RETHINKING FISHERY CARBON SINKS AND CARBON SINK FISHERIES

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Abstract. A comprehensive understanding of the scientific concepts and definitions related to fishery carbon sinks (FCS) and carbon sink fisheries (CSF) is essential for advancing relevant theories and exploiting the potential associated with CSF. This paper draws the following conclusions: (1) The current definition of FCS does not accurately reflect the concept of net reduction of atmospheric greenhouse gases (GHGs), while the carbon footprint assessment of CSF fails to fully encompass its entire life-cycle stages. (2) Both algae and filter-feeding fish release carbon dioxide (CO_2) stored in their bodies after they are harvested and consumed, suggesting that their cultivation has limited potential as a carbon sink. (3) If the stock enhancement of fish can increase net biomass, it may contribute to certain benefits for CSF. (4) Beyond the energy consumption during breeding process, the carbon sink potential of shellfish farming largely depends on how their shells are disposed of and utilized. (5) The most effective approach for enhancing the carbon sink capacity of marine ecosystems is currently to implement fishing bans rather than allowing fishing. (6) Marine fisheries may be more appropriately classified as low-carbon fisheries rather than CSF. (7) The carbon sink potential of Chinese fisheries to be significantly overestimated, which could hinder the innovation and development of carbon sink fisheries.
Keywords: *fishery carbon sinks, carbon sink fisheries, net carbon reduction, carbon footprint, aquaculture, life cycle perspectives*

Introduction

The concepts of “fishery carbon sinks” (FCS) and “carbon sink fisheries” (CSF) were first proposed and named by Tang Qisheng, a renowned aquaculture expert and academician of the Chinese Academy of Engineering (CAE). These concepts are designed to improve the capacity of aquatic ecosystems to sequester atmospheric CO_2, which in turn contributes to a direct or indirect decrease in atmospheric CO_2 levels (Xiao et al., 2010; Tang et al., 2011). After the proposal of these concepts, they received considerable attention and research domestically. For instance, from November 19 to 20, 2010, the 109th Engineering Science and Technology Forum of the CAE, titled “Carbon Sink Fisheries and Low-Carbon Technologies in Fisheries,” was successfully held in Beijing, hosted by the CAE and co-organized by the Agricultural Division of CAE and the Chinese Academy of Fishery Sciences (CAFS). In 2011, China’s first carbon sink fishery laboratory was established at the Yellow Sea Fisheries Research Institute in Qingdao, Shandong Province. From October 27 to 29, 2014, an academic conference on “Carbon Sink Fisheries and Technological Development Strategy Consultation” was held in Jiangxi Province. Under the guidance of the Fisheries and Fishery Administration Bureau (FFAB) of the Ministry of Agriculture and Rural Affairs (MARA), the CAFS and the Qingdao Ecological Society hosted academic seminars in September 2021 and January 2022, respectively, titled “Developing Carbon Sink Fishery Technology to Serve the National Dual Carbon Strategy” and “Carbon Sink

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Processes, Mechanisms, and Amplification Models in Shellfish Farming Ecosystems." Related academic research results continue to be published (Liu et al., 2011; Tang et al., 2016; Shao et al., 2018; Yue et al., 2018; Sun et al., 2020; Xu et al., 2018; Xu et al., 2020; Li et al., 2010), especially after the national "Dual Carbon Goals" (i.e., carbon peaking and carbon neutrality) were proposed, leading to increased attention on relevant studies (Tang et al., 2022; Zhang et al., 2022). On the other hand, these two concepts do not seem to have received attention or recognition internationally, and there are even some contradictions between some of their viewpoints and emerging international perspectives (Mariani et al., 2020; Cavan et al., 2022). Scientific define of FCS and CSF remains a question worth exploring based on the concepts and related discussions proposed by Tang et al. (2010, 2011, 2022), We would like to present some differing views for discussion, hoping to contribute to the further refinement of these concepts and their scientific connotations, and to provide some reference value for the development of low-carbon fisheries in China and other countries.

Existing concepts of FCS and CSF

Tang et al. (2022) initially defined FCS as "the process and mechanism of promoting aquatic organisms to absorb CO_2 from water bodies through fishery activities and removing carbon from water bodies through the harvesting of aquatic biological products." Fishery activities that maximize the carbon sink function and directly or indirectly reduce atmospheric CO_2 concentrations are generally referred to as "CSF." "Any fishery activities that do not require feeding possess a carbon sink function and may contribute to the formation of a biological carbon sink, which can be classified as CSF." Examples include algae cultivation, shellfish farming, filter-feeding fish culture, artificial reproduction and releasing of fishery resource（ARRFR）, artificial reefs, and capture fisheries (Xiao et al., 2010; Zhang et al., 2011).

