TRAINING MODULE SERIES NO.1

Training Module for Integrated Multitrophic Aquaculture in PR China

黄海大海洋生态系二期项目中国海水多营养层次综合养殖培训教材

Edited by
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Implementing the Strategic Action Programme for the Yellow Sea Large Marine Ecosystem: Restoring Ecosystem Goods and Services and Consolidation of a Long-term Regional Environmental Governance Framework (UNDP/GEF YSLME Phase II Project)

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Preface

FAO estimates that 79 percent of fisheries are either fully exploited, overexploited or depleted, with only a small number having the chance to recover from depletion. Global marine capture fishery production has declined by 1.6 per cent from 2006 to 2011. During the same period, marine aquaculture production increased by 20.6 per cent. Overfishing and depletion of wild fishery stocks and increasing global demand for seafood from aquaculture determines that the role of mariculture in seafood supply will be critical in the years to come.

Environmental challenges of mariculture necessitate improvements and innovation in mariculture management and technologies. UNDP/GEF YSLME Phase II Project aims to foster long-term sustainable institutional, policy and financial arrangements for effective ecosystem-based management of the Yellow Sea. Recovery of depleted fish stocks and improved mariculture production and quality and improved ecosystem health are among the outcomes of the project. Capturing and disseminating IMTA through developing training modules and conduct of training programs are part and parcel of the project approaches to promoting sustainable investment in aquaculture that will lead to a more ecologically sustainable mariculture in Yellow Sea region.

Training Module for Integrated Multitrophic Aquaculture in PR China represents the collective efforts of scientists in documenting the practices of IMTA in PR China and elsewhere. It consists of six chapters, starting with an introduction of IMTA development in PR China and other countries, followed by assessment of carrying capacity of IMTA seawaters. In Chapter 3, the modules illustrate IMTA modalities of shellfish-seaweed and shellfish-seaweed-sea cucumber, pond-based IMTA, land-based integrated multi-trophic recirculating aquaculture model and application of IMTA in sea ranching programs. Through case studies, the modules talk about evaluation of ecosystem services of different IMTA models in Chapter 4, introduce two methods to conduct environmental monitoring of IMTA in Chapter 5, followed by prospects and suggestions of IMTA replication in YSLME and coastal areas in other countries.

We hope the module can serve as a useful reference to the aquaculture managers, researchers and university students in their pursuit for environmentally friendly aquaculture.

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1

Global view on the development of IMTA

1.1 Introduction

In 2004, Canadian scientist Chopin proposed the concept of Integrated Multi-Trophic Aquaculture (IMTA) which combined multi-trophic aquaculture with integrated aquaculture. The fundamental theory of IMTA is that the organic or inorganic matter (e.g., waste feed, feces) generated from the feeding culture units (e.g., fish and shrimp) provides the nutrients for other culture units (filter-feeding shellfish) within this culture system combining different tropics. This approach makes efficient use of nutrients in the system and mitigates the pressure of the local ecosystem, thus improving culture diversity and enhancing profit which finally contributes to the sustainable development of aquaculture.

1.2 IMTA in PR China

PR China is one of the earliest countries that operated integrated aquaculture. There are clear records of integrated aquaculture through Chinese history (since 220), including rice-fish integrated culture and orchard land-pool farming. Seawater integrated culture started in the 1970s, and the major culture modes are kelp-mussel culture at coast and pond-based shrimp-fish culture. IMTA in PR China started in the 1990s but developed relatively fast. The major maritime IMTA includes culture modes of shellfish-seaweed, fish-shellfish-seaweed and fish-shellfish-seaweed-sea cucumber; and pond IMTA are mainly shrimp-fish-shellfish-crab culture system. The research of IMTA in PR China achieved brilliant breakthroughs in the bio-element cycle, bio-geochemical process and the carbon sink theory and techniques. IMTA has several characteristics:

1.2.1 Non-top level harvesting strategies

The harvesting of IMTA is mainly on the low-trophic level organisms such as shellfish and seaweed. Research results showed that lower trophic organisms have higher energy and material transfer efficiency, while such transfer efficiency is relatively low for higher trophic organisms. The culture of lower trophic organisms achieves better production rates, which improve the ecosystem level biomass production. PR China has more demand for quantity of biomass production, so low-trophic level as majority of the culture system become a better aquaculture practice instead of high-trophic level organisms, as the higher systematical production.

1.2.2 Carbon sink functions of shellfish and seaweed culture

Cultured organisms such as shellfish and seaweed absorb carbon from seawater by filter feeding phytoplankton and organic particles or the photosynthesis process. And such absorbed carbon will be removed from the system by harvesting, forming the ‘removable carbon sink’ (Jihong Zhang et al., 2005) which have been stored or re-used. China is the largest aquaculture producer of shellfish and seaweed, with annual production of more than 10 million tonnes. Research showed that during 1999–2008, about 3.79 million tonnes of carbon were absorbed and used annually, among which about 1.2 million tonnes of carbon were removed by harvest. Such amount of carbon absorption greatly enhanced carbon storage ability of the coastal marine ecosystem to the carbon dioxide in the atmosphere (Tang et al, 2001). The above results showed that the shellfish-seaweed based aquaculture system represents the ecosystem service of aquaculture, with promoted carbon sink ability at an ecosystem level, such IMTA system is representative of environment-friendly developing mode.

1.2.3 Aquaculture at ecosystem level

IMTA is a sustainable concept of aquaculture development, as the nutrient recycle is an important process in the ecosystem based on the theory of material and energy conservation. IMTA with different trophic levels (e.g., feeding organisms, filter-feeding shellfish, macro algae and sedimentary animals) can efficiently operate input energy and nutrients and reduce nutrient loss and economic risks, allowing the culture system to have high carrying capacity and profit. IMTA can balance the extra nutrient input by culture activity, which contributes to self-rehabilitation of the ecosystem. The culture of deposition feeding organisms can effectively maintain the level of dissolved oxygen content and reduce the risk of eutrophication. Therefore, it is necessary to apply IMTA to the current aquaculture system in an appropriate way, to combine mutual benefit culture species in order to minimize or avoid ecosystem pressure from aquaculture activities, and enhance production of the coastal zone.

1.2.4 Ecosystem level management

Ecosystem management refers to the long-term management of ecosystem production, restoration or maintenance to provide expected status, usage, products and service with ecology, economics, sociology and management principles. The major objective of ecosystem management is to ensure ecological integrity and sustainability by manipulating the physical, chemical and biological processes. Ecosystem-level mariculture is to harmonize mariculture activities with eco-sustainable development request and to achieve the best balance between different social goals, by taking into account the interaction between organisms, non-organisms and human beings within ecosystems.

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1.3 Global IMTA development and current situation

As a sustainable development concept, the research and practice of IMTA has been widely conducted globally and feedbacks are positive.

1.3.1 Canada

In 2013, the total marine production in Canada was about 172,000 tonnes with a value about $740 million. About 16% of production and 35% of total value are contributed by aquaculture. Major cultured shellfish are mussels (*Mytilus edulis*): 69.6% of total production and oysters (*Crassostrea virginica* and *Crassostrea gigas*): 30% of total production. PEI is the major region for mussel production with annual production of 23,000 tonnes, accounting for 78.7% of total mussel production. Mussel produced in NL and NS make up 15.0% and 3.6% of the total respectively. Other than oysters and mussels, there are also cultured shellfish species such as clams, cockles, Japanese scallops, bay scallops, geoduck and round clams.

