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Processes of coastal ecosystem carbon sequestration and approaches for increasing carbon sink

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Abstract The oceans are the largest carbon pools on Earth, and play the role of a "buffer" in climate change. Blue carbon, the carbon (mainly organic carbon) captured by marine ecosystems, is one of the important mechanisms of marine carbon storage. Blue carbon was initially recognized only in the form of visible coastal plant carbon sequestration. In fact, microorganisms (phytoplankton, bacteria, archaea, viruses, and protozoa), which did not receive much attention in the past, account for more than 90% of the total marine biomass and are the main contributors to blue carbon. Chinese coastal seas, equivalent to 1/3 of China's total land area, have a huge carbon sink potential needing urgently research and development. In this paper, we focus on the processes and mechanisms of coastal ocean's carbon sequestration and the approaches for increasing that sequestration. We discuss the structures of coastal ecosystems, the processes of carbon cycle, and the mechanisms of carbon sequestration. Using the evolution of coastal ocean's carbon sinks in sedimentary records over geologic times, we also discuss the possible effects of natural processes and anthropogenic activities on marine carbon sinks. Finally, we discuss the prospect of using carbon sequestration engineering for increasing coastal ocean's carbon storage capacity.

Keywords Coastal ocean's carbon sink, Mechanism for increasing carbon sink, Microorganism, Climate change

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1. Introduction

Climate change is one of the most serious challenges we face for sustainable development of human society. The release of carbon dioxide (CO_2) from human activities is one of the main causes of global warming and climate change. Reducing CO_2 emission and increasing carbon storage is the main way out to control greenhouse effects. China is now one of the world's largest emitters of greenhouse gases, and actively dealing with climate change by reducing emission and increasing storage has become China's strategic consensus for economic and social development. Oceans cover approximately 71% of the Earth's surface, and the carbon content in the ocean is 50 times that in the atmosphere and 20 times that in the soil (Holmén, 2000). Therefore, oceans are the largest carbon pools on Earth and serve as a "buffer" for climate

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change. Approximately 30% of the CO_2 produced by human activities is absorbed by oceans (Le Quéré et al., 2014) (otherwise global warming would have become more intense). In particular, the coastal oceans, which are most affected by anthropogenic activities, account for only 8% of the global ocean area, but absorb more than 20% of the amount of CO_2 taken by open oceans (Field et al., 1998).

The carbon sinks captured by marine ecosystems are called "blue carbon". In 2009, the United Nations Environment Programme (UNEP), Food and Agriculture Organization (FAO) of the United Nations, and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) jointly issued the "Blue Carbon Report", which attracted great attention of world's governments and scientists. The report notes that 55% of the total carbon captured by photosynthesis globally is blue carbon (Nellemann and Corcoran, 2009). The 16th United Nations Climate Change Conference in 2010 formally introduced the Blue Carbon Program, which emphasizes the importance of coastal marine ecosystems in reducing atmospheric CO_2 levels, and, if properly addressed and managed, coastal blue carbon has great potential in slowing down climate change.

In 2013, scientists from the United States, Belgium and some other countries jointly published a paper, entitled "The changing carbon cycle of the coastal ocean" (Bauer et al., 2013). This article pointed out quantitatively for the first time that the coastal ocean may have become a net sink for atmospheric CO_2 during post-industrial times. Past assessments reported by the Intergovernmental Panel on Climate Change (IPCC) and others neglected the coastal contribution to the anthropogenic CO_2 budget. Continued human pressures in coastal zones will probably have an important impact on the future evolution of the coastal ocean's carbon budget (Bauer et al., 2013). Thus, research of the evolution of carbon storage of coastal sediments can help to deduce the effects of natural processes and anthropogenic activities on coastal carbon sinks, which is essential for developing strategies to mitigate climate change.

Blue carbon research had a late start in China. At the 39th Chinese Academy of Sciences (CAS) Science and Technology Frontier Forum and Marine Technology Development Strategy Symposium on August 11, 2014, "China Future Ocean Alliance" was established, and "China Blue Carbon Plan" was formally launched. At the same time, funded by "Program 973, " "Program 863", and other major funding sources, Chinese scientists have carried out a number of studies on blue carbon, laying a solid foundation for conducting comprehensive research and development (R&D) of blue carbon. Since 2008, the concept of "Microbial Carbon Pump (MCP)" (Jiao et al., 2008, 2010a) has attracted wide attention and recognition worldwide. This important carbon storage mechanism has been recognized by the *Science* magazine, "The Invisible Hand Behind a Vast Carbon Reservoir" (Stone, 2010). On the basis of this new scientific understanding, we recognize that blue carbon (mainly organic carbon) is more than the visible coastal plant carbon sequestration, which was recognized early on and included only coastal mangroves, salt marshes and seagrass beds. In fact, microorganisms (particle size less than 20 μm, mainly including phytoplankton, bacteria, archaea, viruses, and most of the protozoa), which were overlooked in the past, account for 90% of the total marine biomass and are the main components of blue carbon (Jiao, 2012; Jiao et al., 2015).

Thus, for the goal of strategic importance, namely "the contribution and significance of coastal ocean's carbon sink to climate change mitigation", there are a number of questions that need to be answered: Where are the places to increase coastal carbon sequestration? What are the underline mechanisms? How will climate change respond to such increased carbon sink? How would ocean global changes (such as ocean warming and acidification) affect the capacity of carbon sink? Is it possible to reduce emissions through increasing blue carbon via geoengineering? These are major scientific issues facing us. In this paper, carbon sequestration of coastal ecosystems from microscopic to macroscopic scales are discussed from four aspects: molecular biology; environmental ecology; biogeochemical processes and environmental effects; and geoengineering for increasing blue carbon. We hope to stimulate systematic research on the contribution of coastal ocean's carbon sequestration to climate change mitigation.

