lowers the CO_2 concentration in surface water. As explained in Chap. 6, such processes include decreasing temperature, increasing total alkalinity (Ca^{2+} and NO_3^-

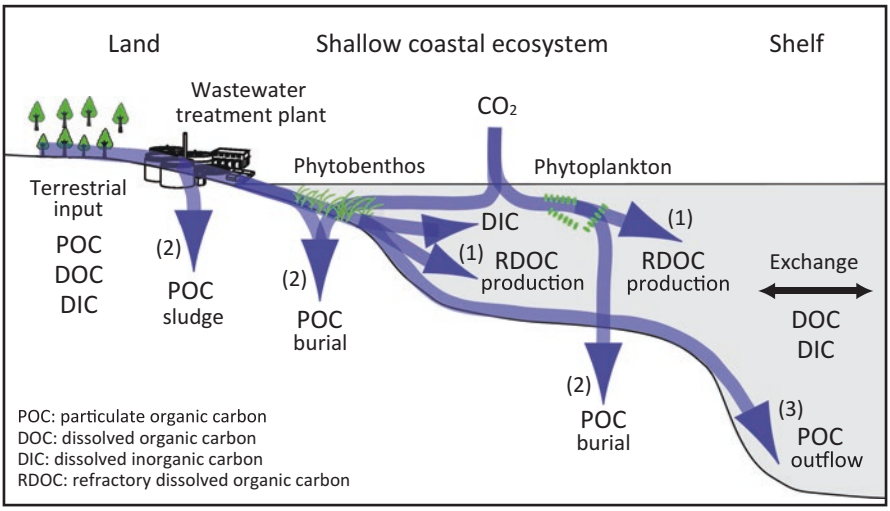

Fig. 11.4 Conceptualized diagram of carbon flow contributing to net uptake of atmospheric CO_2 in SCEs. We assume that net uptake of atmospheric CO_2 occurs only when there is a unidirectional carbon flow (pump) over a long period of time, resulting in the water CO_2 concentration being lower than the atmospheric CO_2 concentration. The net uptake of atmospheric CO_2 occurs when (1) CO_2 emission is suppressed by generation of refractory dissolved organic carbon (RDOC); (2) precipitation and burial of particulate organic carbon (POC); and (3) transportation of POC and DOC to the deep sea. Although the wastewater treatment plant that removes POC (sludge) indirectly contributes to lowering the CO_2 concentration in the SCE, the treatment plant functions as a CO_2 emitter because organic matter in the wastewater is decomposed and CO_2 is generated in the open aeration tank. (Modified from Kuwae et al. 2016)

concentrations are the main ions that determine total alkalinity), and net uptake of CO_2 by organisms (Tokoro et al. 2018).

The environmental conditions that result in the uptake of CO_2 are not continuous in the natural world. In reality, as environmental conditions such as light, temperature, and salinity change from moment to moment, cycles of uptake and emission occur frequently (Tokoro et al. 2014, 2018). In other words, it is critical to take a long-term view of the balance of uptake and emission as we discuss an ecosystem contributing to the mitigation of climate change. The requirements for SCEs serving as long-term net sinks are conceptualized in Fig. 11.4. Overall, the system can also be viewed as a process of transporting carbon like a pump; that is, the carbon transport is unidirectional from the viewpoint of the long-term balance. This type of pump is well-known in the field of marine science: "biological pump" in the open ocean (Longhurst and Harrison 1989) and "continental shelf pump" in shelves (Tsunogai et al. 1999).

Among the various unidirectional pumps, those particularly important for the net uptake of atmospheric CO_2 are (1) formation of refractory dissolved organic carbon (RDOC); (2) particulate organic carbon (POC) being conveyed to the sea bottom and stored in the sediment (Miyajima and Hamaguchi 2018); and (3) POC and

dissolved organic carbon (DOC) export (Sugimatsu et al. 2015; Abo et al. 2018). Although the components of RDOC and the reasons for the refractory properties are still not fully understood, Arrieta et al. (2015) proposed that RDOC has a molecular or physical structure (unspecified) that is difficult for bacteria to use, or its concentration is too low to be available for bacteria. Because these three pumps tend to not flow in reverse (i.e., the opposite process is weak), they function to suppress both the decomposition of organic matter and the emission of CO_2 to the atmosphere over a long period.