Later, the concept of "FCS" was formally revised (Tang et al., 2022): "It refers to the processes and mechanisms by which aquatic organisms absorb or utilize greenhouse gases, such as CO_2, in water through fishery production activities, based on the Intergovernmental Panel on Climate Change's explanation of carbon sinks and sources, as well as the carbon fixation characteristics of aquatic plants. This process involves removing carbon that has been converted into biological products from the water through harvesting or depositing it on the bottom of the water body via biological sedimentation". Tang et al. (2022) believed that "fishery carbon sinks include not only the carbon absorbed and utilized by algae through photosynthesis and filter-feeding organisms, such as shellfish and fish that filter large amounts of particulate organic carbon from the water, but also the carbon utilized by various fishery biological resources through food web mechanisms and growth through feeding.

The recently revised term "CSF" refers to fisheries activities that can function as a biological carbon sink and contribute to the direct or indirect reduction of CO_2 concentrations. This concept embodies the principles of green sustainable development within the fisheries sector. In practical terms, any fishery activities that do not involve artificial feeding demonstrate carbon sink capabilities and may establish a biological carbon sink, thus aligning with the definition of CSF. These activities include algal cultivation, filter-feeding shellfish and fish farming, stock enhancement of aquatic organisms, artificial reef, recreational fisheries, and capture fisheries, among others

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(Tang et al., 2022). Compared to the original definition, the core meaning of this revised definition remains consistent, with only minor distinctions in certain expressions.

Based on the revised definitions of FCS and CSF mentioned above, along with the three fundamental propositions proposed by Tang regarding how to enhance the carbon sink function in fisheries activities (Tang et al., 2022), we identified certain perspectives that lack a scientific basis. Consequently, this article presents a new discussion and introduces several novel viewpoints.

Deficiencies and revisions to the existing concept of FCS

Regarding the recently revised concept of FCS proposed by Tang et al. (2022), we argue that the extraction of carbon from aquatic environments should result in a net reduction of greenhouse gases (GHGs) in the atmosphere, rather than merely transferring them. In simpler terms, if the removal of GHGs from water is counterbalanced by an equal or greater emission of GHGs into the atmosphere from other sources, such processes cannot be classified as carbon sinks. Therefore, for an activity to be designated as a "fisheries carbon sink," it must ensure a "net reduction" of GHGs on a global scale. Even if a specific fishery activity enhances the absorption or utilization of GHGs, such as CO_2, by aquatic organisms, it cannot be considered a true fishery carbon sink if the carbon in these biological products is not stored after harvesting but is instead decomposed and released into the atmosphere through processing and consumption.

The definition provided by Tang et al. (2022) not only overlooks the GHGs emissions resulting from energy consumption and other inputs during fishery production but also neglects the carbon emissions associated with processed and consumed catch products, rendering it incomplete. This highlights a clear lack of an internationally recognized systematic perspective that encompasses the entire life cycle process. If there is a need to define a fisheries carbon sink, we suggest a straightforward definition: "the net reduction of GHGs resulting from fisheries activities." Naturally, such fisheries can be referred to as CSF. Fisheries that do not achieve a net reduction in their carbon footprint but exhibit a significantly lower carbon footprint can be termed "low-carbon fisheries."

Does the cultivation and harvesting of aquatic algae serve a carbon sequestration function?

Tang et al. (2022) posited that "aquatic algae, including cultured varieties such as Laminaria, Gracilaria, and Euestrin, as well as harvested algae like Enteromorpha and macroalgae, serve as typical carbon sink organisms. They absorb CO_2 and other carbon compounds from the water through photosynthesis during reproduction and growth, directly contributing to the carbon sink function and enhancing carbon sequestration." However, we argue that while the cultivation of algae (such as Laminaria, laver, Gracilaria, and Euteca) can significantly increase the yield and fixed CO_2 of the cultured species, it also substantially reduces the original biomass of planktonic algae and their CO_2 fixation due to competition for nutrient salts and light resources. Additionally, as primary producers, some of the carbon from marine planktonic algae can be transformed into various forms of biological carbon in marine fish and shellfish through the food chain, contributing to long-term carbon storage and functioning as a