2. Structure of coastal ecosystems and carbon cycle

Carbon captured by marine ecosystems is mainly organic carbon. The mechanisms include the biological pump (BP; Chisholm, 2000), which depends on photosynthetic fixation of CO_2 and subsequent carbon export driven mainly by sinking of particulate organic carbon (POC), and the recently proposed the microbial carbon pump (MCP; Jiao et al., 2010a, 2013) that emphasizes the microbial transformation of organic carbon from labile to recalcitrant states. The relative dominance of these two mechanisms is different along environmental gradients. For example, a transition from dominance of the BP to dominance of the MCP might be expected along a latitudinal gradient from polar regions to the tropics and from surface waters to the mesopelagic, and the relation of BP to MCP might be altered due to ocean warming (Jiao et al., 2014a). This transition is closely related to different structures of ecosystems, and our understanding and knowledge of these processes and mechanisms are still limited.

Phytoplankton absorb CO_2 dissolved in the water from the atmosphere through photosynthesis and convert it into living particulate organic matter (POM) (mostly single-celled algae, such as diatoms, etc., particle size from a few to tens of microns). These organic matters through the food web is gradually transferred to larger particles, such as zooplankton, fish, etc. Unused POM will be transformed into non-life POM through death, decomposition, and other processes, and sink down accompanied by fecal pellets and molting. At the same time, zooplankton living at different depths transport POM from the surface to the deep sea through their vertical migrations. On the other hand, a variety of marine organisms can produce a large number of dissolved organic matter (DOM) through metabolic activities. Some of these DOMs are degraded to dissolved inorganic matter which will further enter into the next biogeochemical cycles, and the others are uptaken by heterotrophic microorganisms, which are then transported through the microbial food web to the typical marine food chain and then become POM (Azam et al., 1983). This series of processes constitute the carbon export from the ocean surface to the deep sea.

The BP efficiency is typically calculated as the ratio of POC export versus total primary production; but POC export efficiency is not very reliable to estimate biological carbon storage. This is because organic carbon is distributed across water masses with diverse pathways, and the timescales of its return to the surface are diverse (Marinov et al., 2006). Combined the POM export and the storage time of deep-sea organic carbon before it returns to the surface, DeVries et al. (2012) found the sequestration efficiency of the BP is the highest in the tropical oceans, followed by the subpolar oceans, and is the lowest in the polar oceans. If the existing carbon sequestration efficiency is maintained, the BP responses to changes in biological productivity driven by climate change will be dominated by the Southern Ocean, followed by the tropical and subarctic oceans (DeVries et al., 2012). These studies are of great help in understanding the mechanisms by which the BP responds to climate change through primary production.

Studies have shown that the surface phytoplankton community composition largely determines the amount and quality of organic matter that settles to the deep ocean (Ducklow et al., 2001). Therefore, phytoplankton, as the BP "engine", their community structure, photosynthetic rate and primary production have close relationships with the BP efficiency. Although the phytoplankton productivity is a prerequisite for BP's operation, only after the carbon is absorbed by plankton in the surface, and transported to the deep sea, does the BP become effective. In this process, microorganisms and zooplankton have important impacts on the BP efficiency through organic matter transformation and transport by microorganisms, remineralization, and vertical migration and predation by zooplankton. In addition, particle disaggregation due to physical perturbation is an important factor affecting POM export efficiency (Ducklow et al., 2001; Collins et al., 2015; Zhang et al., 2016b).

Approximately 50% of the POC produced by photosynthesis is converted to DOC by processes such as excretion, zooplankton feeding, viral lysis, and microbial extracellular enzymatic hydrolysis (Anderson and Tang, 2010). The nutritional status and community composition of microbial food web can affect DOC production and chemical composition. Organic compounds with particle sizes less than 0.2 µm are generally defined as DOC (Carlson et al., 2002), so the DOC component also includes micro-particles produced by heterotrophic phagocytosis, excretion, and viral lysis such as cell wall debris, cell membranes, viruses, and the like. Most of the newly produced DOC in the ocean is easily utilized by microorganisms, and at the same time, the release of CO_2 is accompanied by the production of new DOC via microbial respiration. It is estimated that about 5–7% of the DOC produced by microorganisms is recalcitrant DOC (RDOC), which is not rapidly mineralized (Ogawa et al., 2001; Koch et al., 2014) and can accumulate in the ocean for a long time. It thus leads to marine RDOC storage, namely marine carbon sequestration. The RDOC pool is huge, about 650 Gt, comparable to the total CO_2 in the atmosphere (Hedges, 1992; Falkowski, 2000; Ogawa and Tanoue, 2003). The RDOC has a mean age of 4000–6000 years based on ^{14}C dating (Hansell et al., 2009; Bauer et al., 1992; McNichol and Aluwihare, 2007), and thus forms the long-term carbon storage in the ocean. Preliminary research shows that ocean acidification may not significantly change DOC composition, but UV radiation and ocean warming is possible. RDOC will be exposed to UV photolysis after being brought to the surface by the thermohaline circulation; while warming can affect microbial metabolisms, thus affecting the RDOC generation.