Within the past eight years, IMTA projects have been developed on both the Atlantic and Pacific coasts. On the Atlantic coast, in the Bay of Fundy, a project integrating the culture of salmon (*Salmo salar*), blue mussels (*Mytilus edulis*) and kelp (*Saccharina latissima*, previously described as *Laminaria saccharina*, and *Alaria esculenta*) has been ongoing since 2001 (Chopin and Robinson, 2004) and the results support the establishment of IMTA systems in this region. Innovative kelp culture techniques have been developed and improved both in the laboratory and at the aquaculture sites. Increased growth rates of kelp (46%; Chopin et al., 2004) and mussels (50%; Lander et al., 2004) cultured in proximity to fish farms, compared to reference sites, reflect the increase in food availability and energy. Nutrient, biomass and oxygen levels are being monitored to estimate the biomitigation potential of an IMTA site. Salmonid solid and soluble nutrient loading is being modelled as the initial step towards the development of an overall flexible IMTA model. The extrapolation of a mass balance approach using bioenergetics is being juxtaposed with modern measures of ecosystem health such as exergy. Over eight years, none of the therapeutants used in salmon aquaculture have been detected in kelp and mussels collected from IMTA sites; levels of heavy metals, arsenic, PCBs and pesticides have always been below Canadian Food Inspection Agency, USA Food and Drug Administration, and European Community Directive regulatory limits. A taste test at market size conducted on site grown versus reference mussels showed no discernable difference (Lander et al., 2004). *Alexandrium fundyense*, the dinoflagellate responsible for producing paralytic shellfish poisoning (PSP) toxins, occurs annually in the Bay of Fundy and mussels can accumulate these toxins above regulatory limits in the summer/early fall. However, PSP toxin concentrations in mussels decreased readily as the blooms of *Alexandrium fundyense* diminished. Domoic acid, released by the diatom *Pseudo-nitzschia pseudodelicatissima*, was never above regulatory limits over eight years. All these results indicate that, with the proper monitoring and management, mussels and seaweeds from IMTA operations can be safely harvested as seafood for human consumption (Haya et al., 2004).

Two attitudinal studies towards salmon farming in general, and IMTA in particular, were conducted (Ridler et al., 2007). The first survey found that the general public was more negative towards current monoculture practices and feels positive that IMTA would be successful (Robinson et al., in press). The second attitudinal survey, a focus group study (Barrington et al., 2008), showed that most participants felt that IMTA has the potential to reduce the environmental impacts of salmon farming (65%), improve waste management in aquaculture (100%), benefit community economies (96%), provide employment opportunities (91%), improve food production (100%), improve industry competitiveness (96%) and overall sustainability (73%). All felt that seafood produced in IMTA systems would be safe to eat and 50 percent were willing to pay 10 percent more for these products if labelled as such, which opens the door to developing markets for differentiated premium IMTA products, either environmentally labelled or organically certified.

Recently, to promote industrialization of IMTA, the National Science and Engineering Research Council (NSERC) set up the Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) with a special IMTA logo. CIMTAN collaborates a provincial research laboratory, 6 federal fisheries branch institutes, 8 universities and 26 professors and researchers in related areas. The objective of CIMTAN is to study the key process and mechanisms of IMTA systems, in order to cover aspects such as technique innovation, profit analysis, industrialization, disease control and quality secure, thus showing the recognition from the government and academics.

1.3.2 Chile

Chile, the largest aquaculture country in South America, ranks among the top ten aquaculture producers in the world since 2005, with about 98.5% of aquatic products from the seawater. Statistics showed that mariculture developed rapidly since mid-1980s in Chile, and production increased from 13,000 tonnes in 1997 to about 1 million tonnes in 2013, with an annual increase of about 18.18%, and the account of mariculture production in total seafood production also increased from 0.26% in 1987 to 30.43% in 2013. In 2013, Chile produced 736,000 tonnes of fish, 252,500 tonnes of shellfish and 12,500 tonnes of seaweed, the total values for each are $4.967 billion, $227 million and $23 million respectively.

The three most economically important salmonids are *Salmo salar*, *Oncorhynchus kisutch* and *Oncorhynchus mykiss*. About 99% of the Atlantic salmon production are from aquaculture in Chile, and rank 2nd in the world since 2000, behind Norway. The Atlantic salmon produced by Chile and Norway accounts for more than 60% of the world total. In 2013, Chile produced 470,300 tonnes of Atlantic salmon, which is most of their culture history. Besides the culture of salmon, monocultures of mussels (*Mytilus chilensis* and *Choromytilus chorus*), scallops (*Argopecten purpuratus*) and oysters (*Tiostrea chilensis* and *Crassostrea gigas*) are commonplace (Buschmann et al., 1996). To date, *Gracilaria chilensis* is the only species cultured on a commercial level (Buschmann et al., 2005; 2006).

IMTA started in the late 1980s in Chile, but is still small. The first attempt considered the development of land-based intensive marine systems using pumped seawater to intensively culture trout (*Oncorhynchus mykiss*). The fish effluents were then first used for the cultivation of oyster (*Crassostrea gigas*) and second for agar-producing alga *Gracilaria chilensis*, both able to significantly reduce nitrogen and phosphorus. The first trials were successful and demonstrated that an IMTA approach was an additional way for developing a more sustainable aquaculture approach. It consists of seaweed-finfish culture sites, where the algae *Gracilaria chilensis* and *Macrocystis pyrifera* are co-cultivated with salmon (Troell et al., 1997). IMTA units are promising as research has shown that biomass productivity of *Gracilaria chilensis* increased by 30 percent when grown with salmon, and it also has a higher agar quality (Buschmann et al., 2005. Longline culture device is proven to be an efficient technique to remove nutrients. Nitrate removed every month (every meter) can be up to 9.3 g, about 100 ha longline. *Gracilaria chilensis* culture farm is able to balance the Nitrate input from a 1,500 t production scale salmon farm. Besides, to reduce waste feed and feces pressure of the sediment under salmon farms, cage culture of crabs and shrimps is conducted under fish cages. Such culture technique innovation follows the ecological culture theory and provides extra profit for farmers.

The development of abalone cultivation is presently emerging in Chile, adding an extra pressure on natural resources of seaweeds as a source of feed. A pilot scale farm (4-5 ha) is already producing the brown alga *Macrocystis pyrifera* and has demonstrated its technical and economic feasibility. Linking salmon aquaculture (source of nutrients for seaweeds) with seaweed aquaculture (source of food for abalone) and abalone aquaculture (final recipient of the food and energy passed along) could represent another interesting IMTA system.

1.3.3 South Africa

South Africa is one of the five major fishery countries in the Southern Hemisphere. Seawater fisheries occupies the aquatic industry, and accounts for more than 99% of total production. In recent few decades, the government of South Africa has committed severe fish catching quota management and greatly promoted aquaculture. The commercial mariculture of South Africa started with oysters in the late 1940s. With aquaculture development, the cultured species have increased: mussel culture in 1980s, abalone culture in 1990s and mariculture of fish since 2000. There are about 16 major culture species in South Africa, including seawater fish, abalone, oysters, mussels, algae, sea urchins, scallops, sea cucumbers, etc. About seven of which have reached commercial scales, including *Argyrosomus japonicus*, *Haliotis midae*, *C. gigas*, *Mytilus galloprovincialis*, *Choromytilus meridionalis, Ulva spp* and *Gracilaria spp*. *Ulva spp.* and *Gracilaria spp.* are mainly cultured as abalone feed. Shellfish are major culture species in South Africa, and they produced 2,205 tonnes of shellfish in 2013. Major species of culture shellfish are abalone and scallops, with total value of $44.8 million.

