Strategic Approach for Mariculture to Practice “Ocean Negative Carbon Emission”

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Recommended Citation
DOI: https://doi.org/10.16418/j.issn.1000-3045.20210217101
Available at: https://bulletinofcas.researchcommons.org/journal/vol36/iss3/3
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Abstract
Reducing CO2 emissions and increasing carbon sinks are basic approaches to achieve carbon neutralization in China. China is the largest mariculture country in the world. China’s mariculture industry is dominated by non-fed culture type and characterized by rich species, diverse nutrition levels, and advanced farming technology. Therefore, mariculture has huge potential for the development of ocean negative carbon emissions (ONCE). However, the ONCE process of bivalves and seaweed farming is complicated, and the scientific principles, process, mechanisms, monitoring and evaluating methods, and approaches of increasing carbon sink are gradually being recognized and yet to be resolved. This study discusses the research progress of fishery carbon sink, existing problems and possible impact of global climate change on ONCE of mariculture. It then proposes technological approaches and policy suggestions to implement ONCE, which include expanding mariculture space and increasing unit yield, green development of mariculture based on carrying capacity regulatory regime, integrated multi-trophic aquaculture, blue carbon engineering of ocean ranching, and marine artificial upwelling.

Keywords
mariculture, negative emission, seaweed, bivalve, microbial carbon pump

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Abstract: Reducing CO$_2$ emissions and increasing carbon sinks are basic approaches to achieve carbon neutrality in China. China is the largest mariculture country in the world. China’s mariculture industry is dominated by non-fed culture type and characterized by rich species, diverse trophic levels, and advanced farming technology. Therefore, mariculture has huge potential for the development of ocean negative carbon emissions (ONCE). However, the ONCE process of bivalve and seaweed farming is complicated, and the scientific principles, processes, mechanisms, monitoring and evaluating methods, and approaches of increasing carbon sink are gradually being recognized and yet to be resolved. This study discusses the research progress of fishery carbon sink, existing problems and possible impact of global climate change on ONCE of mariculture. It then proposes technological approaches and policy suggestions to achieve ONCE, which include expanding mariculture space and increasing unit yield, green development of mariculture based on carrying capacity regulatory regime, integrated multi-trophic aquaculture, blue carbon engineering of ocean ranching, and marine artificial upwelling.

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Global climate change remains one of the severest challenges to the sustainable development of human society. Unbridled emissions of carbon dioxide (CO$_2$) and other greenhouse gases have led to global warming, sea-level rise, ocean acidification, and frequent extreme weather, which have an increasingly negative impact on humans’ production, living, and survival. Greenhouse gas control has become a major international issue to be addressed. As a responsible major country, China in 2020 pledged to peak CO$_2$ emissions by 2030 and reach carbon neutrality by 2060. However, China has large CO$_2$ emissions because of the rapid economic growth. Reducing emissions alone cannot cage CO$_2$ emissions, and thus it should be coupled with increasing carbon sink to achieve carbon neutrality.[1]

Blue carbon sink, otherwise known as ocean carbon sink, is a process, activity, and mechanism that capitalizes on ocean activities and marine organisms to absorb CO$_2$ from the atmosphere and then fixes it in the ocean. Marine ecosystems (e.g., mangrove, coastal marsh, seagrass bed) and phytoplankton in the coastal areas are the chief reservoirs of blue carbon. The offshore area (including mariculture area), open ocean, and deep ocean boast great blue carbon reserve. As the largest carbon reservoir on the earth, oceans store about 39 trillion tons of carbon, annually absorbing about 30% of the CO$_2$ emitted into the atmosphere. The huge potential of ocean negative carbon emissions (ONCE) has arrested international attention and fueled the research on blue carbon. International organizations such as Conservation International (CI), International Union for Conservation of Nature (IUCN), Intergovernmental Oceanographic Commission (IOC) and United Nations Educational, Scientific and Cultural Organization (UNESCO), in cooperation with governments at all levels, globally promote policy and science research on blue carbon. As the concept of marine blue carbon has gradually attracted public attention, the carbon sink function of fishery organisms has also been concerned. It is in this context that the concept of fishery carbon sink is proposed to boost the fishery economy, China, as the largest mariculture country in the world, has more than several decades of experience in the research on fishery carbon sink brought by bivalve and seaweed farming.[2,3]. Regarding blue carbon in a broad sense, cultured bivalves and seaweeds in China are categorized into blue carbon.[4]. The theory of microbial carbon pump (MCP)[5] and potential pathways for increasing carbon sink in mariculture areas[6] are part of the negative carbon emission scheme of the Intergovernmental
Panel on Climate Change (IPCC)’s Special Report on the Ocean and Cryosphere in a Changing Climate in 2019. However, the research on scientific principle, process, mechanism, monitoring and evaluating methods, and approaches of increasing carbon sink remain insufficient.

