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Developing Ocean Negative Carbon Emission Technology to Support National Carbon Neutralization.

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Abstract

Carbon neutrality is the right means to cope with global warming. The basic approaches to achieve carbon neutralization include reducing CO2 emissions to the atmosphere and increasing carbon sinks or negative emissions (absorption of atmospheric CO2). As a developing country and a big emitter, China should try its best to increase carbon sinks while reducing emissions as much as possible. The ocean is the largest active carbon pool on Earth, with great potentials for carbon negative emission. We have established marine carbon sequestration theory, which has laid solid foundation for negative emission and set up the linkage between science and policy. At present, China should take the lead of the international program on the ocean negative carbon emission (ONCE), and put it into practice through top design, timely layout, and development of ONCE technology, and then establish ONCE protocols and standards for carbon trade.

Keywords

carbon neutralization, negative emission, marine carbon sink, microbial carbon pump

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Developing Ocean Negative Carbon Emission Technology to Support National Carbon Neutrality

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Since the industrial revolution, a large amount of CO_2 has been emitted due to human activities, which has led to the aggravation of climate change, triggered a series of environmental and social problems, and threatened the sustainable development of human society. The response to climate change has become a hotter issue than science and technology in international politics and economy. On September 22, 2020, President Xi Jinping put forward China's goal of striving to achieve carbon neutrality by 2060 at the general debate of the 75th UN General Assembly [1]. This is China's solemn commitment to the world, demonstrating the responsibility of a great country. According to the Climate Action Tracker (CAT), China's carbon neutrality will contribute to a global warming reduction of 0.2 °C–0.3 °C in the 21st century [2]. China's carbon neutrality strategy is of global concern for climate change and has attracted worldwide attention. However, China has only 30 years to transit from the carbon emission peak to carbon neutrality, which means it will sacrifice traditional economy and pay a huge price to achieve carbon neutrality in a short time. The Boston Consulting Group estimates that China needs to invest CNY 90–100 trillion in traditional industries to achieve the goal of carbon neutrality by 2060 (1). Reducing CO_2 emissions to the atmosphere and increasing carbon sinks (absorption of atmospheric CO_2) are the two fundamental approaches for carbon neutrality. However, attention has been mainly paid to the former approach. As a large emitter and a developing country, China must find ways to increase carbon sinks to relieve the pressure of emission reduction while reducing emission as much as possible, namely, to develop methods for negative emission. In fact, negative emission has become a necessary action in developed countries. In 2019, the United States National Academy of Sciences, National Academy of Engineering, and National Academy of Medicine jointly published the Negative Emissions Technologies and Reliable Sequestration: A Research Agenda [3]. Obviously, negative emission is an essential way to achieve carbon neutrality.

1 Global carbon neutrality agenda and understanding of ocean carbon sink

Currently, 85 countries have declared the goal of carbon neutrality, including 27 European Union (EU) countries and 58 non-EU countries. These countries are responsible for more than 40% of global carbon emissions. Among them, 29 countries have specified the timetables for achieving carbon neutrality (2). Bhutan has already achieved carbon neutrality; Norway and Uruguay will achieve carbon neutrality by 2030; Finland, Austria, Iceland, and Sweden will achieve it by 2035, 2040, and 2045, respectively. Besides, over 20 countries plan to achieve carbon neutrality by 2050. Among them, the United Kingdom, Germany, France, Spain, Denmark, Hungary, and New Zealand guaranteed carbon neutrality by laws. Among the four largest carbon emitters (China, the United States, India, and Russia), China is the first country to propose the carbon neutrality agenda, which will motivate

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other major carbon emitters to accelerate carbon emission reduction. In the process of achieving carbon neutrality, China will have opportunities to enhance exchanges and dialogues with other countries and further increase its international influence. At the same time, the economic and technical cooperation with other developing countries in China's leading fields such as emission reduction and carbon sink increase will achieve mutual benefits and win-win cooperation and promote the building of a community with a shared future for mankind.