11.2.4 Carbon Storage in Water and Organisms

Of the three requirements for a net long-term CO_2 sink (Fig. 11.4), the storage of RDOC in water is the least understood (Jiao et al. 2014). The organic carbon pool is not limited to sediments and organisms but can be in the water column as well if only the DOC is refractory. DOC accounts for 28% (246 Tg C/year) of the total green carbon flowing from rivers to oceans on the global scale (Cai 2011). Thus, how much DOC decomposes in microbial and photochemical reactions (Moran et al. 2000), how much DOC remains as refractory dissolved green carbon (Kubo et al. 2015), and how much refractory dissolved blue carbon is newly formed at the site can be major factors determining the amount of CO_2 uptake and emission.

Among them, new formation of refractory dissolved blue carbon is particularly unclear. Phytoplankton, bacteria, macrophytes (seagrasses and seaweeds), and corals are organisms responsible for the formation of refractory dissolved blue carbon (Ogawa et al. 2001; Wada et al. 2008; Kragh and Søndergaard 2009; Lønborg et al. 2009; Tanaka et al. 2011a, b). From a technical perspective, however, it is extremely difficult to quantify refractory dissolved blue carbon separately from refractory dissolved green carbon because the concentration of DOC is low and salt in seawater acts as an inhibitor in the chemical analysis.

The sequence of (1) uptake of CO_2 by macrophytes and phytoplankton, (2) production of their body (POC) and mucus (DOC), and (3) transportation and sinking of POC and DOC in the deep ocean is also an important mechanism for carbon storage. Even if POC and DOC get decomposed in the deep ocean and become CO_2, the transport to the surface and return to the atmosphere occur over geological time scales. According to recent reports, the global estimate of POC and DOC derived from seagrasses transported from SCEs to the deep ocean is about 24 Tg C/year (Duarte and Krause-Jensen 2017) and that derived from kelps is around 36–279 Tg C/year (Krause-Jensen and Duarte 2016). However, the variability in these amounts and the factors controlling their transport are still unknown, leading to high uncertainty in the estimates.

11.3 Hypothesis that Human-Impacted SCEs Act As a Net CO_2 Sink

Strong human impacts can result in changes to the carbon cycle (McIntyre et al. 2000). In particular, nutrient load, wastewater treatment, and freshwater use will increase with increasing human and livestock populations and farmland area. As a result of human impacts, the cycling of green carbon and blue carbon related to climate change mitigation, such as CO_2 exchange between the atmosphere and water and carbon storage in SCEs, is affected (Table 11.1).

Kuwae et al. (2016) hypothesized that some characteristics of SCEs subject to human impacts actually strengthen the carbon cycling structure that supports the net uptake of atmospheric CO_2 (net CO_2 sink; Fig. 11.5). This idea is likely to be controversial, because urban coastal waters are seen as places where eutrophication progresses and a large amount of CO_2 is emitted by decomposition of organic matter. In this section, we explain why a human-impacted SCE functions as a sink of atmospheric CO_2 from a mechanistic perspective and provide empirical evidence from previous studies.

11.3.1 Wastewater Treatment

Urban and agricultural nutrient loading and wastewater treatment have a major influence on a SCE's biogeochemical cycling (Grimm et al. 2008; Kaushal and Belt 2012). The following two points are particularly relevant to air–seawater CO_2 gas exchanges and wastewater treatment. First, in the most common wastewater treatment method (i.e., the activated sludge method), carbon is removed more efficiently than nitrogen and phosphorus from wastewater (e.g., Sedlak 1991). Hence, the treated water has relatively less carbon than nitrogen and phosphorous. When such treated water flows into a SCE, primary production is promoted due to the abundant nutrients, while decomposition and mineralization are suppressed by less abundant organic carbon. This means that wastewater treatment suppresses the rise in CO_2 concentration in the water column of a SCE.

The second important point is that organic matter in the treated water is refractory (Kubo et al. 2015), because labile organic matter has already been decomposed and removed during wastewater treatment. Therefore, further decomposition and mineralization of the organic matter contained in the treated water is slow, resulting in suppression of the rise in CO_2 concentration.

Through these two mechanisms, CO_2 concentration in seawater is lowered and uptake of CO_2 from the atmosphere is promoted. That is, both nutrient loads derived

Table 11.1 Characteristics of human-impacted SCEs, drivers, key mechanisms, and the relevance to atmospheric CO_2 uptake and carbon storage