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form of carbon sink. In contrast, the carbon in cultivated algae is rapidly decomposed into CO_2 upon consumption, releasing it back into the atmosphere. Therefore, even without considering the greenhouse gases (GHGs) emitted during energy-intensive production activities such as algae cultivation and harvesting, achieving a net reduction of GHGs is not feasible solely through the cultivation and consumption of algae. In other words, the carbon sink function cannot be realized. However, algae farming may still have a lower carbon footprint than other feed-dependent fisheries, making it more appropriate to categorize it as a low-carbon fishery rather than a carbon sink fishery.

Whether the aquaculture of filter-feeding shellfish and fish serves as a carbon sink function

Tang et al. (2022) posited that filter-feeding shellfish (e.g., oysters, clams, scallops) and fish (e.g., silver carp and bighead carp), along with other cultured organisms, filter substantial amounts of organic carbon particles, including phytoplankton and organic debris, during their growth. Additionally, these organisms utilize inorganic carbon in the shell formation process, thereby indirectly enhancing the carbon sink function. This enhancement is attributed to the biofiltration feeding process, in which a significant portion of particulate organic carbon, primarily phytoplankton, is consumed. Simultaneously, the proliferation of phytoplankton is stimulated, increasing the absorption and utilization of carbon elements such as CO_2 in the water, which results in the generation of new carbon sink products (Tang et al., 2022). We contend that the cultivation of filter-feeding shellfish contributes to carbon fixation in both their shells and soft tissues. While the carbon contained in soft tissues is rapidly broken down and released into the atmosphere upon human consumption, this represents a relatively small portion of the total carbon. In contrast, the carbon contained in shells undergoes slower natural decomposition, indicating that shellfish farming can theoretically enhance both shellfish production and authentic carbon sequestration within a specific marine area. Given that the edible portion of cultured shellfish is limited (Zhou et al., 2002), a significant proportion consists of inedible shells. If these shells are not effectively utilized after consumption or processing, it leads to a substantial increase in kitchen waste, resulting in higher transportation and disposal costs. Opting for landfill disposal ensures long-term carbon storage but raises concerns about land occupation. Conversely, incineration reduces the amount of final landfill space but releases stored CO_2 during the incineration process. Utilizing the shells left behind after mollusks are consumed as fillers for artificial reefs facilitates carbon storage while simultaneously decreasing the need for consumables in artificial reef production and the associated CO_2 emissions. Consequently, the enhanced carbon storage and environmental impact of shellfish farming depend not only on increased yields but also significantly on the ultimate disposal or utilization of shellfish after consumption.

Regarding the cultivation of filter-feeding fish, such as silver carp and bighead carp, it is suggested that these species primarily sequester a portion of carbon in their bodies by consuming planktonic algae and zooplankton. Upon capture and human consumption, the carbon in these fish rapidly converts to CO_2, returning to the atmosphere. As a result, they do not serve as true carbon sinks and can only be considered relatively low-carbon compared to fish that rely on artificial feed.

Does the filter feeding of cultured organisms really promote the reproduction and growth of phytoplankton, thereby increasing the absorption and utilization of carbon