Back in 2014, at the 20th Session of the Conference of the Parties (COP20) to the United Nations Framework Convention on Climate Change, the Chinese government stated for the first time that CO_2 emissions would be controlled below 10 billion tons per year between 2016 and 2020 and peak around 2030. According to the emission trend at that time, the CO_2 emissions of China could reach 15 billion tons per year at the peak. However, according to the current trend, the peak will be about 11.3 billion tons per year. Even taking the peak emission of 11.3 billion tons per year as the basis, we should consider maintaining 2/3–1/3 of the current emission to maintain a steady decrease in emission after reaching the peak, which means that China still needs to rely on alternative energy or negative emission to neutralize about 4–8 billion tons of CO_2 per year. American scientists estimate that China will still have a negative emission gap of 2.5 billion tons per year after reaching the peak (3) even with full use of alternative energy sources. Therefore, measures of emission reduction and carbon sink enhancement are both necessary for achieving carbon neutrality.

In the past, carbon sink is increased mainly by terrestrial afforestation. However, due to the aggravating contradiction between the shortage of agricultural land and the demand of growing population for food [4], this measure alone cannot realize global carbon neutrality. The ocean is the largest active carbon reservoir on Earth, which is 20 times that of the terrestrial carbon reservoir and 50 times that of the atmospheric carbon reservoir [5]. The ocean absorbs about 30% of the CO_2 emitted by human activities each year and can store the carbon for thousands of years, playing an irreplaceable role in the response to climate change [6]. Therefore, the ocean has huge potential for negative emission, which represents the most win-win and cost-effective way to slow down climate warming at present.

The international community is increasingly aware of the value and the potential of ocean carbon sink. In the past few years, the Conservation International (CI) and the Intergovernmental Oceanographic Commission (IOC) have jointly launched the Blue Carbon Initiative (4) and established the International Blue Carbon Scientific Working Group and International Blue Carbon Policy Working Group. Besides, the Policy Working Group has released ocean carbon sink reports including Policy Framework, Policy Framework Executive Summary, and Policy Working Group National Recommendations. The National Oceanic and Atmospheric Administration (NOAA) has put forward recommendations on the work for national ocean carbon sink from three aspects: market opportunities, accreditation and capacity building, and scientific development (5). With the support of the Global Environment Facility (GEF), Indonesia has implemented a four-year Blue Forest Project, established a national ocean carbon sink center, and drawn up the Strategic Plan for Indonesia's Ocean Carbon Sink Research (6). In addition, Kenya, India, Vietnam, and Madagascar have started ocean carbon sink projects in salt marshes, seagrass beds, and mangroves, and carried out pilot demonstration of practicing a voluntary carbon market and a self-financing mechanism.

2 Natural carbon sink potential in China seas

The territorial waters of China cover an area of about 3 million square kilometers, spanning tropical, subtropical, temperate, and northern temperate climatic zones. The South China Sea is adjacent to the "global climate engine," the Western Pacific warm pool. The cross-shelf exchange of the East China Sea has a significant transport function. The Yellow Sea is a confluence of cold and warm currents, and the Bohai Sea is a shallow inner bay highly influenced by human activities. China seas are mainly fed by major rivers such as the Yangtze, Yellow, and Pearl Rivers, and are adjacent to the Kuroshio Current, one of the two major global western boundary currents. These natural conditions not only give China seas great potential for carbon sink but also provide us with space to implement ways of negative emission.