Abalone is the most important culture species in South Africa, since 1990s. Abalone is cultured on land-based ponds and with 20 years of development, a land-based water cycle culture system was developed with Midas ear abalone, Ulva spp. and Gracilaria spp.

Currently, there are 13 such culture systems producing more than 850 tonnes of products. In such IMTA systems, about 25% of seawater is re-circulated and after 19 months of culture, the abalone produced with this system does not have significant difference compared to those cultured with traditional methods, and showing higher efficiency. Further, as seaweeds remove ammonium from the seawater and add oxygen, abalone wastewater passing through seaweed ponds can be partially re-circulated back to abalone tanks, thus potentially reducing pumping costs. It has been shown that a farm can operate successfully at 50 percent re-circulation, and even higher recirculation (up to 100 percent) can be sustained for shorter periods. This can, of course, be optimized, depending on what the main objective is with re-circulation. The ability to operate in re-circulation mode is important as red tides occasionally occur along the South African coast. Moreover, some coastal areas experience heavy traffic of tanker boats, which represent potential risks for oil spills. There is also strong socioeconomic pressure on the South African government to create more jobs in the area, which has high unemployment and poverty levels (Troell et al., 2006). The further expansion and permanent job creation potential of this industry, as well as indirect related jobs, in remote coastal communities, is very attractive. There is much support for this practice of co-cultivating kelp with abalone, from government, industry and the general population.

1.3.4 Norway, Sweden and Finland

Aquaculture in the Scandinavian countries of Norway, Sweden and Finland is largely focused on monocultures of salmonids and mussels. A review of the existing literature shows that there are no commercial harvests of cultured seaweed in these countries, nor are there any commercial IMTA systems. Norway is by far the leader in salmon aquaculture in Europe, producing 71 percent of the region's Atlantic salmon (FAO, 2006a). The Norwegian aquaculture industry produces large amounts of salmon and rainbow trout, to a lesser extent cod, halibut, turbot and eel, and shellfish – mussels, oysters and scallops (Maroni, 2000). In 2013, Norway produced 1,245,400 tonnes of fish and 2,363 tonnes of shellfish, with a respective value of 6.89 billion and 2.23 billion. The Swedish and Finnish aquaculture industries are substantially smaller than that of Norway. The Swedish aquaculture industry produces rainbow trout, salmon, eel, arctic char, blue mussel and crayfish (Ackefors, 2000). The Finnish aquaculture industry produces primarily rainbow trout and salmon (Varjopuro et al., 2000). In 2013, Sweden produced 1,702 tonnes of shellfish and 3,122 tonnes of fish, with a respective value of US$ 1.57million and US$ 15.04 million. Finland produced 11,480 tonnes of fish, with a value of US$ 53.99 million.

These countries, especially Norway, experienced a large boom in salmon and trout monoculture in the late 1980s and throughout the 1990s (Maroni, 2000). As a result of this rapid and largely unchecked expansion, disease and parasite outbreaks were common. To help control this situation, the government began to strictly control the salmon culture industry, and as a result have some of the most detailed records of farm activity in the world (Maroni, 2000). License applications have strict outlines and environmental monitoring programs in place. With such stringent industry control on environmental monitoring, and the large volume of monocultured fish, Norway could be an excellent candidate for IMTA systems. Researchers in Norway have tried the IMTA of *Mytilus edulis*, *Pecten Maximus* and *Saccharina latissima* at Atlantic salmon farms at Tristein, Flåtegrunnen, etc. Results showed that the kelp at 2m, 5m and 8m at IMTA sites grow to about 0.45cm/d during February to June, compared to 0.2cm/d at a control site about 1 km away at same depths (Handå A et al., 2012). Stable carbon and nitrogen isotope and aliphatic acid tracer results showed that mussels and European scallops can effectively utilize waste feed and feces generated during the Atlantic salmon farming and 18: 1 n-9 unsaturated aliphatic acid as biomarkers has been screened as bio-indicators (Handå A et al., 2012; Handå A et al., 2013).

1.3.5 Israel

As a country with water stress, Israel has long been working on efficient and ecological aquaculture research. In recent years, the land-based fish-shellfish-algae IMTA and shrimp-algae IMTA has developed rapidly in Israel. In the land-based fish-shellfish-algae IMTA system, water is re-circulated from the fish culture unit (such as Tilapia with annual production of 25 kg per m^2) to filter-feeding culture unit (*Crassostrea gigas*, *Tapes philippinarum* with annual production of 5–10 kg per m^2), the large-size suspending particles in water will be filtered and water transparency will increase, such water will continue to transpor macro algae such as *Ulva lactuca* and *Gracilaria conferta* (annual production 50 kg per m^2). Macro algae will effectively reduce the organic matters in the culture water, and the protein concentration within *Ulva lactuca* could be 40% per gram dry weight, which is 2-4 times than that of wild ones, which is better feed for abalone. Only 10%-20% of the algae culture water is discharged into the sea. The rest of the seawater is recycled again to fish, abalone and sea urchin culture (Lai Qifang et al., 2007; Shpigel M et al., 2007). Nitrogen budget analysis results show that fish, filter feeding shellfish and algae respectively assimilate 21%, 15% and 22% of nitrogen, and 32% of nitrogen is deposited to the bottom in the form of feces, peusdo-feces and wasted feed, only about 10% of the nitrogen is released into the sea (Shpigel M et al., 2007). In the shrimp-algae IMTA system, the major farming shrimp is *penaeus vannamei* and the major algae is red algae (*Gracilaria*). The yield of shrimp was 11.75g / (m2*d) and the survival rate was over 98% in such IMTA system of about 20 m^3 (27.4 m^2 in area). The specific growth rate of algae was 4.8%/d, nitrogen content of algae was about 5.7% and C/N ratio was 4.8. The results showed that shrimp and algae assimilated 35% of the nitrogen in the feed, which greatly increased nitrogen use efficiency.

1.3.6 South Korea

Modern intensive aquaculture has begun in 1980's in South Korea. During the past 30 years, the development of aquaculture is quick, with the aquaculture production increasing from 790,000 MT in 1985 to nearly 1.7 million MT in 2015. The commercial value of aquaculture in 2015 was over US$2.1 billion (FAO, 2018). The Korean aquaculture production is dominated by seaweed (1.2 million MT), followed by shellfish (330,000 MT) and finfish (85,000 MT) in 2015 (FAO, 2018).

South Korea is an early country to conduct IMTA research. The National Fisheries Research and Development Institute (NFRDI) has already established guidelines for polyculture since 1994 (NFRDI 1994). They have carried out a series of basic biological and ecological studies to provide basic data and theory for IMTA mode. Significant results have been achieved in the following areas. Among the extractive organisms, seaweeds are found essential in IMTA. Nutrient uptake, storage, assimilation, and growth of seaweeds using nutrient sources from fish pond effluents have been reported (Chung et al., 2002; Kim et al., 2007; Kim et al. 2012; 2013a; 2013b; Kang et al., 2014). In Korea, the principal candidate macroalgal genera for aquaculture are *Porphyra*, *Laminaria*, and *Undaria*, which growth seasons are from autumn to spring. But most fish species are grown in summer. In order to solve the problem, based on culture season and economic benefits, they carried out screening work for seaweed suitable in summer. They found that *Codium fragile* and *Gracilaria vermiculophylla* could grow well in summer and have great capability as ammonium biofilter in IMTA system (Kang et al., 2008; Kim et al., 2016). The ammonium removal efficiency of *Codium fragile* was significantly greater at 20°C and 25°C under irradiance of 100 μmol photons m^{-2} s^{-1} than under other conditions tested, *Codium fragile* would be a prime candidate for summertime IMTA (Kang et al., 2008). A kelp strain of *Saccharina japonica* tolerant to high temperature has also been developed using selective breeding technologies in Korea (Hwang et al., 2017). These strains can be potential summer species for the Korean IMTA practices. Development of a series of sustainable land-based seaweed cultivation system, such as for *Gracilaria tikvahiae* and *Ulva compressa*, and demonstrated the use of high stocking density and high PAR, coupled with CO_2 enhancement, may be most efficacious option to optimize productivity of *G. tikvahiae* in land-based nursery cultivation systems. These results promoted development of land-based IMTA (Kim and Yarish, 2014; Mendoza et al., 2018).