China’s Central Economic Work Conference held in December 2020 listed reaching carbon emission peak and realizing carbon neutrality as one of the eight key missions to be accomplished by 2021. Accomplishing this mission has profound implications for China to achieve stable economic development and develop into a modern socialist country in all aspects. Thereby, considering the strategic position and role of mariculture in ONCE, this paper summarizes the research progress, problems and possible impacts of fishery carbon sink and proposes technological approaches to achieve ONCE. It is expected to provide implications for China to fulfill its carbon neutrality commitment and vigorously engage in global carbon emissions governance.

1 Strategic position and role of mariculture in ONCE

1.1 Chinese mariculture is characterized by non-fed culture type of bivalves and seaweeds

China is the largest mariculture country in the world. China’s mariculture industry is dominated by non-fed and oligotrophic culture type of bivalves and seaweeds, with stable structure. Compared with that in other countries, the mariculture in China features high yield, large scale, rich species, diverse trophic levels, and high ecological efficiency.\(^7\) For example, the production of mariculture in China, 2019 was 20.65 million tons, dominated by non-fed seaweeds (2.54 million tons dry weight) and bivalves (14.39 million tons)\(^8\), which accounted for about 80% of total mariculture production. The trophic level of cultured organisms in China ranged from 2.24 to 2.27, much lower than that in developed countries (e.g., European countries) and other developing countries (e.g., Southeast Asian countries)\(^9\). Data released by the Food and Agriculture Organization (FAO) in 2020 showed that China in 2018 topped the world in terms of production and output of bivalve and seaweed farming. Chinese aquaculture features the structure satisfying the need of modern development, provides high-quality protein, widens residents’ access to fish, increases farmers’ income, and helps restructure the fishery industry. At the same time, this structure contributes to reducing CO\(_2\) emissions and relieving marine eutrophication.

1.2 Marine removable carbon sink: biomass carbon of bivalves and seaweeds

Marine primary production is the process in which marine photosynthetic organisms use light to assimilate CO\(_2\) into organic matter. As primary producers, seaweeds are the starting point and the key part of ocean carbon cycle. Seaweeds convert inorganic carbon in seawater into organic carbon through photosynthesis while absorbing nutrient salts to build their own structural material. The uptake of dissolved CO\(_2\) by seaweeds can reduce the partial pressure of CO\(_2\), break the carbon chemical balance of seawater, and accelerate the dissolution of atmospheric CO\(_2\) into seawater. Furthermore, the uptake of nutrient salts by seaweeds for growth can increase the surface water pH, reduce the partial pressure of CO\(_2\), and accelerate the diffusion of atmospheric CO\(_2\) into seawater through the carbonate system. Both pathways play a positive role in carbon sink.

Filter-feeding bivalves can use carbon from the ocean through calcification and ingestion to increase the carbon content of organisms. However, considering the storage cycle of carbon, such carbon cannot be fixed permanently. As statistics indicates, by harvesting bivalves, China can remove nearly two million tons of carbon from seawater each year, which is equivalent to the afforestation of about 500,000 hectares\(^3\).

1.3 Blue carbon to be industrialized: great potential of carbon sink of marine fishery in China

As a large marine country and the first major country of mariculture, China, with the following conditions, has great potential to increase the carbon sink of marine fishery. (1) Favorable marine conditions and spatial resources. China has nearly 3 million square kilometers of jurisdictional sea areas, 12.4 million hectares of shallow mudflat areas within 15 m isobath, and 37 million hectares of 20–40 m deep sea areas. However, the country only develops mariculture in 2.04 million hectares of sea area, with large sea areas to be developed. (2) Rich marine biological resources. China harbors rich and multi-trophic mariculture species, and new varieties keep emerging thanks to the advance in breeding technology, which makes it possible to screen out the varieties with efficient C fixation to establish diverse approaches (e.g., rotational culture, interculture, three-dimension culture, multi-trophic integrated culture) to increase carbon sink. (3) Mature mariculture technologies. China’s mariculture industry is fully-fledged as it encompasses the entire industrial chain ranging from new variety breeding, seed rearing, proliferation, harvesting, to processing. To its credit, mariculture can provide quality blue marine food and contribute to ONCE. It is a win-win human activity expected to sequestrate blue carbon in an industrialized manner, exhibiting promising potential.