To reveal the mechanism of RDOC formation, Jiao et al. (2010a) proposed MCP as a conceptual framework to address the role of microbial generation of RDOM and relevant carbon storage, which describes three main pathways for RDOC production: direct exudation of microbial cells during production and proliferation, viral lysis of microbial cells to release microbial cell wall and cell surface macromolecules, and POM degradation. The MCP emphasizes the rate of RDOC production, as well as the mineralization rates of POC and DOC; together they determine the time scale of carbon in the ocean. Any small changes in these three rates will affect global atmospheric CO_2 concentration. The microbial process-driven RDOC generation and sequestration mechanisms revealed by the MCP are of great importance for the global carbon cycle and blue carbon. Therefore, for microorganisms (mainly prokaryotes) as the MCP "engine", their community structure, organic matter transformation and transport, and respiration rate all have close relationships with the MCP efficiency and RDOC pool.

In a natural environment, the utilization of DOC by microorganisms depends on species and environmental traits. For example, Aerobic Anoxyenic Phototrophic Bacteria (AAPB) has been shown to be able to selectively use DOC produced by phytoplankton (Jiao et al., 2007; Zhang and Jiao, 2007), and to produce AAPB-specific RDOC. In contrast, archaea widely distributed in the deep sea are relatively more adept at using deep DOC, such as D-amino acids (Herndl et al., 2005; Zhang et al., 2009), resulting in more refractory DOC in deep carbon pool. The recent research in the South China Sea was based on Stable Isotope Probe (SIP) combined with high-throughput sequencing analysis, in which microbial populations that incorporate two ^{13}C-labeled substrates, namely glucose (D-Glc) and glucosamine (D-GlcN), among typical water masses were analyzed (Zhang et al., 2016a). The results implies that ecologically, the levels of labile or recalcitrance of DOC can be maintained in a specific environmental context with specific bacterial community composition. A series of selective utilization of DOC result in fractionation of DOC pool in the ocean, causing the accumulation of RDOC in marine carbon pool in both quantity and inertness.

The BP and the MCP are interrelated, and they interact with each other. The BP and MCP are essentially the processes of POC export, DOC conversion and RDOC generation. At the same time, the two can be transformed into each other; for example, the attenuation of POC flux is accompanied by the production of DOC in the water column; and microbial transformation and transport of DOC are accompanied by the formation and sinking of particles. However, very few studies have investigated POC and DOC/RDOC interconversion and their respective effects in the BP and the MCP. Such studies will provide a better understanding of the dynamics of BP and MCP and of their effects on marine carbon sequestration, which will help us to predict global climate change over the entire geological time scale.

Microscopically, the above-mentioned processes in the ocean are mainly mediated by particle-attached (PA) or free-living (FL) microbial communities. Many marine heterotrophic prokaryotes can produce polysaccharides, which help them attach to biological and non-biological surfaces to form aggregates. Aggregates are generally considered to be extracellular polymers or polysaccharide particles, mainly by polysaccharides, proteins, nucleic acids, and lipids. These aggregates contributes to POC flux. Microorganisms reside in sinking aggregates, and enzymatic degradation can form DOC plume around settling particles (Azam and Malfatti, 2007). The plume contributes largely to the remineralization of microorganisms (Kiørboe and Jackson, 2001). Therefore, POC as a direct substrate will directly affect the PA bacterial community composition. At the same time, the release of DOC from particles will affect the surrounding FL bacterial community composition. As revealed by a study that covered the area from the Pearl River Estuary to the South China Sea (Zhang et al., 2016a), there were significant differences in the compositions of PA and FL bacterial communities. Along the gradient from freshwater to ocean basin, there was a consistent spatial variation trend between bacterial community composition and POC chemical composition. In contrast to PA bacterial communities, the elemental composition and chemical compound composition of particulate matter were more closely related to FL bacterial communities. The microenvironment of particles, such as low-oxygen micro-zones, significantly affects PA bacterial community composition, which was composed of relatively abundant anaerobic bacteria and those taxa preferring low-oxygen conditions. The results of Zhang et al. (2016b) have suggested that release from particles significantly contributed to the bioavailability of DOC for FL bacterial populations and to carbon sequestration by the ocean through the MCP (Figure 1). Evaluating the relative contributions of various biological or mechanical disaggregation of particulate matter to the observed attenuation of the POC flux remains by far a significant challenge (Sanders et al., 2014; Siegel et al., 2014). Collins et al. (2015) estimated that particle material was transferred to the water column by various biological processes and mechanical disaggregation nearly 3.5 times as fast as it was directly respired, which matched the metabolic demands by bacteria as indicated by respiration rate in the water column. This result is consistent with the finding of Zhang et al. (2016a).

We have had a general understanding of microbial community structure, temporal and spatial distribution of biomass, characteristics of important functional groups' activities, and environmental regulatory mechanisms in many Chinese coastal areas, such as from the Pearl River Estuary to the South China Sea, from the Yangtze River Estuary to the East China Sea, and the adjacent western Pacific Ocean (Jiao et

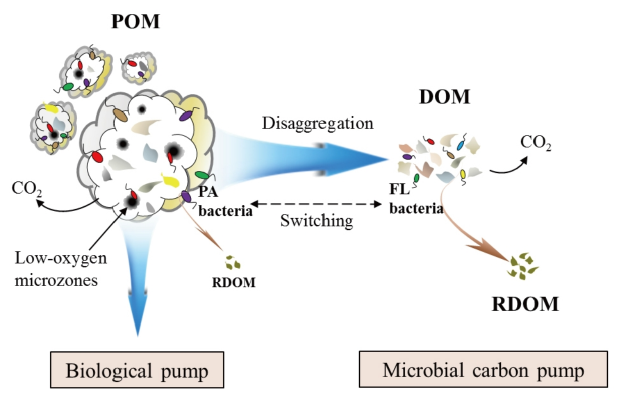

Figure 1 Schematic diagram of the main processes mediating transformation of POM to DOM and influencing POM sinking and recalcitrant DOM (RDOM) production. PA: particle-associated; FL: free-living; POM: particulate organic matter; DOM: dissolved organic matter; RDOM: refractory DOM. Disaggregation processes of POM significantly contribute to carbon sequestration by the ocean through the microbial carbon pump.