Characteristics	Driver	Key mechanism	Relevance to atmospheric CO_2 uptake and carbon storage
Large amount of nutrient input	Human, livestock, and farmland	Enhancement of high primary production	Low CO_2 in surface water
Relatively small amount of labile carbon input	Wastewater treatment (removal and mineralization of labile organic carbon)	Low carbon/nutrient ratio water inflow	Low CO_2 in water
		Suppression of mineralization but less suppression of primary production	
Large amount of freshwater discharge	Freshwater demand due to population (importation of water, watershed alteration)	Enhancement of stratification	Low CO_2 in surface water
		Suppression of upwelling of bottom waters with high DIC concentration due to stratification	
		Low turbidity in surface water due to suppression of resuspension and upwelling of POC from bottom water, enhancing light availability and photosynthesis	
Presence of hypoxic water mass	Stratification	Anoxia/hypoxia in both bottom water and surface sediments	Enhancement of carbon storage
	High organic matter input		
	Freshwater input	Suppression of mineralization	
		Production of POC by anoxic/hypoxic polymerization	
Shallow water depth	Geological settings	Short degradation time during POC sinking in water column	Enhancement of carbon storage
High turbidity	Plankton blooming	Enhancement of primary production due to increase in phytoplankton biomass, lowering CO_2	Variability of CO_2 in surface water
	Mineral particle input from land		
		Suspended particles suppressing light availability and photosynthesis, raising CO_2	
Change in residence time	Freshwater input	Influenced by the quantity and quality (CO_2 and POC) of inflowing water	Variability of CO_2 in surface water and carbon storage
	Alteration of sea-bottom topography		

Modified from Kuwae et al. (2016)

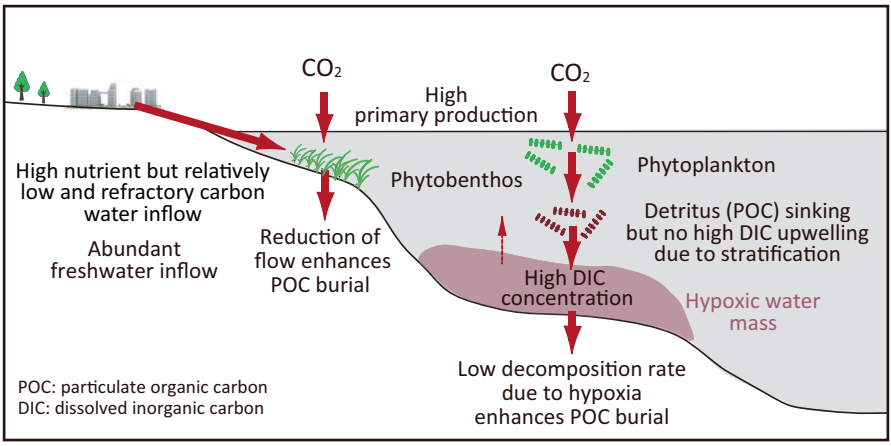

Fig. 11.5 Conceptual diagram illustrating how human-impacted SCEs become net sinks for atmospheric CO_2. (Modified from Kuwae et al. 2016)

from urban/agricultural land uses and wastewater treatment that reduces the labile organic carbon load are important factors in a human-impacted SCE becoming a net sink for atmospheric CO_2.

However, the inflow of treated water may accelerate decomposition of refractory organic matter in a SCE and may somewhat slow the decrease of CO_2 concentration in seawater. This is due to the "priming effect" of decomposing refractory organic matter, which is enhanced at high nutrient concentrations (Taylor and Townsend 2010; Jiao et al. 2014). This phenomenon occurs due to the presence of bacteria that decompose and mineralize refractory organic matter using nutrients in the natural environment. Therefore, how the interaction between refractory organic matter and nutrients affects carbon storage is complex.

11.3.2 Freshwater Inflow, Stratification, and Hypoxic Water Mass

The large inflow of fresh water, stratification (the state where water bodies with different properties, such as temperature or salinity, are layered without mixing), and oxygen-depleted (hypoxic) conditions of human-impacted SCEs are also deeply involved in CO_2 gas exchange. Urban centers often divert rivers to meet their demand for fresh water. An increase in the inflow of fresh water and heated effluents from urban areas strengthen the stratification structure and promote seawater exchange in SCEs. Changes in the physical oceanographic structure caused by such human impacts have an indirect but major influence on the SCE's biogeochemical cycling. When a SCE becomes stratified, upwelling of the high concentration of dissolved inorganic carbon (DIC) in the bottom layer and the subsequent rise in the

surface CO_2 concentration, which is exchanged with the atmosphere, are suppressed (Fig. 11.5). In turn, POC as a source for increasing the surface CO_2 concentration gradually precipitates due to its own weight. Thus, even if there is stratification, the SCE's sedimentation is not disturbed (Kone et al. 2009).

Because SCEs are shallow, POC sinks and reaches the sea bottom in a short time, leading to less mineralization during sinking in the water column. This also suppresses a rise in the CO_2 concentration in surface water. Furthermore, sediments are often resuspended due to the effects of wind-driven waves in SCEs, but the resuspension is suppressed when stratification develops. This suppression decreases the turbidity of the surface water and increases the light intensity available for photosynthesis, and the increased photosynthesis by phytoplankton lowers the CO_2 concentration in the surface water (Chen et al. 2008).