The total blue carbon sink in China's coastal zones is relatively small. The organic carbon burial flux of mangroves, salt marshes, and seagrass beds is 0.36 $Tg\ C\cdot a^{-1}$, and the dissolved organic carbon (DOC) output flux of seagrass beds is 0.59 $Tg\ C\cdot a^{-1}$[7]. By contrast, the carbon sink in the open sea is much larger. According to preliminary estimate, the sedimentary organic carbon flux in the marginal sea of the continental shelf in China is 20.49 $Tg\ C\cdot a^{-1}$, including 17.8 $Tg\ C\cdot a^{-1}$ from terrestrial organic matter. The fluxes of organic carbon output from the East China Sea and the South China Sea to the adjacent oceans are 15.25–36.70 $Tg\ C\cdot a^{-1}$ and 43.39 $Tg\ C\cdot a^{-1}$, respectively. The cultured seaweeds in China have the primary productivity (the fixed carbon) of 3.52 $Tg\ C\cdot a^{-1}$, the removable carbon flux of 0.68 $Tg\ C\cdot a^{-1}$, and the associated particulate organic carbon (POC) depositional and DOC releasing fluxes of 0.14 $Tg\ C\cdot a^{-1}$ and 0.82 $Tg\ C\cdot a^{-1}$, respectively [7]. In addition, the artificial upwelling increased the fixed carbon in the culture area by 0.09 $Tg\ C\cdot a^{-1}$, which, together with seaweed culture, can realize the carbon sink of 3.61 $Tg\ C\cdot a^{-1}$.

To sum up, the amount of carbon stored in China seas and exported to the ocean is about 100 $Tg\ C\cdot a^{-1}$, equivalent to 342 $Tg\ CO_2$ per year. Obviously, natural ocean carbon sink alone is not enough to achieve carbon neutrality, which means it is necessary to develop ocean negative carbon emission

(ONCE) technologies. The application of these technologies can multiply the ocean carbon sink.

3 Foundation and reserves for the research and development of ONCE technologies in China

The concept of ocean microbial carbon pump (MCP) proposed by Chinese scientists explains the mechanism of carbon storage by microorganisms which transform organic carbon to produce recalcitrant dissolved organic carbon (RDOC) [8]. This concept breaks through the classical theory that the sedimentation and burial of organic carbon rely on particulates and uncovers the cause of formation of a huge dissolved organic carbon reservoir in the ocean [9], which is commented by *Science* as the invisible hand behind a vast carbon reservoir [10]. In 2008, the Scientific Committee on Oceanic Research (SCOR) set up a scientific working group on MCP. In 2015, North Pacific Marine Science Organization (PICES) and International Council for the Exploration of the Sea (ICES) established a joint working group on MCP to set up the linkage between science and policy. In 2016, Chinese scientists led to set up a permanent forum on ocean carbon sink at the Gordon Research Conferences. In 2019, the MCP theory was included in the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCCC) released by the Intergovernmental Panel on Climate Change (IPCC), as well as the related Chinese solutions about land–sea coordination and artificial upwelling for carbon emission reduction and carbon sequestration enhancement in mariculture areas.

In China, as early as in 2011, the author put forward the proposal of Research and Development of Ocean Carbon Sink to Ensure Economic Development, which won the first prize of Excellent Proposal at the 12th Five-Year Plan Proposal Commendation Conference held by the National Development and Reform Commission. In 2013, the first Interdisciplinary Science and Technology Frontier Forum of the Chinese Academy of Sciences was held with the theme of research and development of ocean carbon sink with land-sea coordination. In the same year, more than 30 marine science-related research institutes, ministries, and enterprises established the Pan-China Ocean Carbon Alliance (COCA), which is led by basic research and covers government, industry, university, research, and application. In 2015, ocean carbon sink was included in the Overall Plan for the Reform of Ecological Civilization System issued by the CPC Central Committee and the State Council. In 2017, ocean carbon sink was selected as the theme of the Yanqi Lake International Conference which was held by the Chinese Academy of Sciences to build an international academic brand. At the Marine Eco-Economy International Forum in November 2020, COCA launched the Initiative for Implementing Negative Ocean Emission and Practicing Carbon Neutrality Strategy. In December, a symposium on ONCE to support carbon neutrality was held. In the same month, some marine science-related universities in China, with the support of relevant government departments, established the ocean negative carbon emission research center and carbon neutrality innovation research center. At this point, the conditions for China to carry out research and development of ONCE technologies have already been in place.

4 Recommendations for research and development of ONCE in China

At present, the ocean carbon sink that receives the most attention is coastal blue carbon from mangroves, seaweeds, and salt marshes. However, the amount of blue carbon in China's coastal zone is limited and cannot meet the need for carbon neutrality. Therefore, other negative emission ways should be developed.