al., 2002, 2005, 2007, 2010b; Zhang and Jiao, 2007; Zhang et al., 2006, 2008, 2009, 2011a, 2011b, 2014a, 2014b, 2016a, 2016b; Chen et al., 2011; Liu et al., 2010). We have also accumulated a large amount of data on phytoplankton and protozoan communities in coastal waters for a number of years. There is, however, a lack of comprehensive understanding of the processes and mechanisms that have effects on carbon storage efficiency of these two carbon sequestration processes, namely the BP and MCP.

3. Formation process and mechanism of coastal carbon sinks

Blue carbon was initially recognized only in the form of visible coastal plant carbon sequestration, such as coastal mangroves, salt marshes and seagrass beds (Mcleod et al., 2011). These plants have high productivity and carbon sink capacity; they are important contributors to coastal carbon sinks (Bauer et al., 2013; Alongi, 2014). However, invisible microorganisms account for more than 90% of the total marine biomass and are the main contributors to blue carbon (Nellemann and Corcoran, 2009; Jiao et al., 2015). A series of microbial metabolic processes form a huge ocean organic carbon pool, about 97% of which is in the form of DOC (Figure 2). The key processes of carbon sequestration are microbial carbon fixation and RDOC production/release, aiming at which analysis at the levels of genes, proteins and metabolites will reveal the key pathways of carbon metabolism and the mechanisms of ocean carbon sinks. Recent studies show that bacteria are generally able to synthesize D-amino acids, which can be divided into two types: combined D-amino acids that are used to construct the peptidoglycan layer in the bacterial cell wall, and free D-amino acids that are secreted by bacteria. These

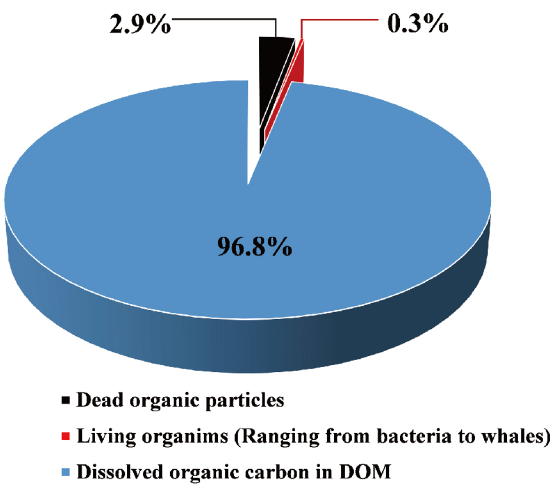

Figure 2 Distribution of organic carbon in the oceans. After Hedges (2002).

two types of D-amino acids can be released through active secretion or passive processes into sea-water (Zhang Z L et al., 2016). Preliminary research indicates that D-amino acids are relatively refractory for marine bacteria, suggesting that D-amino acids can remain in the ocean for a very long time and contribute to ocean carbon storage.

In addition, complex interactions between microorganisms (algal-bacteria-virus interactions, zooplankton predation of microorganisms, etc.) are an important factor affecting the transport and export of carbon in the ocean. For example, some symbiosis of bacteria and algae promotes photosynthetic carbon fixation of algae and, in turn organic carbon released during the growth of algae promotes bacterial growth, which forms carbon transmission in the food chain. Some bacteria (such as algae-lysing bacteria) can cause algae cracking and sedimentation, which contributes organic carbon export and at the same time, releases a large number of organic carbon to activate microbial metabolism. In addition, viruses and protists cause high bacterial mortality in coastal seawater, which is as high as ~30%, respectively and releases large amounts of organic carbon in the ocean (Fuhrman and Noble, 1995).

Towards a comprehensive understanding of the formation process and mechanism of coastal carbon sinks, we should not only study microscopic mechanisms, but also combine macroscopic effects in carbon sequestration. Sedimentary carbon sink is a major component of ocean carbon sinks, and it is a long-term (millennial timescale) or even permanent carbon sink. The marginal seas are characterized by high sedimentation rates, high organic carbon burial efficiency and high carbon sink potential (Tao et al., 2016). Sedimentary carbon sink is mainly controlled by the following factors. First, the ultimate source of the organic carbon buried in the sediments is past and present primary production. Therefore, the estuarine areas with high primary productivity have high sediment organic carbon burial rates, while in low productivity continental shelf areas, the amount of sediment organic carbon buried is relatively low (Hu et al., 2016). Second, the physical, chemical and biological processes in the water column also determine the degradation and sedimentation of POC, which ultimately determines the burial efficiency of sediment organic carbon. Particles are prone to multi-process degradation in deep water, resulting in low sediment organic carbon content and low burial efficiency. Biodegradation process in the hypoxic zone is complex. Anaerobic degradation cannot completely degrade organic matter into CO_2 and H_2O, allowing more organic carbon to settle into sediments (Yao et al., 2015). Third, the depositional environment and dynamic processes at the sediment-water interface are important for sediment organic carbon burial. High deposition rate can quickly bury organic matter and increase the preservation efficiency, so in the coastal areas of high deposition rate, the amount of organic carbon buried is also high, such as at the Yellow River Mouth, in the Yangtze River Estuary and along the Fujian-Zhejiang coast. In addition, sediment properties also affect the conservation and burial of organic matter. The preservation efficiency of organic carbon in fine-grained sediments is high, while the organic carbon in the coarse-grained sediments is easier to oxidize and its burial efficiency is low.