2 Achievements and problems of the research on mariculture carbon sink

2.1 Carbon sink of aquaculture ecosystem

Marine bivalves have strong influence on the biogeochemical
cycling of carbon in phytoplankton, particulate organic debris, seawater carbonate system, and sedimentation via filter feeding, respiration, calcification, and biogenic deposition [10]. Cultured bivalves can make use of marine carbon in two ways. One way is to directly convert bicarbonate (HCO$_3^-$) in seawater through calcification into calcium carbonate (CaCO$_3$) in shells. The other way is to increase the organism carbon content by synthesizing its own material through filter feeding on particulate organic carbon (including phytoplankton, microzooplankton, organic detritus, microorganisms) in the water [11]. The unused organic carbon settles to the seafloor in the form of fecal pellets and pseudofecal pellets, accelerating the transport of organic carbon to the seafloor [12]. Thus, we can remove carbon from seawater by not only harvesting cultured bivalves but also biological and carbonate pumps of cultured bivalves. However, overloade bivalve culture can negatively affect phytoplankton and the primary productivity. Moreover, bivalve calcification is a dual-way complex process. Therefore, the carbon sink of cultured bivalves should be considered in the context of the whole ecosystem, which necessitates further studies.

2.2 Research on the mechanism of fishery carbon sink should be strengthened

The research on carbon footprint should be enhanced to measure the fishery carbon sink. For example, seaweeds have a strong ability to absorb and fix carbon via photosynthesis. The mature seaweeds, if not harvested in time, will quickly decay and decompose. Then, the fixed carbon will return to seawater and even to the atmosphere under the further action of microorganisms. Therefore, the harvested seaweeds can be used as food, bait, feed, and industrial raw materials to prolong carbon release. Moreover, they can even be used as products with low carbon intensity to replace those with high carbon intensity.

The farming of seaweeds may become a long-term carbon sink [4]. The detrital organic carbon produced during seaweed growth [13] can become a food source for other organisms through the traditional food chain, or be deposited and buried on the seafloor through direct sedimentation [14], or be transported to deep sea [15]. In addition, dissolved organic carbon (DOC) and particulate organic carbon (POC) released by seaweeds during their growth can enter the food network or form recalcitrant dissolved organic carbon (RDOC) and linger in seawater for a long time via the microbial loop [10,16].

At present, artificial upwelling for nutrient salt regulation is included in the IPCC report. The fishery carbon sink by integrated culture of seaweeds and bivalves involves traditional solubility pump, carbonate pump, biological pump, and recently proposed microbial carbon pump [17], which is an extremely complex process. From the initial removable carbon sink to the sedimentation and burial of POC and the formation of RDOC, the research on the fishery carbon sink by seaweed and bivalve culture has been intensiﬁed (Figure 1), which indicates that only by revealing the mechanism and quantification process can we develop a scientiﬁc method to promote the compensation, trading, and market development of fishery carbon sink.

![Schematic diagram of ocean negative carbon emission based on seaweed farming and integrated culture of seaweeds and bivalves](image)

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2.3 Impact of global climate change on mariculture

Mariculture has a huge potential for ONCE, while global climate change counteracts the mariculture industry. The impact of global climate change on mariculture shows uncertainties and presents two major trends. (1) Global warming and extreme weather are getting frequent and intensified. Global warming will change the metabolisms (e.g., growth and respiration) and further the net accumulation of substances and quality of cultured seaweeds and bivalves, finally affecting their carbon fixation and sequestration as well as their carbon sinks. It is even more difficult to estimate the destruction caused by extreme weather such as typhoon to mariculture. (2) Ocean acidification. Ocean acidification can affect the content and ratio of biochemical components such as biomacromolecules (e.g., fatty acids), secondary metabolites (e.g., phenols), and biogenic elements (e.g., iodine) in primary producers \[18,19\]. It can also alter the biocoenosis structure and composition of primary producers \[20\]. In this way, ocean acidification affects the transfer of material and energy from primary producers to secondary producers and even higher trophic levels in the marine food chain \[21\]. This upward effect can affect the quality of seafood and even endanger human health. The results of net present value (NPV) analysis show that ocean acidification has huge potential influence on the Chinese shellfish industry. The Chinese shellfish industry may suffer a loss of 14.2–1 150 billion dollars of present worth over the next 100 years, and the degree of loss is correlated with that of ocean acidification \[22\].