4.1 Implementation of land-sea coordination project for negative carbon emission

The import of massive terrestrial nutrients into the offshore not only leads to eutrophication and cause ecological disasters such as red tides, but also makes it difficult to store organic carbon in the sea. Especially, most of the organic carbon input from terrestrial sources (about 1/4 of the net carbon sequestration on land, 0.5 Gt) [11,12] are converted into CO_2 when they are in estuaries and offshore waters and then released into the atmosphere, which makes such sea areas with the highest productivity in the ecosystem become the source for CO_2 emission [13–15]. How to restore them to carbon sink is a tough problem that should be solved through land–sea coordination.

Based on MCP theory [8,14], the concept of land–sea coordination, and the eutrophication situation in China's offshore waters, the amount of inorganic fertilizers such as nitrogen and phosphorus in agricultural land should be reasonably reduced in view of the over-fertilization and serious fertilizer loss in China's agricultural land at present. This measure can reduce nutrients leakage into rivers and alleviate the eutrophication in coastal waters. Reducing the respiratory consumption of organic carbon and improving the conversion efficiency of RDOC while keeping a high level of carbon sequestration can maximize the total carbon storage, namely the total amount of biological pump (BP) and MCP [16]. Correspondingly, the evaluation system of offshore carbon storage should be established, which should involve not only the sedimentary and buried organic carbon but also RDOC, a previously missed product of MCP. RDOC can not only increase offshore carbon sink but also be exported to the open sea along with the current. In the deep sea, it can be stored for 4 000–6 000 years [17]. According to the statistical analysis, there is a negative correlation between inorganic nitrogen and organic carbon in various environments such as in the soil, river, lake, reservoir, estuary, offshore, shelf sea, and ocean [18].

This indicates that organic carbon is difficult to be stored in the case of too much nutrients in the environment. Besides, nutrient supplementation experiments in rivers, offshore areas, and the open sea also confirm this conclusion [19,20].

According to the data from National Bureau of Statistics, the consumption of chemical fertilizer in China has increased by nearly 30 times in the past 50 years. Especially at the early stage of reform and opening up, fertilizer production capacity had greatly increased, and the consumption of chemical fertilizer had experienced an explosive growth from less than one million tons per year in the early 1950s to 100 million tons per year in the late 1970s. Since then, it has been growing stably, from 120 million tons in 1980 to a record of 600 million tons in 2015 (7). As the consumption of chemical fertilizer is generally higher than the actual needs of crops, the excess fertilizer is leaked into rivers with rainwater and finally into the offshore waters, which is the main cause of marine eutrophication in China's estuaries and coastal areas at present [21]. In addition to the red tide as the result of eutrophication, green tide has occurred in China's coastal waters in the last decade with its scale reaching an alarming level (Figure 1a) and caused environmental stress and economic losses [22]. A sharp contrast is the situation of a forest estuary in northeastern Canada (Figure 1b). The water quality seems very poor based on water color alone and should be classified as V+ grade according to China's national standard based on chemical oxygen demand (COD). However, this is a misconception. In fact, this forest river has low nutrient content and sufficient dissolved oxygen, and eels can live well here (Figure 1c). The seemingly harmful color demonstrates that it is rich in organic matter, just like the tea. If the environmental condition remains, the organic matter can be preserved for a long time and form into carbon sink with a concentration of more than 1 000 μmol/L, which is over 10 times that of seawater organic carbon in China. Obviously, land–sea coordination is a low-cost and high-benefit ONCE path to reduce carbon emissions and increase carbon sink.

Combining new understanding and new theories with the local conditions facilitates the development and implementation of effective measures for the quantification of ecological compensation mechanism, which is expected to achieve multiple benefits. By developing relevant methods, techniques, standards and norms, we can scientifically quantify the ecological compensation mechanism, practice the theory of "clear waters and green mountains are as valuable as mountains of gold and silver" and promote a new model of domestic systemic circulation that drives sustainable economic and social development.