Previous studies of the Chinese marginal seas have shown that the spatial distribution of total organic carbon in sediments is similar to that of the mud deposition. The high values of sediment organic carbon content appear in the west of the Bohai Bay, and in the middle of the Bohai Sea and the Yellow Sea. The low values appear in the Liaodong shoal and the Bohai Strait, which is also characterized by large sediment grain-size and low sedimentation rate (Hu et al., 2016). In the East China Sea, the high values of sediment organic carbon content are mainly in the coastal and inner shelf mud areas of the Yangtze River Estuary, which is also the region with high accumulation rate of sediments, while the sandy sediments of the outer shelf have lower sediment organic carbon content (Deng et al., 2006). The correlation between sediment organic carbon and median sediment size indicates that sediment organic carbon is mainly associated with fine-grained material such as clay. In addition, hydrodynamic condition is an important factor controlling the distribution of sediment organic carbon. Therefore, the mud area of the marginal sea is not only a "sink" of fine-grain particulate matter but also an important organic carbon sink.

4. Evolution of coastal ocean's carbon sinks in sedimentary records over geologic times

To increase coastal carbon sinks means to increase the sinking and burial of POC, and to enhance the generation of RDOC mediated by microorganisms (Jiao et al., 2014a). Sinking POC buried in the sediments, refractory organic carbon that is not easily degraded, and anthropogenic and terrestrial inputs can all be determined from sedimentation records (biomarkers, carbon and hydrogen isotopes). We can establish the relationship between changes in coastal carbon stocks and past global events by studying ocean carbon sequestration in ancient and modern times, and assess the impact of natural processes and anthropogenic activities on carbon sequestration.

The total amount of organic carbon buried in the Chinese marginal seas (including the Bohai Sea, Yellow Sea, East China Sea Shelf, but not the South China Sea Shelf, unless stated otherwise) is about 13 Mt yr^{-1} (Hu et al., 2016), accounting for ~10% of the total organic carbon buried in the global marginal seas (~138 Mt yr^{-1}), indicating that these Chinese marginal seas play an important role in the global carbon cycle. However, Chinese marginal seas are affected by land-sea interaction (such as river input and ocean circulation) and human activities (such as dam construction, offshore engineering, fossil fuel combustion, etc.). The sources of these sedimentary organic carbon are complex. Therefore, the nature and the amount of deposited organic carbon have changed greatly over the past several hundred years, affecting ocean carbon sinks. The contributions of organic carbon from different sources and different geological times (ages) to marine carbon cycle and carbon sinks are different, and they have different effects on atmospheric CO_2 at different time scales. First of all, organic carbon can be divided into two types, namely sea and land sources. The marine-source organic carbon already buried can directly affect marine carbon sink. Second, terrigenous organic carbon transported to the ocean can be classified into three types: the organic carbon of modern terrestrial vegetation which is a terrestrial carbon sink transported to the ocean and can affect marine biogeochemical processes and marine carbon sinks; pre-aged terrestrial-soil organic carbon that is a terrestrial carbon sink on the millennial timescale, can also affect marine biogeochemical processes but does not affect the contemporary concentration of atmospheric CO_2; and fossil organic carbon (from erosion of ancient sedimentary rock and fossil fuel sources) that does not affect terrestrial and marine carbon sinks on millennial and shorter timescales. Therefore, how to distinguish the sources and ages of sediment organic carbon and to clarify the temporal and spatial distribution patterns in marginal sea sediments is the key to quantitatively estimate pattern and potential of sediment organic carbon sinks in Chinese marginal seas.

Radiocarbon dating of total organic matter can be used to estimate the source of organic matter and its significance in carbon sequestration. As shown in Figure 3, $\Delta^{14}C$ values of total organic matter in Chinese marginal sea sediments varied widely, ranging from 0 to −700‰ (modern to about 10000 years before present) (Bao et al., 2016). Their study revealed that terrigenous organic carbon (aged) contributed greatly to Chinese marginal sea sediment organic carbon; and suggested that strong dynamic sedimentary environment had promoted aging of sediment organic carbon (Bao et al., 2016).

^{14}C dating can further quantitatively estimate the contributions of organic carbon from different sources and with different ages. The latest estimates indicated that the proportion of terrigenous organic carbon buried in Chinese marginal sea sediments is 35%, which is slightly lower than the average in global marginal sea sediments (44%), but comparable to that of global marine sediments. The organic carbon contents of modern, pre-aged soil and ancient fossil sources in the Bohai Sea were 0.9, 0.9 and 0.3 Mt yr^{-1}, respectively, according to the compound specific $\Delta^{14}C$ values (Tao et al., 2016). These values in the Yellow Sea are, respectively, 1.9, 1.2 and 0.6 Mt yr^{-1}. According to the $\Delta^{14}C$ values of total organic carbon in the surface sediments of the East China Sea continental shelf, the contribution of the ancient fossil organic carbon was estimated to be ~3 Mt yr^{-1}. Taken together, the ancient fossil