The history of land-based integrated farming is earlier than that of open water. Most Korean IMTA practices have been conducted in small land-based systems (Chung et al., 2002; Kang et al., 2008, 2013, 2014). Juvenile *Apostichopus japonicus* and *Stichopus japonicus* have been successfully incorporated into land-based systems usually used for the production of abalone, *Haliotis discus hannai* (Kang et al. 2003; Jin et al. 2011; Kim et al. 2015). The levels of ammonium nitrogen and nitrite in the water of integrated groups were lower than those in control group (abalone alone) throughout the experiment, and abalone in integrated groups showed significantly better growth performance and higher survival, suggesting that integration of juvenile abalone with sea cucumber, a deposit-feeding species, can reduce the levels of inorganic nitrogen in the water and consequently enhance growth. Recently, Korea has made significant progress in sea cucumber hatchery technique, such as hatchery culture systems (including culture facilities, culture tanks, equipment). The technique breakthrough provides sufficient seed for scaled application of sea cucumber-based IMTA in open water.

The first attempt of a small-scale open water IMTA practice (<0.25 ha) occurred in 2012 in the east coast of Korea. Seaweeds (*Saccharina japonica* and *Sargassum fulvellum*), pacific oysters (*Crassostrea gigas*) and sea cucumbers (*Stichopus japonicas*) were cultivated adjacent to a finfish *Sebastes schlegeli* cage (Park et al., 2015, 2016). The growth of seaweed and oysters in the IMTA system was faster than monoculture. Especially, sea cucumbers underneath of the fish cage grew 2.7 times faster than monoculture (Park et al., 2016). Following that success, a large commercial scale IMTA (>2 ha) was installed in 2016 in the southeast coast of Korea. In the fish + seaweed + bivalve + sea cucumber IMTA system, Pacific oyster (*Crassostrea gigas*) and seaweed were cultivated adjacent to red seabream cages and sea cucumber were cultivated underneath the cages (Kim et al., 2017; Park, 2017). Oysters and the kelps near the cages grew well in this IMTA system, but the growth was similar to monoculture of each species in farther locations (Hwang et al., 2014, 2017; Kim et al., 2017). However, the tissue nitrogen contents in these seaweeds (~3.5%) and oysters (~0.97%) in the IMTA system were much higher than those in monocultures. These results indicate higher nutrient availability for extractive species in the IMTA system than in the monocultures. The optimal density of sea cucumber per hectare of finfish farm is about 30,000 individuals (Ren et al., 2012). Recent attempts of IMTA in Korean coastal waters suggest that IMTA can be a good management tool for improving Korean aquaculture, however, there are still challenges to overcome, such as the mismatch of cultivated location and season of fed species and extractive species. Scientists are searching for sustainable IMTA model balancing wastes and extraction, and new regulatory framework of coastal zone management.

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CHAPTER 2

Carrying capacity assessment for Integrated Multitrophic Aquaculture seawaters

2.1 Definition of carrying capacity

High quality aquatic products are pursued by consumers and fishery producers, including fishers and fish farmers. To obtain massive aquatic products, stocking (planting) density or aquaculture scale needs to be improved generally. Just like decreased dissolved oxygen (DO) concentration, sharp variations in nutrient concentrations, decreased biodiversity, increased organic matter contents in sediments and significant changes of acid/alkali and oxidation/redox environments, the negative effects of aquaculture worsen as increased stocking density or aquaculture scale, utilization period of fish farms (Degefu et al., 2011; Ge, 2009; Ge et al., 2007; Ge and Fang, 2006; Ge and Zhang, 2013; Han et al., 2017; Li et al., 2010; Wood et al., 2017; Yokoyama et al., 2002). Moreover, nutrient concentrations may rise in animal breeding waters, however, they may decline in plant culture areas. As the negative impacts of aquaculture on the environment worsens, the growth rate and the quality of cultured organisms may decline, and aquaculture diseases may occur frequently. Moreover, mass fish deaths may result from these negative impacts. Some key ecological processes such as material circulation and energy transfer which maintains the normal functions of ecosystem may be obstructed by the self-pollution of aquaculture, and ecological safety may be influenced subsequently. The main cause of negative impacts in aquaculture is the mismatch of stocking density and self-purification abilities or the material supply capacity, which implies that the stocking density or the aquaculture scale exceeds the carrying capacity of the aquaculture waters.

Carrying capacity, or load power, is derived from the restriction effect of population density on population growth (Tang et al., 1996). Carrying capacity may be distinguished as environmental, ecological and aquaculture capacity.

In environment science, carrying capacity is considered the environmental capacity — the maximum bearing quantity of contamination for water, air, soil and organisms. Humans and organisms can adapt to the condition when the contamination concentration is less than the threshold value. Otherwise, there will be occurrence of human and organism diseases.

In ecology, carrying capacity is regarded as the ecological capacity — the maximum population size supported by one ecosystem in a given period and under given environmental conditions.

In aquaculture, carrying capacity is called aquaculture capacity. There are five kinds of aquaculture capacity: (a) physical carrying capacity that is the maximum population size limited by the appropriate spatial scale; (b) production capacity that is the maximum stocking density with the maximum production; (c) ecological carrying capacity that is the minimum stocking density leading to negative effect on aquatic ecosystem; (d) social carrying capacity that is the maximum stocking density or aquaculture scale leading to negative social effects (McKindsey et al., 2006); and (e) environmental carrying capacity that is the maximum stocking density leading to the exceeding of the environmental standard threshold value of one given state or region (Abo and Yokoyama, 2003), respectively.

The physical carrying capacity is determined by the spatial limitation effect of aquatic sediment and hydrologic conditions on the cultured organisms. The social carrying capacity is based on the effects of aquaculture on fishers and their families using traditional fishery during which fishing industry is the principle composition. The success of aquaculture is determined by the relation between the stocking density and the production carrying capacity (either ecological carrying capacity or environmental carrying capacity), thus, production carrying capacity is the main focus in this document. Moreover, the environmental carrying capacity is determined by the technological, economic and political conditions as it is limited by the environmental standard threshold. Further, ecological carrying capacity focuses on effects of aquaculture on ecological safety. Thus, production carrying capacity is larger than environmental carrying capacity and ecological carrying capacity in the given water areas used for a given species of organism culture.

Carrying capacity is also called finfish carrying capacity (Middleton et al., 2014), shrimp or crab carrying capacity (Jin et al., 2003), shellfish carrying capacity (Filgueira et al., 2015) and algae carrying capacity (Fang et al., 1996a), which implies that carrying capacity assessments are also conducted for monoculture of finfish, shrimp, shellfish and algae. The mode of Integrated Multitrophic Aquaculture (IMTA) is the inevitable trend of aquaculture because the negative environmental effects of monoculture worsens as stocking density or aquaculture scale increases (Ferreira et al., 2012). IMTA can use the materials and energy in culture ecosystems effectively and the aquatic products can produce sustainably. Nevertheless, the IMTA is one anthropological interference to the natural ecosystem (Liu et al. 2016), which implies that it may be limited by carrying capacity as well.