4.2 Research and development of ONCE technologies in anoxic and acidified sea areas

Oxygen shortage and acidification of seawater have become serious environmental problems prevalent in the global offshore areas, which directly lead to the degradation of fishery resources, the decline of biodiversity, and the risk of ecosystem sustainability. In response to these problems, Chinese scientists put forward the principle and technical scheme of implementing negative emission under anaerobic conditions [23], which is expected to improve the environment while increasing carbon sink by establishing a comprehensive negative emission way based on the principles of MCP, BP, and carbonate pump [24]. Promoting the production of authigenic carbonates through adding minerals, increasing alkalinity in the anoxic and acidified environment and burying them with organic carbon can increase the carbon storage volume. Alkalinity moderates changes in the ocean carbonate balance system in response to natural or human disturbance, particularly ocean acidification. There are various ways to enhance ocean alkalinity. For example, 1 mol of olivine can chelate 4 mol of CO_2. The coupling of anaerobic microbial metabolism with the circulation of carbon, nitrogen, and sulfur is important for the massive deposition of carbon in the ocean, which is expected to restore the historical scene of vast carbon reservoir in the ocean [25].

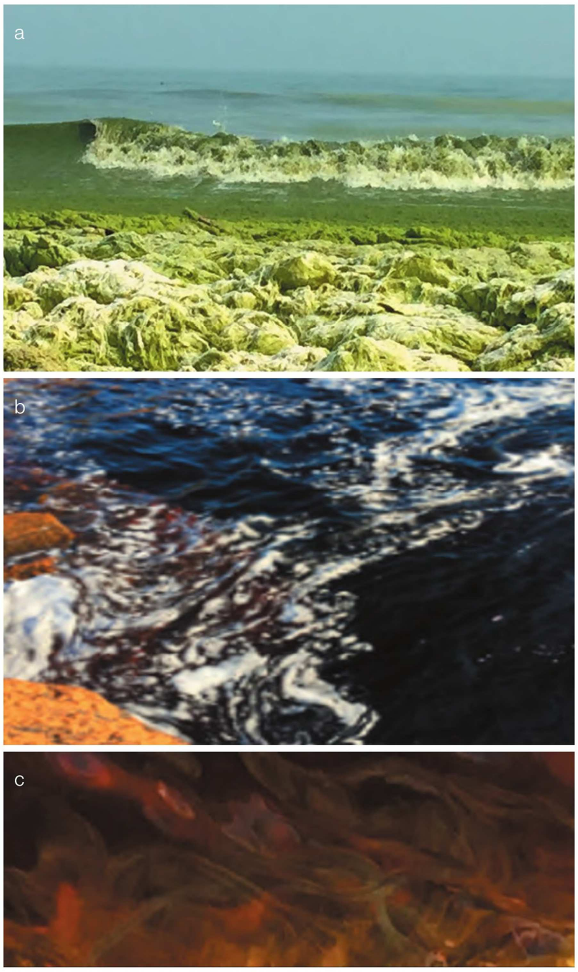

Figure 1 Contrasting extreme cases in eutrophic and oligotrophic coastal waters in China (a) and Canada (b), respectively, and eels live in brown water of latter in Canada (c)

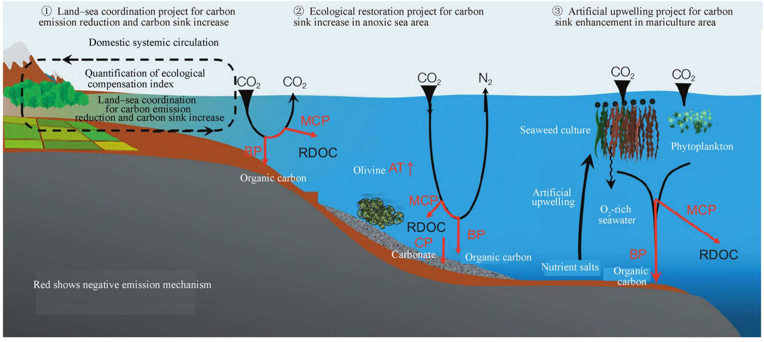

Figure 2 Schematic illustration of eco-engineering approaches for ONCE.AT, alkalinity; BP, biological pump; MCP, microbial carbon pump; CP, carbonate pump; RDOC, recalcitrant dissolved organic carbon.