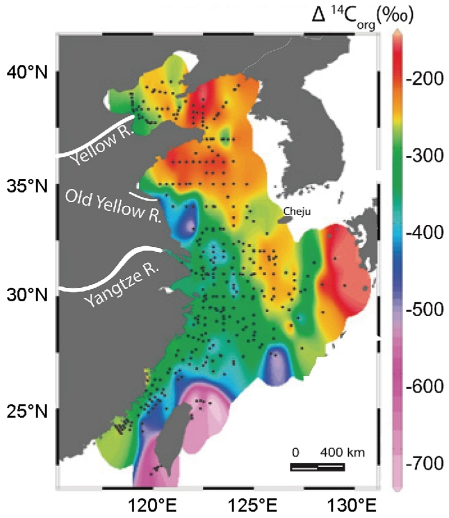

Figure 3 Geographical variations in $\Delta^{14}C_{org}$ (‰) of surface sediments in the Chinese marginal seas (not including the South China Sea). Reproduced with permission from ref. (Bao et al., 2016), © 2016 The Geological Society of America.

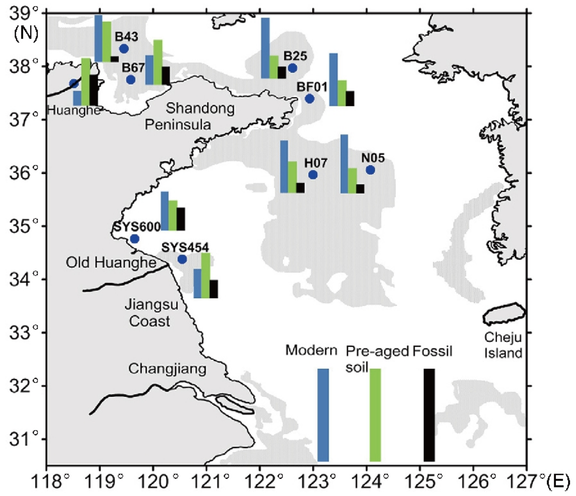

Figure 4 The fractional contributions of organic carbon from modern, pre-aged soil and ancient fossil sources in surface sediments of the Bohai Sea and Yellow Sea basin. The heights of bars shown at the bottom are set for 100%. Reproduced with permission from ref. (Tao et al., 2016), © 2016 Elsevier.

organic carbon in Chinese marginal sea sediments is ~ 3.9 Mt yr^{-1}, which accounts for 30% of the total organic carbon burial and is equal to that of terrestrial organic carbon content (Figure 4). If non-modern organic carbon (pre-aged and ancient fossil organic carbon) is assumed to be primarily of terrestrial origin, the amount of non-modern organic carbon buried in Chinese marginal sea sediments is ~6 Mt yr^{-1}, accounting for ~46% of the total organic carbon burial, and is comparable to the average of terrestrial organic carbon in global marginal sea sediments.

Based on qualitative estimates, the amount of organic carbon buried in Chinese marginal sea sediments has changed greatly over the past 50 years. Coastal eutrophication caused by human activities increased primary productivity, so the amount of organic matter from marine source buried in the coastal seas increased significantly. Coastal anoxic condition also increased the sediment flux and deposition efficiency of organic matter. At the same time, human activities have changed the input of terrestrial organic matter into the ocean. For example, the input and transport time of POC were changed by large-scale projects such as water-sediment regulation in the Yellow River, which affected the burial efficiency in its coastal seas. The construction of a dam on the Yangtze River reduced the input of riverine POC into the sea. As a result, human activities increased the input of ancient organic matter into the coastal oceans. These processes not only change the amount of organic matter buried in the coastal oceans, but also changed the age characteristics of sedimentary organic matter greatly. Therefore, towards an accurate evaluation of evolution of Chinese coastal ocean's carbon sinks over geologic times, it is necessary to quantitatively estimate the contributions of organic carbon from different sources and with different ages to sediment carbon sinks, and to compare them at different geologic times (human activities-influenced versus natural).

The natural processes affecting Chinese coastal ocean's carbon sinks include changes in ocean primary production driven by monsoons and ocean circulations. In the case of the Little Ice Age, for example, the coastal circulation was strengthened, leading to increased marine productivity and high burial efficiency of sediment organic carbon. On the contrary, the summer monsoon intensified during warming climate, and the increase of riverine input increased the productivity of estuarine and nearshore areas, resulting in increasing amount of buried organic matter from marine source in sediments. At the same time, the increase of riverine input also increased the input and buried amount of organic matter from land source. These processes need to be quantified using different biomarkers and isotopic indices, carrying out studies on the relationship between changes in coastal carbon stocks and past global events, and assessing the impact of natural processes and anthropogenic activities on carbon sinks.

5. Approaches for increasing coastal ocean's carbon sinks

Coastal areas are important potential sites for the implementation of climate engineering. Some implementable projects (such as ocean iron fertilization, artificial upwelling, etc.) are aimed at improving marine carbon storage capacity and increasing marine carbon sinks. In most oceans, such as large continental shelf areas, nutrient availability (nitrogen, phosphorus, silicon, and trace elements such as iron) is one of the major factors limiting primary productivity (Hlaili et al., 2006; Arrigo et al., 1999; Leinen, 2008). Artificial upwelling as a geoengineering system, can bring low-temperature, high-nutrient deep ocean waters to the euphotic zone. This process not only increases the total nutrient concentration, but also adjusts the ratio of nitrogen/phosphorus/silicon/iron to promote photosynthesis, increases fishing catches and carbon sink of mariculture, and increases BP efficiency in exporting organic carbon to the deep sea (Lovelock and Rapley, 2007; Kirke, 2003). Therefore, artificial upwelling is considered a great prospect and can be used to stimulate the Earth's capability of self-healing as engineering means (Lovelock and Rapley, 2007; Williamson et al., 2012).