Stratification occurs seasonally: it develops in the summer when the surface water is heated with strong sunlight. This seasonality also plays an important role in CO_2 gas exchange. During the summer, upwelling of the bottom layer water containing a high DIC concentration is blocked due to stratification. Seawater is well mixed vertically in other seasons when stratification does not develop. As a result of this mixing, the surface CO_2 concentration rises. However, because the water temperature is lower and solubility of CO_2 is higher in seasons other than summer, less CO_2 is emitted into the atmosphere.

Although there is debate on the topic, the decomposition and mineralization rates of organic matter are generally considered to be faster when the oxygen concentration is higher (Canfield 1994; Hartnett et al. 1998; Miyajima and Hamaguchi 2018). In addition, the rate of decomposition of organic matter increases where conditions fluctuate between aerobic and anaerobic, thus promoting symbiosis between aerobic and anaerobic heterotrophic bacteria (Zonneveld et al. 2010). This suggests that the presence of diverse chemical and biological environments may promote the decomposition of more diverse organic matter. For example, if labile organic matter is first decomposed and mineralized under aerobic conditions in the bottom water and sedimentary surface layer and then undecomposed organic matter is transported to the deeper anaerobic environment and further mineralized, the mineralization rate per unit area may increase as a whole.

Nevertheless, when hypoxic conditions occur in the bottom water during stratification, the aerobic sediment surface layer becomes anaerobic throughout the sediment layers, and the decomposition and mineralization rates of organic matter decrease. Consequently, organic matter accumulates at the seabed at a faster rate. Also, because decomposition of organic matter by benthic animals is suppressed under hypoxic conditions, the presence of hypoxia facilitates the accumulation of organic matter in sediments (Koho et al. 2013).

Hypoxic water masses are usually seen as purely detrimental, as hypoxia causes mortality of benthic macrofauna such as fish and shellfish. From the viewpoint of carbon storage or climate change mitigation, however, hypoxic water masses have some positive effects, as we have explained. However, hypoxic water masses may promote the production of other greenhouse gases, such as N_2O and CH_4, and further research on the topic is warranted.

Increased turbidity may function to either increase or decrease the CO_2 concentration of surface water, depending on the cause. If the source of turbidity is phytoplankton, primary production is promoted and the surface CO_2 concentration is reduced. If the source of turbidity is inorganic mineral particles (sand and mud), photosynthesis is suppressed due to decreased light intensity in water and the concentration of CO_2 increases (Chen et al. 2012).

Furthermore, the residence time (exchange) of seawater is also an important factor determining CO_2 and organic matter concentrations (Gazeau et al. 2005). These depend on the concentrations in and amount of incoming river water and offshore seawater. Thus, changes in the residence time of seawater may function both in increasing and decreasing CO_2 and organic matter concentrations.

11.3.3 Evidence from Field Studies

The air–seawater CO_2 exchange in the world's SCEs was summarized by Borges and Abril (2011), who noted only one case serving as a net sink for atmospheric CO_2, and by Laruelle et al. (2013) and Regnier et al. (2013), who concluding that SCEs serve as a net emitter worldwide. In light of the growing literature after those summaries were published, however, we used the Google Scholar and Scopus databases to identify new reported cases of SCEs serving as net sinks for CO_2 (Table 11.2) to clarify the characteristics of these exceptional SCE cases.

First, a SCE serving as a net sink of atmospheric CO_2 is often located next to an urbanized area or agricultural lands. These findings support our hypothesis that human-impacted SCEs can act as a sink for atmospheric CO_2. Second, such SCEs are often affected by wastewater treatment, stratification, and hypoxia. These three characteristics are consistent with the Japanese cases of Tokyo Bay (Fig. 11.6) (Kubo et al. 2017) and Osaka Bay (Fig. 11.7) (Fujii et al. 2013). The effluent flowing into human-impacted SCEs has high nutrient and phytoplankton (chlorophyll *a*) concentrations and high primary production due to loads derived from urban and agricultural activities. In addition, previous studies revealed that net uptake of atmospheric CO_2 occurs when net ecosystem production increases (Maher and Eyre 2012; Tokoro et al. 2014, 2018).