Moreover, the carrying capacity is the result of interaction between cultured organisms and the environmental self-purification capacity or materials supply ability. Environmental self-purification is driven by the physical, chemical, biological and biochemical effects, during which the physical and biochemical effects influence it dominantly. The physical self-purification is influenced by the hydrodynamic characteristics such as current velocity and water exchange period directly. The biochemical effects are influenced by the DO concentrations significantly, which is affected by the oxygen recovery process related to hydrodynamic characteristics. Moreover, the hydrodynamic characteristics influence food or nutrients supply capacity by influencing the spatial distribution of materials in waters. Further, materials circulation and energy transfer in the aquaculture ecosystem run through the food chain or food web, which has a close relationship with the biogeochemical processes of biogenic elements such as nitrogen and phosphorus. Thus, the best models used to evaluate carrying capacity should include hydrodynamic characteristics, biogeochemical processes of biogenic elements. With increased knowledge in ecological safety, the stability and safety of the ecosystem gets more attention from fishfarm holders, fishery managers and stakeholders. Thus, ecological carrying capacity of aquaculture attaches appreciation step by step (Zhang et al., 2008).

2.2 Assessment of carrying capacity for farmed seaweeds

2.2.1 Key parameters for assessment of carrying capacity for farmed seaweeds

Water chemistry

The water chemistry analysis is determined according to the standards set by the ocean survey regulations and the marine pollution survey regulations.

Chlorophyll

The chlorophyll a was measured by 500 ml water samples in each survey layer. After the water samples were filtered out by 100 mesh screens in order to remove zooplanktons and large algae, filtered in M-50 filtration bottles with microporous glass fiber membranes in 0.45 M pore diameter, the chlorophyll concentration was determined by spectrophotometer.

The calculation methods of filtration, determination and chlorophyll were found in Parsons (1984).

Measurement of sea water velocity and exchange cycle

Each successive measurement of flow velocity and flow lasted to 25 hours during the spring and neap tides.

Each time the water exchange cycle of spring and neap tides is calculated respectively, then the average of the spring and neap tidal exchange cycles is used to determine the seasonal water exchange cycle of given areas.

Determination of primary productivity

The chlorophyll a method is used to determine primary productivity. After the assimilation coefficient was measured by C_{14} method, primary productivity and primary production were calculated according to chlorophyll concentration.

The primary production of the given waters is calculated according to the simplified formula proposed by Cadee and Hegeman.

Determination of nitrogen content of algae and attached algae

The content of total nitrogen (TN) of farmed, wild and fouling macro algae in the given waters were determined once a month. The procedures are: seaweed were sampled from different areas and dried under sunlight, and then put into the oven dried for 48 hours under 60°C ready for determination of the total nitrogen content.

Nutrients transported by land runoff

According to the river runoff around the given estimated waters, and the concentration of nitrogen and phosphorus in land runoff during different seasons, provided by the local relevant authorities, the total nutrients transported from runoff to the carrying capacity assessment sea area is calculated year-round.

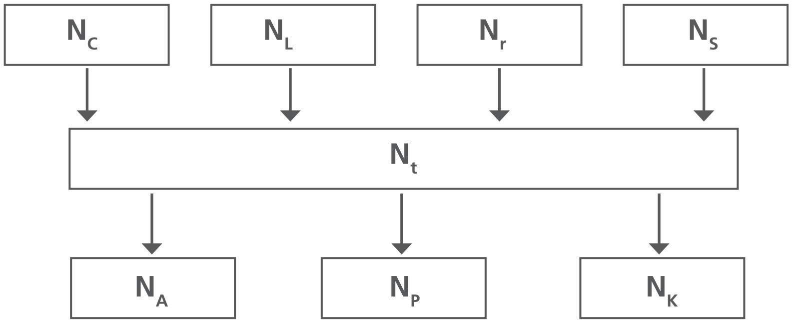
Nutrients excreted by farmed animals

The total amount of ammonia nitrogen excreted or discharged by farmed animals (fish, shrimp and scallops) and wild animal in the carrying capacity assessment sea area in different seasons is calculated based on the different farmed and wild animals' (fish, shrimp and shellfish) individual physiological metabolism during different seasons, and the biomass of different kinds of animals.

Nutrients released from the sediment

Sediment samples is sampled from different regions of waters by the columnar sampler, and incubated indoor for analyzing the contents of nutrients, and then the sedimentary nutrient release rate and the amount of nutrients released by seabed sediments is calculated.

FIG. 1-1 The budget of inorganic nitrogen seaweed aquaculture area.



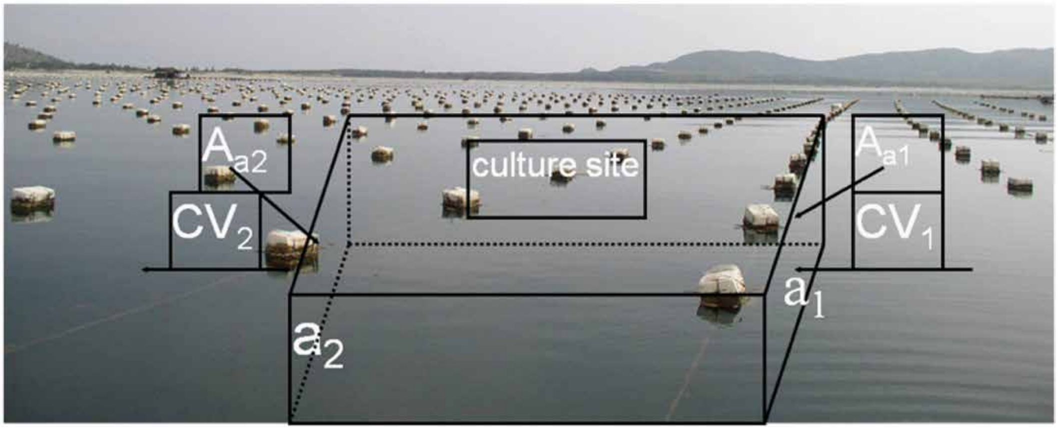
N_C: the supplemental N for current exchange; N_L: supplements N for land runoff; N_r: for animal excretion; N_S: N for seabed sediment release; N_t: the total supply of sea area N; N_A: fouling and wild large algal N demand; N_P: phytoplankton N demand; N_K: cultured large algae N demand.

2.2.2 Assessment models of carrying capacity for farmed seaweeds

2.2.2.1 Assessment model of carrying capacity for farmed seaweeds in open sea area

In the past 20 years, the data for ecological environment surveys showed that the inorganic nitrogen in most sea areas was restricted nutrients during seaweed cultivation periods. Therefore, the inorganic nitrogen is regarded as the main index for assessing carrying capacity for farmed seaweeds in the open waters based on the budget of inorganic nitrogen transported by the current, demand by farmed, fouling and wild seaweeds and phytoplankton, the supplement of inorganic nitrogen from animal excretion and release from sediment. The models for assessment of carrying capacity for farmed seaweeds in the open waters is set up (Figure 2-2).

FIG. 2-2 Schematic diagram for assessment of carrying capacity for farmed seaweeds in open waters.