Artificial upwelling has received increasing attention worldwide due to its potential positive environmental effects. One of the most serious challenges to an artificial upwelling system is the design and preparation of robust equipment capable of continuous operation in the complex marine environment. A series of devices have been successfully tested in sea trials for artificial upwelling over the past decades, and some devices were operated continuously for several months. Based on the results of sea trials and related model simulations, some artificial upwelling systems are considered to have a positive effect on increasing ocean primary production and can enhance the capability of absorbing atmospheric CO_2 locally (Masuda et al., 2010; McClimans et al., 2010; Pan et al., 2015, 2016). China's artificial upwelling system is on par with the advanced international level. A self-powered artificial upwelling system has been designed and tested to bring deep water to the euphotic zone by injecting compressed air (Fan et al., 2013, 2015, 2016; Zhang D H et al., 2016; Pan et al., 2015, 2016). This highly efficient and durable artificial upwelling device has been put in trial twice in the Qiandao Lake (a freshwater lake) and one time in the East China Sea (Figure 5). The results showed that low temperature and low oxygen deep water can be brought to the euphotic zone, which can change the nutrition distribution, regulate the nitrogen/phosphorus ratio, and stimulate the primary productivity locally.

To truly improve marine carbon storage, increasing primary productivity alone is not enough. According to the mechanisms of BP and MCP, we should combine artificial upwelling and microbial processes mediating carbon sequestration as an effective way to increase coastal ocean's carbon sinks. Therefore, we need to study artificial upwelling, its relationships with nutrients, primary production, oxygen concentration, pH, and air-sea CO_2 exchange, and the follow-up processes of POC export, DOC conversion and RDOC generation, to realize effective approaches for increasing ocean carbon sinks. Jiao et al. (2014b) have observed and analyzed the effects of BP and MCP in the two natural upwelling processes in the western South China Sea. It was found that the phytoplankton community structure shifted differently during the initial and later intensification periods of upwelling. At the initial intensification period, upwelling brought nutrients to the upper layer of the euphotic zone, and diatoms responded and bloomed, causing high POC export; at the later period, nutrients translocated by weak upwelling can reach only the lower layer of the euphotic zone, where picoplankton are dominant, causing the phytoplankton community dominated by picoplankton (such as *Prochlorococcus* and *Synechococcus*) and a low POC export. At the same time, bac-

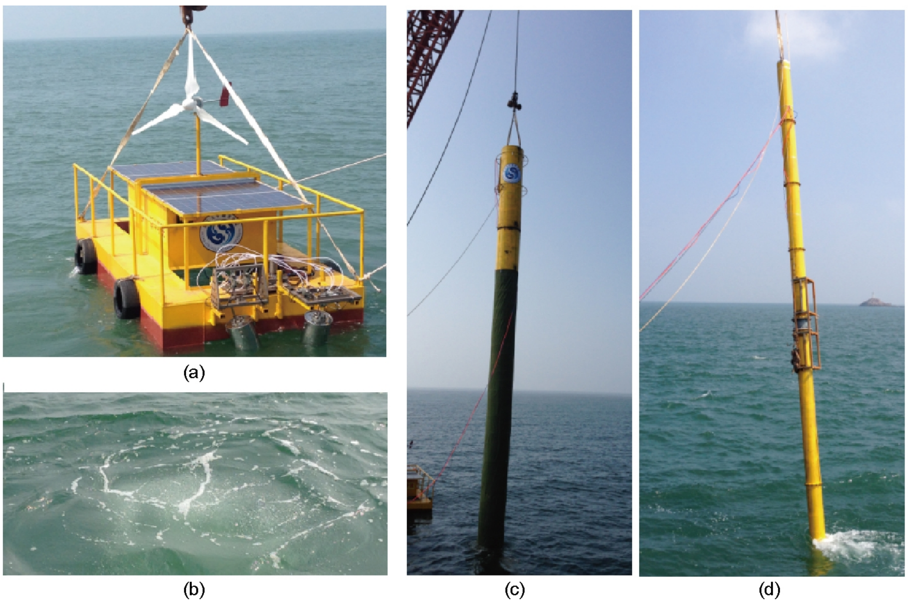

Figure 5 Pictures of a Pneumatic Lifting Artificial Upwelling System during a test. (a) Release of the system; (b) artificial upwelling visible at the surface; (c) 1-m diameter upwelling pipe; and (d) 0.4-m diameter upwelling pipe.

teria were subsequently stimulated by nutrients and labile DOC produced by phytoplankton, resulting in high respiration rates. In terms of carbon sequestration, upwelling usually strengthens the POC-based BP; however, if picoplankton rather than net-phytoplankton dominate the system, their non-sinking POC favors the microbial loop rather than the BP and the MCP can be the prevailing mechanism for carbon sequestration (Figure 6) (Jiao et al., 2014b).

At the same time, artificial upwelling (especially in large-scale application) can also cause significant disturbances to the environment. Its potential impact on ecosystems and associated uncertainty remain unresolved. To further validate the environmental effects caused by artificial upwelling, it is necessary to design a long-term test scheme of artificial upwelling to verify various scientific hypotheses. Research results will guide future application of the system, without artificially adding any nutrients, to achieve ecological restoration and maintain sustainable development of ecosystems.