As cases of vegetated ecosystems acting as net sinks of atmospheric CO_2, seagrass meadows and one kelp bed were extracted. The uptake rate in the seagrass meadows was 24.6 ± 44.1 mmol C/m^2/day and that in the kelp bed was 59.4 mmol C/m^2/day (Ikawa and Oechel 2015), all of which were faster than the uptake rate of SCEs without seagrass meadows (9.6 ± 6.7 mmol C/m^2/day). There were also cases of coral reefs in which the CO_2 concentration in water was undersaturated and the system acted as a sink (Kayanne et al. 1995, 2005; Delille et al. 2009), although the uptake rate was not described.

The global average of the net CO_2 emission rate from SCEs is about 40–50 mmol C/m^2/day (Laruelle et al. 2013). However, most of the data for these statistics were acquired intermittently at fragmented spatial scales; there are very few cases for

Table 11.2 Previous reports of SCEs affected by both seawater and fresh water (salinity range limited to 1–33) that act as net atmospheric CO_2 sinks

Location	Site condition					Flux and measurement condition			References
	Land use	Treated wastewater input	Stratification	Hypoxic water mass	Chl-*a* (μg/L)	CO_2 uptake rate (mmol C/m^2/day)	Measurement interval	Measurement season	
Estuarine systems									
Noordwijk	Urban/farmland	Yes	Yes	–	–	<20.0	24 h continuous	September	Bakker et al. (1996)
York River estuary	Urban/forest	Yes	Yes	–	–	2.1–5.6	Daytime snapshot	November to April	Raymond et al. (2000)
Randers Fjord	Farmland	Yes	Yes	No	2–6	10.0	24 h	April	Gazeau et al. (2005)
Tendo lagoon	Farmland	No	Yes	Yes	8–27	3.0–17.7	Snapshot	March to December	Kone et al. (2009), Kouame et al. (2009)
Aby lagoon	Farmland	No	Yes	Yes	–	7.4	Snapshot	Annual average	Kone et al. (2009), Kouame et al. (2009)
Changjiang estuary	Urban/farmland	Yes	Yes	Yes	0–18	0.7	Snapshot	Annual average	Zhai and Dai (2009)
Bellamy River estuary	Urban/farmland	No	–	–	3–7	12.0	–	April	Hunt et al. (2011)
Oyster River estuary	Urban/farmland	Yes	–	–	4–5	17.2	–	April	Hunt et al. (2011)
Neuse River estuary	Urban/farmland	Yes	Yes	–	7–20	0.5	Daytime continuous	Annual average	Crosswell et al. (2012)
Neuse River estuary	Urban/farmland	Yes	Yes	–	–	0.1	Day/night	Annual average	Crosswell et al. (2017)
Godthabsfjord	Icecap	–	–	–	–	20.0	Snapshot	Annual average	Rysgaard et al. (2012)

Columbia River estuary	Urban/ farmland	Yes	Yes	Yes	6	6.5–9.5	Daytime continuous	April	Evans et al. (2013)
Osaka Bay	Urban	Yes	Yes	Yes	10–50	8.3	Snapshot	Annual average	Fujii et al. (2013)
Tokyo Bay	Urban	Yes	Yes	Yes	0–300	8.8	Daytime snapshot	Annual average	Kubo et al. (2017)
Guanabara Bay	Urban	No	Yes	Yes	19–108	26.4–49.7	Day/night	Annual average	Cotovicz et al. (2015)
Matla estuary	Forest/ farmland	Yes	No	No	3	7.9–8.6	24 h	Annual average	Akhand et al. (2016)
Simple mean and SD						10.8 ± 9.51			
Seagrass meadows, % cover									
Hasting River 10%	Farmland	Yes	–	–	–	1.0	Day/night	Annual average	Maher and Eyre (2012)
Camden haven 37%	Forest	Yes	–	–	–	5.0	Day/night	Annual average	Maher and Eyre (2012)
Wallis Lake 37%	Forest	Yes	–	–	–	5.0	Day/night	Annual average	Maher and Eyre (2012)
Albufera des Grau	Urban/ farmland	Yes	Yes (slight)	Yes	0–200	8.1	Daytime snapshot	Annual average	Obrador and Pretus (2012)
Shiraho	Farmland	No	No	No	–	1.9	24 h	September	Watanabe et al. (2013)
Furen lagoon 80%	Farmland	Yes	Yes	No	1–7	6.0–10.4	24 h continuous	August	Tokoro et al. (2014)
Furen lagoon 80%	Farmland	Yes	Yes	No	–	1.5	Daytime snapshot	Annual average	Tokoro et al. (2014)
Kurihama Bay	Urban	Yes	No	No	1–4	2.5	Daytime snapshot	March and April	Tokoro et al. (2014)

(continued)

Table 11.2 (continued)