Assessment model of carrying capacity for farmed seaweeds in open waters:

$$CC \le \frac{\overline{N}_I \times S \times D + [\overline{N}_{a1} \times CV_{a1} \times A_{a1} - \overline{N}_{a2} \times CV_{a2} \times A_{a2}] \times T_i - \sum_{j=1}^{m} (B_j \times \overline{AR}_j) \times S \times D}{T_i \times AR_{kelp}}$$

S: Water area (m^2);
D: Water depth (m);
T_i: The time (h) of high tide (or low tide) to I;
N_{a1}: The average concentration of N (mg/m^3) in the water body in the assessment area was evaluated at point a_1 at time T.
N^{a2}: The average concentration of N (mg/m^3) in the water body in the assessment area was evaluated at point a_2 at time T.
CV^{a1}: average current velocity of sea flow (m/h) at point a_1 at time T;
CV^{a2}: the average current velocity of sea flow (m/h) at point a_2 at time T;
A_{a1}: the sectional area (m^2) at point a_1;
A_{a2}: the sectional area (m^2) at point a_2;
N_I : Average inorganic nitrogen concentration (mg/m^3) in farmed waters;
AR_j: the absorption rate of inorganic nitrogen by jth species of seaweed (mg/h/g);
B_j: biomass (g/m^3) of the j species of algae (phytoplankton or fouling algae).
m: the number of species of phytoplankton or other large attached algae;
AR_{kelp}: the absorption rate of inorganic nitrogen (mg/h/g) of farmed algae.

2.2.2.2 Calculation formula of assessment of carrying capacity for seaweed based on the budget of inorganic nitrogen in the bay/sheltered waters

$$N_C = \sum_{i=1}^{n} C_{Ni} \times S \times D \times \frac{Ti}{t} \times 10^{9} \qquad (1)$$

$$N_S = \sum_{i=1}^{n} C_{Bi} \times T_i \times S \times 10^{-9} \qquad (2)$$

$$N_L = \sum_{i=1}^{n} C_{Fi} \times Q_i \times T_i \times 10^{-9} \qquad (3)$$

$$N_p = K_0 \sum_{i=1}^{n} P_i \times S \times T \times 10^{-9} \qquad (4)$$

$$N_A = \sum_{i=1}^{n} \sum_{i=1}^{m} K_j(W_j - W0 \times S \times 10^{-9}) \qquad (5)$$

$$N_K = N_C + N_S + N_L - N_p - N_A \qquad (6)$$

$$P_T = \frac{N_K}{K_1} \qquad (7)$$

N_c : the inorganic nitrogen (t) that was brought into the bay by current during seaweed cultivation;
N_s : inorganic nitrogen (t) released from seabed sediments during seaweed cultivation;
N_L : inorganic nitrogen (t) brought by land runoff during seaweed cultivation;
N_p : inorganic nitrogen (t) required for primary production during seaweed cultivation;
N_A : inorganic nitrogen (t) for other macro algae growth during seaweed cultivation;
N_K : total organic nitrogen (t) for demand of farmed and wild seaweeds growing in given waters;
P_T : production carrying capacity for seaweed in dry weight (t);
C_{Ni} : the average inorganic nitrogen concentration (mg/m^3) of survey stations at i time at the open side of sheltered area in the growth period of seaweeds;
C_{Bi} : the daily release rate of inorganic nitrogen in the seabed sediments at i time (mg/m^2/d);
C_{Fi} : inorganic nitrogen concentration (mg/m^3) at i time in land runoff;
Q_i : for daily land runoff (m^3/d);
S : the given area (m^2);
D : average depth (m);
T_i : the sampling interval (d);
t : the days for full exchange of sea water during the growth of seaweed cultivation in the sheltered/bay area (d);
P_i : the primary production of phytoplankton (mg C/m^2/d) at i time;
W_0 : the biomass (mg/m^2) of fouling and wild macro algae at the initial growth season of farmed seaweed in the bay area;
W_j : biomass (mg/m^2) for different fouling and wild algae in the season of harvest of farmed seaweeds;
K_0 : the ratio of N:C inside phytoplankton;
K_j : nitrogen content (%) for large wild macro algae of different species;
K_1 : the nitrogen content (%) of dried seaweed wen harvested;
m : species of fouling algae;
N : the number of sampling observations.

2.2.3 Case study: the assessment of carrying capacity for farmed kelp in Sungo Bay

2.2.3.1 Stations

Sungo Bay is a C shaped bay located at the eastern end of the Shandong peninsula, with an area of 13,333 hectares and an average depth of 7.5 meters. The maximum depth is 14 meters in the mouth of the bay. The main types of cultivation include kelp, oyster, scallop, etc. In the 1990s, the annual production of farmed macro algal production was about 80,000 tons (dry weight), and the annual production of shellfish was about 5,000 tons (wet weight). The shallow areas near shore of the bay are mainly used for longline culture of shellfish. In the central areas of the bay, integrated culture of the shellfish and seaweeds was well developed, while in the deep part of the bay around the mouth is used for large-scale seaweeds cultivation. In the mid-1990s, in order to assess the carrying capacities for seaweeds and bivalves, 19 survey stations were set up for hydrodynamic, chemical, biological and environmental condition investigations (Figure 2-3).

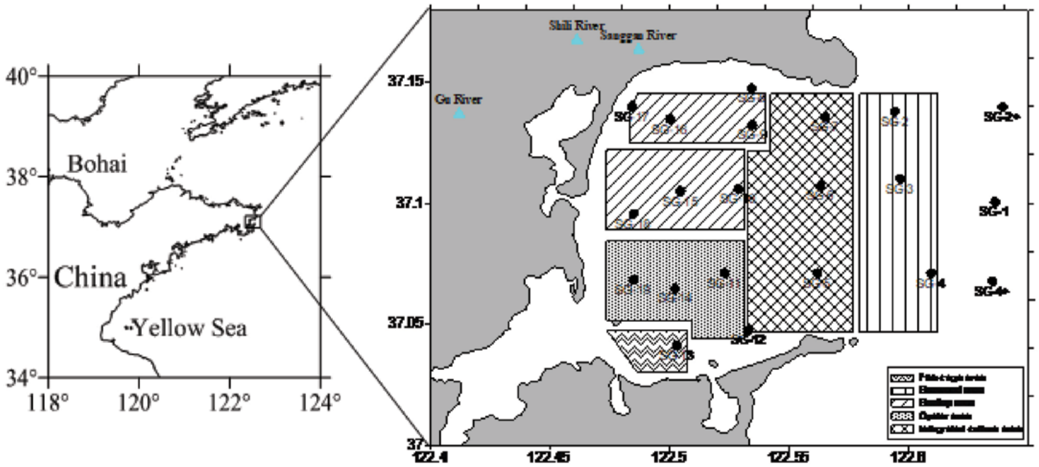


FIG. 2-3 Survey station for assessment of carrying capacity for seaweed (kelp) in Sungo Bay, Shandong, China.

2.2.3.2 The total inorganic nitrogen brought by seawater exchange into the bay

When estimating total inorganic nitrogen (NC) brought by seawater exchange into the bay, the average of sum of inorganic nitrogen NO_3-N, NO_2-N and NH_4-N from Stations 1, 2, 3, 4 is used as the average inorganic nitrogen concentration for indicating outside inorganic nitrogen flows into the bay during each survey. The total amount of inorganic nitrogen carried by seawater exchange into the bay during the growth of kelp was calculated according to each time interval of survey and the water exchange period (Table 2-1).

Table 2-1 Changes of the water exchange cycle of Sungo Bay in different seasons.

Date (yyyy-mm-dd)	Water exchange periods (d)		
	Spring tide	Neap tide	Mean
1994-03-27	24		
1994-04-03		54	39
1994-07-04	28		
1994-07-11		62	45
1994-10-16		43	
1994-10-27	23		33

Since the growth period of kelp is from November to late May, the mean value 39d of spring is used as the seawater exchange cycle for calculating the capacity of this bay.