In addition, for the coastal area of eutrophication, which is greatly affected by the terrestrial input of nutrients, Jiao et al. (2011) proposed a feasible ecological strategy: reducing terrestrial nutrient input, and increase costal carbon storage. At present, over-fertilization is common on the land in China, resulting in a large amount of nutrient input to coastal waters, causing eutrophication with excessive nitrogen and phosphorus. Excessive nutrients stimulate the microbial biodegradation of RDOC, resulting in the long-term stored DOC being converted back to CO_2 and re-released into the atmosphere (Figure 6). If we can control the input of terrestrial nutrients and reduce the total amount of nutrients released into coastal waters, the ratio of carbon/nitrogen/phosphorus in the waters can be increased, so that more RDOC will be retained in the water, ultimately achieving the goal of increasing carbon sinks (Jiao et al., 2011). The results of *in-situ* incubation experiments from Liu et al. (2014) demonstrated that low concentrations of nutrients can preserve more organic carbon in the water. The analysis of bacterial cultures from Xiao and Jiao (2011) also showed that bacterial cells begin to accumulate organic carbon when phosphorus and nitrogen were limited. In addition, a variety of natural environment statistics and river survey results by US and European scientists also confirmed this view (Taylor and Townsend, 2010). Therefore, reasonable reduction of inorganic fertilizers such as nitrogen and phosphorous applied to farmland can reduce the amount of nutrient discharge into rivers, and make microorganisms in coastal waters more effective at converting organic carbon to RDOC, achieving long-term carbon storage in ocean. This will be a realistic and feasible way to increase carbon sinks without risking the environment. This will also help the realization of China's land and sea ecological engineering and ecological compensation. It is an important way to implement China's marine power strategy and low-carbon economic policies to protect sustainable development of ecosystems, and is expected to make an unprecedented contribution to marine ecological security and ecological civilization construction.

6. Perspectives

For China, a country whose vast continental shelves are equivalent to 1/3 of the country's total land area, blue carbon research is one of major national strategic needs. As one of the largest carbon sinks of the Earth system, marine carbon sink studies need collaboration among different disciplines to clarify carbon sequestration processes and mechanisms of coastal ecosystems, to reveal carbon sequestration dynamics and main controlling factors, and to assess the capacity and potential of China's coastal ocean's carbon sinks. At the same time, a variety of research approaches and methods, comparison of data, and verification of conclusions are needed, and the needs for marine carbon sink protocols are emerging. Thus we need to propose a framework of core measurements of carbon sink for peers to work on, towards the development of a standard protocol of multiple disciplines with comparable parameters of inorganic carbon, organic carbon, ecological processes, and even physical oceanographic parameters and models. Furthermore, we need to explore effective ecological engineering approaches

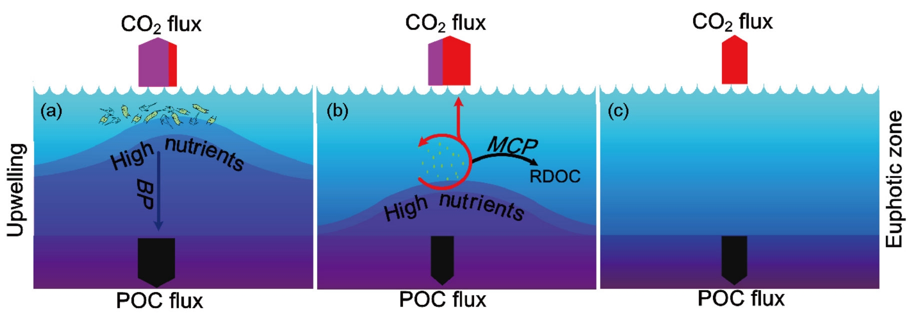

Figure 6 Scenario models for the effects of upwelling on ocean carbon sequestration (Jiao et al., 2014b). Red arrows indicate respiration flux; pink arrows indicate DIC release from the deep water. (a) BP is the prevailing mechanisms for carbon sequestration when diatoms are dominant during upwelling intensification period; (b) MCP is the prevailing mechanisms for carbon sequestration when upwelling is weak and phytoplankton blooming does not occur or picophytoplankton dominates the community; (c) a non-upwelling scenario for reference.

for increasing coastal ocean's carbon sinks, and establish a model for increasing carbon sinks based on land-sea coupling to cope future climate change. Such a model can be used to guide human activities and ecological compensation policy making, to support the sustainable development of marine ecosystems and coastal economy.

In the future, it is possible to set up a "marine carbon sink research and development center" at the national level to attract scientific and technological talents of marine carbon sinks. It will also attract social forces, especially state-owned enterprises to participate in the synergistic innovation. It is also possible to establish funds for promoting R&D achievements in marine carbon sinks and encouraging a Government-Industry-University-Research-Use Cooperation. The R&D of marine carbon sinks will become a new engine for low-carbon economy through encouraging enterprises to take part in the R&D and in the transformation of scientific and technological achievements. Furthermore, we need to establish funding for international exchange of science and technology, and use our expertise in marine carbon sinks to promote multilateral international cooperation. On the one hand, we can train talents for the surrounding countries of the South China Sea, contributing to its marine ecological environment protection. On the other hand, we need to disseminate Chinese civilization and our own modern scientific and technological ideas, to boost the 21st-century maritime Silk Road strategy. Through establishing permanent monitoring stations for oceanic carbon sequestration in representative areas of Chinese coastline, we will strengthen cooperation with international research institutions, showcase our achievements in marine science and technology, and contribute to China's strategy as a maritime power.

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