Location	Site condition					Flux and measurement condition			References
	Land use	Treated wastewater input	Stratification	Hypoxic water mass	Chl-*a* (μg/L)	CO_2 uptake rate (mmol C/m^2/day)	Measurement interval	Measurement season	
Fukido estuary	Forest	No	No	No	<2	86.4	24 h continuous	August	Tokoro et al. (2014)
Simple mean and SD						24.6 ± 44.1			
Kelp bed									
Southern California bight	Urban	–	–	–	0.5–8	59.4	24 h continuous	Annual average	Ikawa and Oechel (2015)

Most of the data summarized here were measured as snapshots (not 24-h continuous measurements) and did not include an annual cycle, so they may be biased and have high uncertainty. Modified from Kuwae et al. (2016)

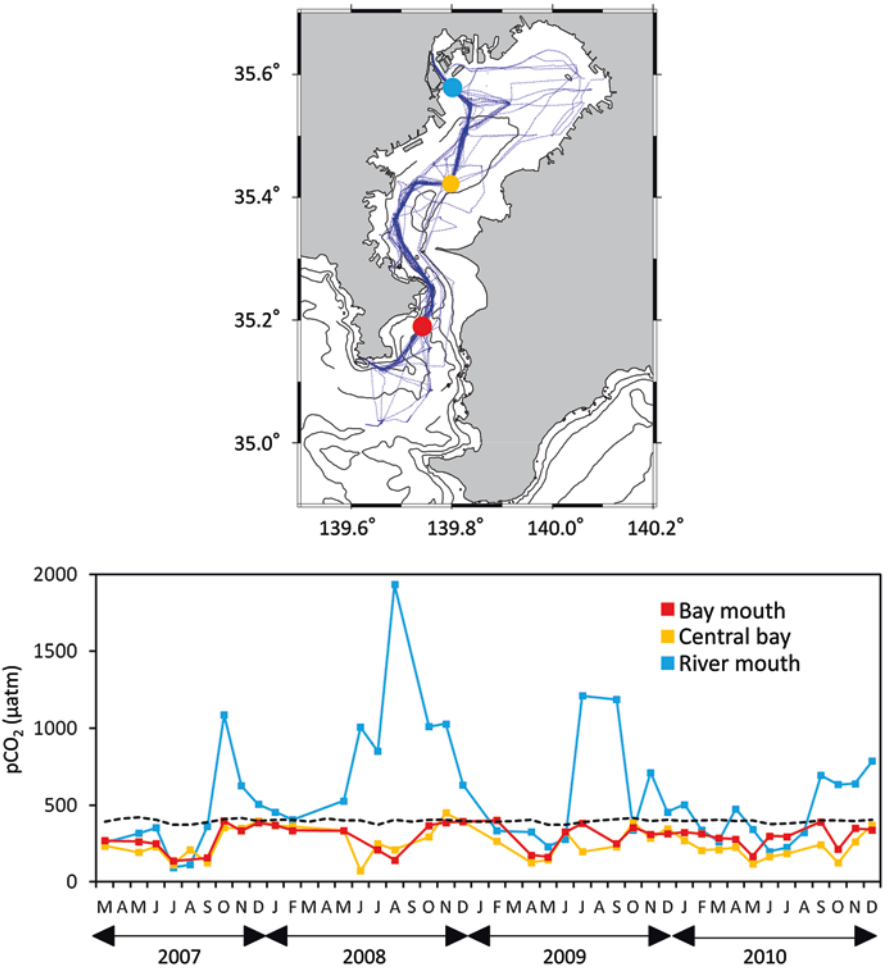

Fig. 11.6 The CO_2 concentration in seawater in Tokyo Bay. The dotted line shows the concentration of CO_2 in the atmosphere. When the concentration is below the dotted line, CO_2 in the atmosphere is taken up by the seawater. Except for the site near the incoming river, atmospheric CO_2 is taken up in the seawater throughout the year in Tokyo Bay. The bay becomes a sink even when considering the annual average of CO_2 gas exchange over its entire area (ca. 140 g CO_2/m^2/year). (Modified from Kubo et al. 2017)

which fluctuations in CO_2 concentration were measured continuously at various time scales, such as 24 h or throughout the year. Therefore, these statistics include large uncertainty and bias. In particular, in low-salinity waters, total alkalinity is generally low and the buffer effect of carbonate chemistry is weak, causing high temporal variability in CO_2 in water.