4.3 Implementation of comprehensive ONCE project in mariculture areas

China has the largest mariculture industry, an important part of marine economy, in the world [8]. The further development of mariculture industry can help relieve the fishing pressure on natural resources and guarantee people's demand for protein and food from animals and plants. With the growth of the global population and the further shortage of resources, global demand for aquatic products is also increasing. The successful experience of China can be shared with all the other countries in the world. However, many problems still need to be solved urgently, such as the ecological load and environmental pressure resulted from large-scale mariculture, especially the ecological risks of seabed organic matter pollution in mariculture areas, the imbalance between supply and demand of nitrogen and phosphorus nutrients, inorganic carbon, and dissolved oxygen, as well as eutrophication, oxygen shortage, and acidification in the sea.

The Special Report on the Ocean and Cryosphere in a Changing Climate recently released by IPCC includes the artificial upwelling measures based on the concept of internal regulation of ecosystem, which is put forward by Chinese scientists to relieve the ecological and environmental pressure caused by large-scale mariculture and address the imbalance between the supply and demand of nutrients, inorganic carbon, and dissolved oxygen. Artificial upwelling driven by clean energy such as solar energy can bring nutrient-rich water from the bottom of the mariculture area to the upper layer to supply the nutrients for photosynthesis of the cultured seaweeds. At the same time, high-concentration nutrients can be released slowly from the bottom in this process, which can avoid ecological disasters such as red tides caused by sudden disturbance events like storm surges. In addition, when the oxygen-rich water from the surface layer was brought to the deep layer, it can moderate the oxygen shortage at the bottom. On the basis of scientific evaluation and overall planning of mariculture capacity and its contribution to ocean carbon sink, we will develop an optimal mariculture model to increase carbon sink, in which both environmental and economic benefits are taken into account. Moreover, it is expected to create a sustainable and healthy mariculture model and a comprehensive engineering model for ONCE (③Artificial upwelling project for carbon sink enhancement in mariculture area in Figure 2).

4.4 Development of standard system for ocean carbon sink

The ocean carbon sink component receiving the most attention is the blue carbon in coastal zones such as mangroves. However, because of the limited amount, it can hardly play a role in dealing with the climate change except its ecosystem service function. However, other ocean carbon sink components which can really affect climate change involve transport of carbon in various spheres including the atmosphere, hydrosphere, biosphere, and lithosphere. Therefore, interdisciplinary research needs to be carried out to establish effective monitoring technologies, assessment methods, and standard systems. There is no unified standard for ocean carbon sink measurement in the world. Thus, formulating a standard system of ocean carbon sink is an important task.

Though China's carbon market is the second largest in the world in terms of quota turnover, there is still a gap in the standard system of ocean carbon sink. Therefore, it is recommended to step up the integration of disciplines related to ONCE and speed up the research on ocean carbon neutrality accounting mechanism and methodology. Efforts should be made to establish the corresponding methods, technologies, measurement procedures, operation specifications, and evaluation standards of ocean carbon fingerprint, carbon footprint, and carbon label, and establish an intact ocean carbon sink trading system.

4.5 Leading international science program of ONCE

The international science program of ONCE initiated by Chinese scientists has received positive response from international peers and approval from ICES and PICES [8]. As of 2019, scientists from 14 countries have signed up to implement the ONCE program. Several ONCE peers have been funded by their host countries or regions in 2020. Moreover, the European Union has funded a research project of 7.16 million euros led by the German scientists.

China should implement ONCE program as soon as possible. Specifically, efforts should be made to establish and improve the scientific planning and technical engineering system for ONCE in response to climate change. China should take the lead to build a standard system for ocean carbon sink and negative emission through ONCE to provide Chinese solutions for global governance.

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