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elements such as CO_2 in the water, and generating new carbon sink products? If the answer is affirmative, it suggests an increase in the value of net primary productivity (NPP) within the water body following the introduction of filter-feeders. However, is this outcome affirmative? The answer is not necessarily yes. The value of NPP in a water body primarily depends on various factors, including the type of primary producers present, their density, nutrient concentration, and local light and temperature conditions (Anderson et al., 2021; Lemmen, 2018). In natural ecosystems, primary producers are often not the limiting factors; instead, nutrient concentrations, light availability, and air temperature typically serve as the primary constraints influencing local NPP (Sun et al., 2023; Gao et al., 2021). In conventional large-scale aquaculture, the carrying capacity of species such as silver carp and bighead carp is generally assessed based on the NPP of the water body (Wang et al., 1981; Han et al., 2002; Zhao et al., 2022). Notably, in efforts to control cyanobacterial blooms in eutrophic waters, numerous studies—both domestic and international—have examined the impact of silver carp and bighead carp on plankton communities. Currently, there is a relatively consistent conclusion that the introduction of these species alters the species composition of the phytoplankton community. This alteration includes a reduction in the abundance of larger planktonic algae, such as *Microcystis aeruginosa*, and zooplankton, while promoting the growth of smaller planktonic algae (Wang et al., 2009, 2011, 2016; Feng et al., 2018; Fukushima et al., 1999; Dong et al., 1994; Domaizon et al., 1999; Zhao et al., 2013; Yang et al., 2019). However, regarding whether this introduction enhances the biomass of planktonic algae, the answer is not uniform; divergent opinions exist, with some studies suggesting it may reduce the biomass or production of phytoplankton. For instance, Kajak et al. (1975) conducted an experiment by releasing silver carp (at densities of 30 to 90 $g \cdot m^{-3}$) into Lake Warniak, Poland, resulting in a significant decrease in the total biomass of phytoplankton (Kajak et al., 1975). Zhao (1993) observed that at low densities of silver carp and bighead carp, algal production and biomass increased with density. However, upon reaching a certain density and continuing to increase it, algal production and biomass exhibited varying degrees of decline (Zhao, 1993). Li et al. (1993) reported a substantial decline in zooplankton biomass (58.7%), phytoplankton biomass (63.6%), chlorophyll a (52.5%), and phytoplankton gross yield (65.0%) following the introduction of silver carp (Li et al., 1993). In a large-scale enclosure experiment in Paranoa Reservoir, Starling et al. (1998) demonstrated a significant reduction in net phytoplankton biomass at a silver carp stocking density of 60 $g \cdot m^{-3}$ (Starling et al., 1998). Fukushima et al. (1999) found that in a simplified system lacking large zooplankton, silver carp effectively suppressed cyanobacterial propagation and reduced total algal biomass (Fukushima et al., 1999). Guo et al. (2015) found that the phytoplankton biomass within the enclosures stocked with silver carp was significantly lower than that in the surrounding lake. The study by Zhang et al. (2023) indicates that after the stocking of filter-feeding fish in a subtropical plateau reservoir in Southwest China, although the nutrient concentrations did not decrease, the total biomass of phytoplankton and the biomass of cyanobacteria significantly decreased. Certainly, some studies have reported that the biomass of plankton algae may remain stable or even increase after the introduction of filter-feeding fish (Wang et al., 2009, 2016, 1986; Feng et al., 2018; da Silva et al., 2014). In summary, the current consensus acknowledges that alterations in phytoplankton productivity following the introduction of filter-feeding fish are contingent on various factors,

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including the nutrient status of the water body, fish stocking density, water body depth, substrate conditions, and the species composition of the phytoplankton community, and may not necessarily result in an increase.

How many is the true carbon sink resulting from fishery biological groups?

Tang et al. (2022) argued that "fishery biological groups, including fishing and breeding groups, consist of organisms such as fish, crustaceans, cephalopods, and shellfish that depend on plankton, shellfish, and other lower trophic species for their food. These groups utilize carbon products across various trophic levels through food web mechanisms and growth processes. This indirect interaction enhances the carbon sink function. Species at higher trophic levels feed on natural aquatic resources, consuming a significant amount of particulate organic carbon, primarily sourced from phytoplankton at the lower levels of the food chain. The harvesting and proliferation of these species effectively remove a considerable quantity of carbon from the water, thereby increasing the carbon sink".

We argue that fishing industry involves the harvesting and processing of various marine organisms, including fish, shellfish, and crustaceans, for human consumption. Beyond the energy consumed during the fishing process and the greenhouse gas emissions generated from this organism post-consumption, the impact on the original aquatic ecosystem is twofold. On one hand, it reduces the carbon storage capacity of the original fishery organisms. On the other hand, it leads to a decline in the number of breeding individuals within the population, thereby diminishing both the breeding potential and overall biomass of the entire population. Consequently, this reduction limits the future capacity to sequester carbon in aquatic environments such as oceans. Therefore, the extraction of natural fishery populations does not fulfill a genuine carbon sink function. As argued by Mariani et al. (2020) in their publication in the esteemed academic journal Science Advances, "unlike most terrestrial organisms that release carbon into the atmosphere upon death, the carcasses of large marine fish sink and sequester carbon in the deep ocean. Nevertheless, fisheries have extracted a substantial amount of this 'blue carbon,' contributing to additional atmospheric CO_2 emissions." By utilizing historical catch and fuel consumption data, Mariani et al. (2020) estimated that marine fisheries released at least 0.73 billion metric tons of CO_2 into the atmosphere between 1950 and 2014 (Mariani et al., 2020). Additionally, Cavan et al. (2021) demonstrated that biomass and ecosystem changes resulting from marine fishing may adversely impact carbon deposition and storage throughout the entire water column and seafloor, consequently influencing atmospheric CO_2 levels (Cavan et al., 2021). Hence, fishing appears to impede blue carbon sequestration, contrary to the assertion by Tang et al. (2022) that it a considerable amount of carbon from the water and increases the carbon sink.