Based on the formula (1), the calculation results of inorganic nitrogen brought by the seawater exchange during the growth period of kelp are shown in Table 2-2.

Table 2-2 The total inorganic nitrogen in the bay at different periods from November 1993 to May 1994.

Period (yyyy-mm-dd)	CN Concentration of N (μg N/L)	S Area ($\times 10^8 m^2$)	D Mean depth (m)	T Time span (d)	t Exchange period (d)	NC Subtotal of N (t)
1993-11-01 – 1993-12-18	148.31	1.33	8	49	39	198.76
1993-12-19 – 1994-02-22	36.19	1.33	8	66	39	65.32
1994-02-23 – 1994-04-10	40.29	1.33	8	48	39	52.90
1994-04-11 – 1994-05-09	37.49	1.33	8	31	39	3179
1994-05-12 – 1994-05-31	27.90	1.33	8	37	39	28.23
TOTAL			**8**	**213**	**39**	**377.00**

2.2.3.3 Calculation of nitrogen (NS) release in seabed sediments

In May 1994, columnar sediment sample with 10 cm height were carefully taken by divers from the designated positions using cylindrical organic glass tubes, after which the sediment release rate of total inorganic and organic nitrogen, total phosphorus ware measured in the lab.

According to the measurement data of six stations in the bay and the formula (2), the total release amount of inorganic nitrogen in the seabed sediments of Sungo Bay is shown in Table 2-3.

Table 2-3 The release amount of inorganic nitrogen in the seabed sediments of Sungo Bay during the growth period of kelp.

CB releasing rate (mg/m²/d)	S area (m²)	T time span (d)	N_L total N (t)
19.14	1.33×10^8	213	543.84

2.2.3.4 Determination of inorganic nitrogen (NL) on land runoff

The main source of sewage in Sungo Bay comes from Rongcheng's city sewage, flowing into Sungo Bay though Gu River, and the other sewage discharge systems are the Xiaohai River and the Sango River. According to the results of the survey data of Wang Lixia etc. (1994) and formula (3), the inorganic nitrogen of sewage discharge is shown in Table 2-4.

Table 2-4 The release amount of inorganic nitrogen in the seabed sediments of Sungo Bay during the growth period of kelp.

CF releasing rate (mg/m²/d)	Q mean flowing rate (m³/d)	T time span (d)	N_L total N (t)
1.7	20,000	213	7.24

2.2.3.5 Estimation of the excretion of inorganic nitrogen (NT) by animals

The main aquaculture and fouling animals in Sungo Bay were scallops (*Chlamys farreri*) and mussels (*Mytilus edulis*) in the mid-1990s. Inorganic nitrogen excretion of *Chlamys farreri* is estimated according to the data of Li Shunzhi, etc. (1983), inorganic nitrogen excretion of *Mytilus edulis* is calculated according to the corresponding season's ammonia-n excretion regression curve given by Widdows (1978).

According to the experimental results of Li, et al. (1983), the inorganic nitrogen excretion of a 5.5 cm scallop was 142 mg during the seaweed cultivation period.

The amount of scallop culture in Sungo Bay was 2 billion. Therefore, the inorganic nitrogen excretion of scallops during the growth period of kelp is 284 t.

Widdows' (1978) studies on mussels showed that in spring, the average excretion of ammonia nitrogen in each mussel was about 200 μg.

There are about 270 million mussels in Sungo Bay. Therefore, the inorganic nitrogen excretion of the mussel in Sungo Bay during the production of kelp is about 11 t.

Including the inorganic nitrogen excretion of other animals such as sea squirts and oysters, the total inorganic nitrogen excreted by animals in Sungo Bay is about 300 t during the growth period of kelp.

2.2.3.6 Calculation of inorganic nitrogen (NP) needed for phytoplankton reproduction and growth

According to the seasonal changes of primary productivity and chlorophyll a concentration as well as the ratio of total nitrogen and organic carbon content of phytoplankton in the bay, the amount of inorganic nitrogen needed for phytoplankton growth and reproduction was calculated.

According to the results of the study by the First Institute of State Oceanic Administration of China, the ratio of total nitrogen to organic carbon of phytoplankton in the bay was 9.25:1.

Based on the formula (4), the inorganic nitrogen needed for the primary production of phytoplankton in Sungo Bay during the growth of kelp are shown in Table 2-5.

Table 2-5 The total inorganic nitrogen needed for phytoplankton growth in the bay during the growth season of kelp.

Period (yyyy-mm-dd)	chlorophyll a (μg/L)	AE* (mg C/mg chla/d)	area (10^5m^2)	time (d)	subtotal C (t)	k	subtotal N (t)
1993-11-01 – 1993-12-18	0.95	4.40	1.33	48	1,364.90	9.25	147.56
1993-12-19 – 1994-02-22	4.13	1.10	1.33	66	1,575.30	9.25	170.80
1994-02-23 – 1994-04-10	5.24	1.19	1.33	48	859.86	9.25	92.96
1994-04-11 – 1994-05-09	2.14	1.36	1.33	30	250.81	9.25	27.11
1994-05-12 – 1994-05-31	2.26	2.19	1.33	21	895.77	9.25	96.84
TOTAL					**4,946.64**		**534.77**

* AE refers to Assimilation Efficiency.

2.2.3.7 Calculation of inorganic nitrogen demanded by other living organisms in Sungo Bay during the growth period of kelp

According to the formula (5) and the determination of nitrogen content of main macro algae in the growing period of kelp, the total inorganic ammonia demand of the algae in the growth period of Sungo Bay is shown in Table 2-6.

Table 2-6 The total inorganic nitrogen requirement of algae during the growth of kelp.

Mean biomass (g/m^2)	N content (%)	Area (1×10^8m^2)	Total N (t)
12	3	1.33	47.88

2.2.3.8 The budget of inorganic nitrogen during the growth period of kelp in Sungo Bay

As described above, the total supply of inorganic nitrogen during the growing period of kelp in Sungo Bay is: NT=NC+NL+NP+NS=1228 t. Among these, 30.7 percent was provided by water exchange, 44.3 percent from sediment release, 0.6 percent from land runoff and 24.4 percent from animal excretion.

The total amount of inorganic nitrogen needed for the phytoplankton and the fouling algae in Sungo Bay during kelp growth period is about 583 t.

According to the formula (6), the total inorganic nitrogen available for the growth of kelp is 645 t.

2.2.3.9 The production carrying capacity of Sungo Bay for kelp

Table 2-7 Sungo Bay kelp culture capacity.

Available N for kelp (t)	Content of N in kelp (%)	Carrying capacity
645	1.2	53,750

According to the formula (7), the production carrying capacity of Sungo Bay for kelp is about 54,000 t in dry weight, and the unit area capacity is 600 kg/1,500 m^2 (0.4kg/m^2).

2.2.4 Evaluation of assessed production carrying capacity and aquaculture status

Aquaculture production carrying capacity is the dynamic balance of interactions between many ecological environment factors and cultivated organisms. Many factors can influence production carrying capacity such as nutrition levels, climate, water chemistry, hydrology, physics and biology, etc.

How to correctly determine the key factors on estimating the production carrying capacity is the key point in estimating whether the production carrying capacity model can accurately reflect objective reality.

A large number of studies have shown that nitrogen and phosphorus in the marine environment are more likely to be the limiting factors for primary production than other nutrient elements.