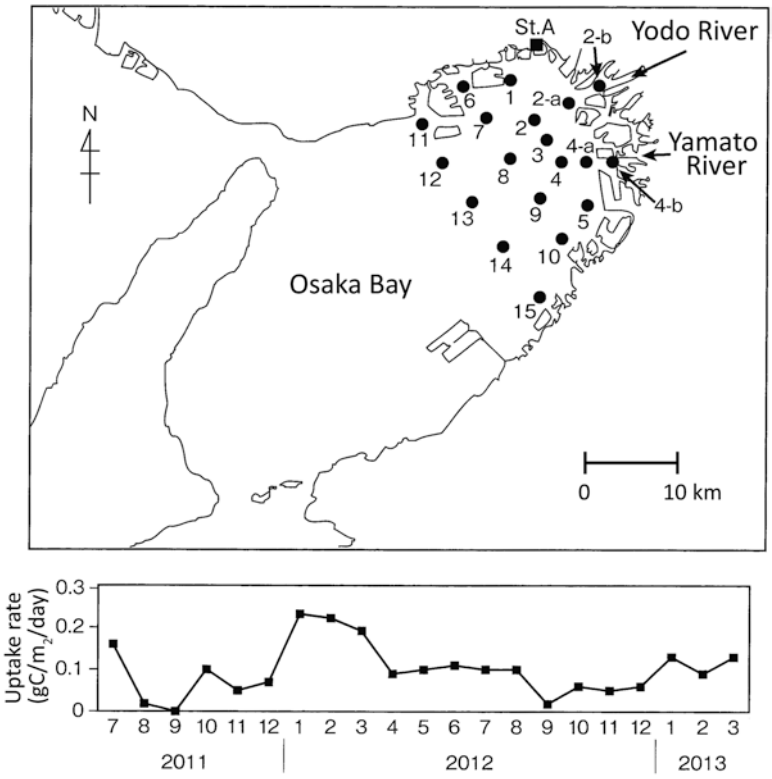

Fig. 11.7 Atmospheric CO_2 uptake rate in Osaka Bay. Atmospheric CO_2 is taken up throughout the year (ca. 133 g CO_2/m^2/year). The numbered dots indicate the sampling locations. (Modified from Fujii et al. 2013)

11.4 Future Studies

11.4.1 Enhancement of CO_2 Gas Exchange Data

Compared to terrestrial and open oceans, the data for CO_2 gas exchange in SCEs are limited (Laruelle et al. 2013), and there has been no description of SCE gas exchange even in the latest assessment report of the Intergovernmental Panel on Climate Change (IPCC 2013). In order to evaluate whether each SCE is a net sink or source, key data for carbon cycling such as CO_2 gas exchange, carbon chemistry in water, and the dynamics of organic carbon are indispensable (Maher and Eyre 2012; Obrador and Pretus 2012; Tokoro et al. 2014; Watanabe and Kuwae 2015). Furthermore, because the range and uncertainty of the gas exchange rate differ depending on the measurement period, long-term data are important for predicting future gas exchange rates and the extent of human impacts (Crosswell et al. 2017). Indeed, a numerical simulation predicted that the uptake rate of atmospheric CO_2 in

areas from estuaries to shelves will be accelerated in the future due to an increase in atmospheric CO_2 concentration and increased nutrient loads (Andersson and Mackenzie 2004).

11.4.2 Revaluation of Stored Carbon

Many studies on the importance of blue carbon ecosystems and their conservation are based on the premise that if the ecosystem degrades or disappears, all of the carbon stored will be mineralized and released into the atmosphere as CO_2 (e.g., McLeod et al. 2011). This assumption, however, is a worst case scenario and clearly overestimates emissions (Pendleton et al. 2012; Macreadie et al. 2014; Lovelock et al. 2017). Thus, further research is needed to examine the relationship between the degree of degradation or extinction of the ecosystem and indices such as the ecosystem area, vegetation biomass, net ecosystem production rate, and amount of carbon storage (Kuwae and Hori 2018).

As green carbon is stored in SCEs together with blue carbon, there is room for discussion as to whether the land-derived green carbon should also be included in the blue carbon storage function. It may be reasonable to include green carbon if the decision is based on the site where carbon is stored. Similarly, it may be reasonable to exclude green carbon if it is based on the site where CO_2 is first captured from the atmosphere. Indeed, some studies have estimated the contribution of blue carbon and green carbon separately (Middelburg et al. 1997; Kennedy et al. 2010; Dubois et al. 2012; Miyajima et al. 2015; Watanabe and Kuwae 2015; Kubo and Kanda 2017). Likewise, there needs to be discussion as to whether particulate blue carbon (POC) and macrophyte drifts that flow out of the SCE and are stored at the seabed of the shelf or the open ocean is also included as SCE blue carbon storage (Krause-Jensen and Duarte 2016; Duarte and Krause-Jensen 2017; Abo et al. 2018).