The stock enhancement of fish contributes to an increase in the biomass of fishery organisms within aquatic ecosystems. This growth allows fish to store carbon derived from plankton and other aquatic organisms in their bodies, creating a genuine carbon sink effect. However, it is important to note that if all proliferating fish are harvested for consumption, the carbon sink effect will be diminished, potentially reaching zero or even becoming negative. This reduction is due to the energy expenditure associated with fishing activities and the release of CO_2 during the decomposition of consumed fish.

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Do fishery activities without feed input necessarily have carbon sink function?

Tang et al. (2022) posited that "fishery production activities devoid of feeding exhibit carbon sink capabilities and may give rise to a biological carbon sink, referred to as CSF. This includes algal cultivation, filter-feeding shellfish and fish farming, enhancement of fishery resource (such as stock enhancement of fish and deployment of artificial reefs.), recreational fisheries, and capture fisheries". From our perspective, in addition to the previously mentioned analysis, two additional issues warrant consideration. Firstly, fishery activities that do not involve feeding do not necessarily indicate an absence of CO_2 emissions; numerous processes contribute to both direct and indirect CO_2 emissions. For instance, in algae seeding, raft construction, product harvesting, drying, and other related processes, as well as in shellfish production, activities such as seeding, harvesting, transportation, and marketing all contribute to CO_2 emissions. Additionally, the production and proliferation of filter-feeding fish involve CO_2 emissions during breeding, seeding, fishing, transportation, and marketing. The construction and placement of artificial reefs, along with activities in capture fisheries—such as fishing operations, fishing vessel manufacturing, and maintenance—also require energy input, resulting in direct or indirect CO_2 emissions. Clearly, if the CO_2 emissions from these fishery production activities do not significantly exceed the newly added CO_2 captured in their operations, the concept of a fishery "carbon sink," even if it exists, holds little practical significance. Secondly, the value of the newly increased CO_2 storage in marine organisms must be evaluated in comparison to the state prior to the introduction of fishery activities. If there is no substantial increase, or if the increase is insufficient to offset the CO_2 emissions from the fishery process, a genuine carbon sink does not exist.

Conclusion

Based on the analysis above, it is evident that the current definition of FCS does not accurately capture the concept of a net reduction in atmospheric GHGs. Similarly, CSF fails to adopt a comprehensive life cycle perspective, addressing only the reduction of GHGs at specific life cycle stages of fishery activities. In fact, current fishery practices, with exception of fish stock enhancement and use of artificial fish reefs, demonstrate limited capacity for carbon sequestration. Furthermore, various fishery production processes require substantial energy inputs. We argue that, given current technologies, the carbon sink potential of fisheries is minimal, if it exists at all. Concurrently, it becomes evident that, given the ongoing depletion of marine resources, implementing fishing bans is the most effective strategy for enhancing the carbon sink potential of marine organisms. This approach could even be considered the true carbon sink within the fisheries sector. Given the existing definition, there is a risk of significantly overestimating China's FCS potential, which could hinder the innovation and development of fisheries with genuine carbon sink capabilities.

It is essential to emphasize that, given current fishing practices, we argue that the carbon sink potential from fisheries is not significant. However, this assertion does not undermine the importance of research in this field, nor does it suggest that marine fisheries lack developmental value. On the contrary, marine fisheries play a vital role in providing abundant, high-quality protein and food for humanity. Furthermore, when compared to other sources of animal protein, such as livestock farming, marine fisheries may have a relatively lower carbon footprint and reduced environmental impacts. From

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this perspective, the development of marine fisheries can simultaneously meet human protein needs while minimizing the carbon footprint associated with human activities. Therefore, it may be more appropriate to consider marine fisheries as low-carbon fisheries rather than categorizing them explicitly as carbon sink fisheries. Nevertheless, the true nature of CSF in real-world scenarios remains an unanswered question that requires further investigation.

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