3 Technological approaches for mariculture to achieve ONCE

Mariculture mainly sequestrates carbon by the burial of POC in the sedimentary environment through biological pumping, the formation of RDOC through microbial carbon pumping, and the fixation of carbon imported into deep sea. On the basis of strengthening research on carbon fixation mechanism, monitoring and evaluating methods, and carbon footprint of mariculture, we should enhance the biological pump and microbial carbon pump by artificial upwelling, integrated seaweed and bivalve farming, and marine ranching to improve the ability of carbon fixation and sequestration in offshore and estuarine areas and promote ONCE.

(1) Expanding mariculture space and improving unit yield. The amount of removable carbon from cultured seaweeds and bivalves is positively correlated with the seaweed and bivalve yield per unit area as well as the carbon content per unit individual. Therefore, increasing the yield per unit area and screening out the seaweeds and bivalves with higher carbon content helps to enhance carbon sink. Farming of the varieties with high carbon fixation rate, improving the mariculture mode, and making efficient use of sea area can elevate the yield per unit area and further the amount of removable carbon per unit area. At the same time, overcoming the limitations of the conventional growth environment (e.g., temperature range), breeding the strains with a wider temperature range, broadening the growth space of specific species, and increasing culture area are effective alternatives to enhance the carbon sink of mariculture.

(2) Improving the capacity management system and promoting the green development of mariculture. Based on the ecological capacity, mariculture should be standardized to ensure stable and high yield of seaweeds and bivalves. The past aimless expansion of the scale and the overloading have brought severe damage to the water environment and aggravated pests, red tide and other disaster events. This not only fails to increase the production but also seriously jeopardizes the sustainable development of the mariculture industry. Taking capacity management system into account, we should shape a mariculture ecosystem with optimized structure, appropriate density, and efficient function to realize the green development of mariculture.

(3) Promoting integrated multi-trophic aquaculture (IMTA) mode. The IMTA mode realizes the effective recycling of carbon, accelerates the operation of biological pump, gives full play to the carbon sink capacity of organisms in different trophic levels, and further enhances the CO₂ absorption and utilization of the aquaculture system. In addition, IMTA can reduce or even eliminate the pressure of aquaculture on the environment and contribute to the stable and sustainable output of the aquaculture system. In a well-proportioned integrated farming system of seaweeds and bivalves, seaweeds can not only absorb nutrients such as nitrogen and phosphorus but also the CO₂ released by bivalves. Bivalves can filter and feed on phytoplankton, seaweed detritus, and litter. On one hand, this can purify the water, enhance the light, and provide more energy for the growth of seaweeds. On the other hand, this can prevent phytoplankton from competing against seaweeds for nutrient salts, which is beneficial to the growth and carbon accumulation of seaweeds. During the interaction between seaweeds and bivalves, the carbon sink in the integrated aquaculture system is improved to a great extent compared with that of monoculture.

(4) Implementing artificial blue carbon ranching (marine ranching) project. Through artificial reefs and other engineering technologies, we can restore the original populations and communities, and promote the recovery of traditional fishing grounds and marine ranch resources. An example is the oyster reef algae forest project. Building the artificial oyster reefs in shallow sea and the wild seaweed field with live oyster reefs as the base will form a wild seaweed-bivalve ecosystem, which can expand blue carbon enrichment area, provide habitat for marine organisms, and thus ensure stable and long-lasting carbon sink.
(5) Implementing artificial upwelling to enhance marine carbon sink. In kelp-dense aquaculture area, the too high density will cause severe shortage of nutrient salts in the upper water, which fails to meet the need of rapid growth and may even trigger the mass death of seaweeds in spring. Although nitrogen and phosphorus are abundant in the lower water where seaweed cannot grow, they cannot be effectively used. By employing artificial upwelling to transport excess nutrient salts from deep to upper water, we can meet the demand of seaweeds for carbon sequestration and growth by photosynthesis. An appropriate nutrient salt concentration not only improves seaweed production but also increases the combined effect of biological and microbial carbon pumps, thus increasing offshore carbon sink. Artificial upwelling, as a geoenineering system, can continuously bring deep seawater with rich nutrient salts up to the euphotic layer. This process will not only enhance the total nutrient salt concentration in the upper layer, but also adjust the imbalance of the ratio of nitrogen, phosphorus, silicon, and iron caused by biological growth and release. It is conducive to the photosynthesis of seaweeds and phytoplankton, which will increase the fish catch, aquaculture carbon sink, and the amount of organic carbon exported to the deep sea by improving the efficiency of biological carbon pump. The development of artificial upwelling system in China leads the international community. China has designed and prepared an artificial upwelling system which lifts marine deep layer water to the euphotic layer by using self-sufficient energy and injecting compressed air. This system has been proved effective through marine trials.

References


(Translated by WEN JX)