11.4.3 Mitigation of Climate Change Through Wastewater Treatment

In this chapter, we noted that CO_2 emission from human-impacted SCEs is suppressed because carbon flowing into the SCE has been largely removed by wastewater treatment. This means that CO_2 that would be emitted from the sea surface is instead emitted from the wastewater treatment plant. In other words, if we view the land and SCE as an integrated system, the amount of CO_2 taken up by the SCE may be canceled out by the emission from decomposition of organic matter in the open aeration tank of the wastewater treatment plant. However, by appropriate management of wastewater treatment, we are able to suppress CO_2 emission from the treatment plant or capture carbon (Fig. 11.8). For example, the generated sludge can be

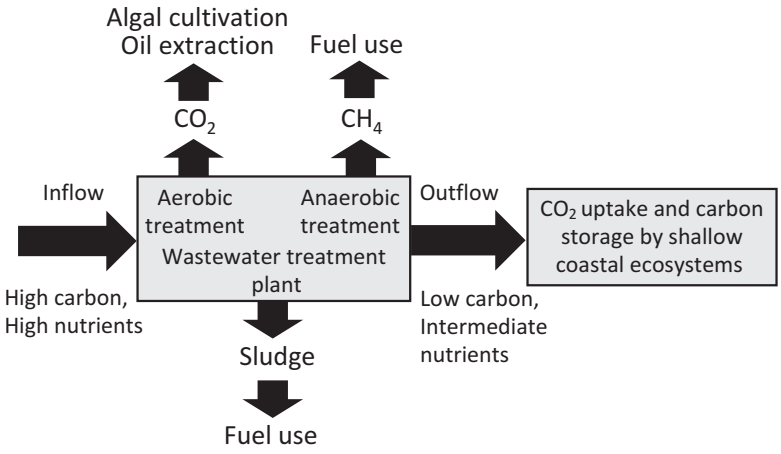

Fig. 11.8 Conceptual diagram for the effective reduction of greenhouse gas emissions using wastewater treatment and SCEs in an integrated terrestrial–marine system

used as fuel. In addition, by collecting CO_2 generated by wastewater treatment and introducing it into a culture tank of algae, CO_2 can be absorbed by algae. The oils extracted from the algal bodies can also be used as an alternative fuel and industrial material. Moreover, by using an anaerobic treatment method (e.g., methane fermentation), the generated gas can also be converted into fuel (Parkin and Owen 1986). Furthermore, it is also possible to adjust the quality of the treated water, such as the carbon and nutrient concentrations, by regulating the extent of the treatment as well as selecting the treatment method, including removal of phosphorus by the coagulating sedimentation method and removal of nitrogen by the anaerobic-anoxic-oxic (A2O) method.

The complexity of the relationship between wastewater treatment and CO_2 gas exchange in SCEs reflects the complex relationship between the social system and adjacent ecosystem. Therefore, biogeochemical models and numerical simulations are necessary to enact appropriate ecosystem-based mitigation measures.

11.5 Conclusions

In this chapter we discussed how human-impacted SCEs can be managed to help mitigate climate change. Through a detailed review of past findings and in situ case studies, we provided a mechanistic explanation of how SCEs can serve as net sinks for atmospheric CO_2. Furthermore, we showed that the environmental conditions necessary for a net sink match with those of SCEs affected by human impacts. That is, by coordinating the interrelationships between social systems and ecosystems, we can create new means of utilizing human-impacted SCEs to mitigate climate

change (as a carbon reservoir and as a sink of atmospheric CO_2). In particular, vegetated SCEs or blue carbon ecosystems (e.g., mangroves, salt marshes, and seagrass meadows) are important because of their strong capability for carbon accumulation and long-term storage.

In addition, technology to mitigate climate change through conservation and restoration of SCEs, that is, technology utilizing blue carbon ecosystems, is both feasible and more sustainable than other mitigation measures (e.g., marine iron fertilization and carbon capture and storage) in terms of technical difficulty, cost, ecological risk, social acceptance, operation, and ethics (Nellemann et al. 2009; Cusack et al. 2014). Furthermore, the conservation and restoration of SCEs can result in not only the mitigation of climate change but also other ecosystem services (co-benefits), including an improved food supply, water purification, tourism, recreation, and disaster prevention (Kuwae and Hori 2018). However, because ecosystem-based mitigation technologies use natural systems, there are large diurnal, seasonal, and annual fluctuations and high uncertainty. Therefore, as we develop systems for the utilization of SCEs to help mitigate climate change, it is necessary to gather field data enabling the evaluation of uncertainty as well as to improve coupled geophysical–biogeochemical modeling for future projections.

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