In this study, the inorganic nitrogen was chosen as the key factor to estimate the carrying capacity of the bay for kelp, based on the deficiency of inorganic nitrogen and the serious imbalance of nitrogen and phosphorus in Sungo Bay during the growing period of kelp.

Meanwhile, the assessment is carried out under the assumption that the total inorganic nitrogen brought into Sungo Bay by the water exchange, the seabed sediment release and land runoff can all be absorbed by kelp and other algae.

The calculation results show that the capacity of aquaculture kelp is about 54,000 t in Sungo Bay, and the unit culture capacity is 600 kg/1,500 m^2, or 0.4 kg/m^2 in dry weight. In 1994, the aquaculture area of the bay was about 3,200 hm^2, and the production carrying capacity was about 20,000 t. Compared with the assessed production carrying capacity, the actual amount of cultivation in the bay is less than 30,000 t, while the actual amount of the unit area is about 300 kg higher than estimated in each 1,500 m^2.

The main reasons causing big differences between production carrying capacity and actual aquaculture quantities were: (l) the current kelp farmed area in the bay is about 3,200 hm^2, only about 25% of the total area of Sungo Bay, so the estimated production carrying capacity is larger than the actual aquaculture quantity; (2) due to the effect of ocean current, kelp cultivation can take advantage of inorganic nitrogen in some non-marine aquaculture waters. Therefore, the actual unit area yield is slightly higher than the estimated one; (3) kelp production carrying capacity estimation model is under the theory of inorganic nitrogen balance between supply and demand, and is under the assumption that seaweed can absorb and use all the inorganic nitrogen as the premise. The supply of inorganic nitrogen in the bay is mainly influenced by the water exchange period, sea current, water depth and other environmental factors. For the whole Sungo Bay, its kelp cultivation capacity can reach about 50,000 t. However, there are also significant variations in unit area production carrying capacity in different farming areas. Velocity at bay mouth and outside is faster than that of inner bay, and the water exchange period is shorter than the inner bay, which can supply more inorganic nitrogen and other nutrients for kelp demand. Therefore, output of farmed kelp in the mouth of the bay area was significantly higher than that of the inner bay. According to the results of the current measurement, the current velocity is decreased gradually from the mouth area to the inner bay, so the output of farmed kelp is gradually decreasing from the outside to the bay.

The variation of production carrying capacity caused by different flow rates can be estimated by the following formula:

$$\boxed{\Delta P = \frac{N_C}{k_2 \times S} \times \frac{(v - \bar{v})}{\bar{v}}}$$

ΔP : the increased or decreased unit yield of dry kelp based on the average unit area cultivation capacity (kg/m^2).

N_c : the total inorganic nitrogen (t) that was brought into the bay during the growth of kelp;

k_2 : inorganic nitrogen content (%) for the harvest of kelp;

S : the total area (m^2) of Sungo Bay;

V : current velocity in the given area (m/s);

$\bar{v}$: the average velocity in the bay.

The average velocity at the mouth of the bay was 24 cm/s, and 10 cm/s in inner of the bay, results from measurement in 1994. According to this formula, the production carrying capacity of the mouth area of the bay can increase by 500 kg/1,500 m^2, and the total production carrying capacity of the unit area is 1,100 kg/1,500 m^2. It is close to the actual farming quantity. The production carrying capacity is 600 kg/1,500 m^2 in central area of the bay and is about 400-500 kg/1,500 m^2 at the bottom of the bay respectively.

2.2.5 Error estimation of production carrying capacity

The main error sources are: (1) the method of determination of carbon and nitrogen ratio in phytoplankton. The carbon nitrogen ratio in phytoplankton was 9.25:1 determined by carbon-hydrogen-analyzer. Due to the influence of season, phytoplankton growth and seawater turbidity, the result of determination may vary significantly and influence the estimation. (2) changes in weather and hydrodynamic in the given area. Table 2-3 shows that the inorganic nitrogen released from the seabed sediments is about 540 t, accounting for about 45 percent of the total inorganic nitrogen supply and is one of the main sources of inorganic nitrogen in Sungo Bay for farmed kelp. Therefore, the estimation error in the carrying capacity model is mainly derived from physical and hydrological factors such as strong wind and wave during the kelp growth period. In the kelp growing season, if there is more wind and windy weather, the inorganic nitrogen in seawater will greatly increase due to more nutrients from sediments due to strong winds and waves, and the production carrying capacity will be greatly increased. The practical experience confirms that frequent northeast winds brings higher yield and better quality of kelp, especially during main growing season (November to March). On the contrary, if there is less windy weather in winter and spring, there would be probable reduction in farmed kelp yield. This is due to the shallowness of Sungo Bay, which allows the waves to agitate seabed sediments and release inorganic nitrogen in the sediment into the seawater to meet the growing needs of kelp. If there are no more winds and waves, the amount of inorganic nitrogen released into the seawater will be greatly reduced, thus, it is difficult to meet the demand for inorganic nitrogen. In this study, the release rate of inorganic nitrogen in seabed sediments was calculated only according to the average release rate of inorganic nitrogen in the seabed sediments under normal weather conditions, and factors such as winds and waves were not taken into account. How to estimate the influence of the wind-wave factor on estimating the production carrying capacity of kelp will be one of the key points for the future.

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2.3 Assessment of carrying capacity for filter feeding shellfish

2.3.1 Filter feeding physiological ecology of bivalves

2.3.1.1 The main factors that affect the filter-feeding physiological ecology of bivalves

The filter-feeding physiological ecology of bivalves is the physiological process of feeding and interaction with the environment. The bivalves feeding physiological ecology includes the ecological effect of filtration rate, feeding rate, feeding strategy (selective of food grains, etc.), and environmental factors influence on filter-feeder shellfish. Studies show that in the health status of the coastal zone ecosystem, bivalves such as oysters, mussels and clams is a very important component with its extremely remarkable economic and ecological benefits. The bivalve filter plays a significant role in the material circulation and energy flow of the coastal ecosystem. Due to strong filtering capacity, for example, filtration rate of oysters and mussel can reach 5 l/g•·h. Such filter-feeding bivalves are often called “biological filter” because they are able to filter large amounts of fine particulate matter, including phytoplankton, suspended particulate matter, microorganisms, small protozoa, copepods, and so on, with sizes ranging from a few microns to 1,000 microns in the water column. The main influencing factors on the feeding physiology of bivalves include water temperature, salinity, food concentration and quality, the size and age of shellfish, and water flowing rate. The effects of weight, temperature and feed concentration on the physiological effects of feeding shellfish were described as follows:

Body weight: weight is one of the most important factors that affect the feeding of filter-feeding shellfish. The study shows that water filtration rate, feeding rate and weight are power function relationships: $Y=aW^b$, where b is the weight index, and its value is generally less than 1. The value of b is related to the type and size of food, and temperature. The b value of the filter-feeding bivalves is around 0.62.

Temperature: the change in temperature has a significant effect on feeding of shellfish. In the appropriate temperature range, feeding rates and water filtration rates increase with temperature increase and reach a maximum at optimum temperature. When temperature exceeds the appropriate temperature for bivalves, the feeding rate and water filtration rate will decrease rapidly.

Food concentration: the feeding rate and water filtration rate of the filter-feeding shellfish increased with increase in food concentration in the appropriate concentration range of food. The feeding rate decreased slightly with the increase of food concentration, while the water filtration rate decreased sharply.

Filter-feeder shellfish itself can make corresponding feeding physiological responses to the environment conditions and changes for adapting to the environment.

2.3.1.2 Physiological and ecological parameters of bivalve shellfish

Most mollusks of class Lamellibranchia (also known as *Bivilvia*) animals, such as mussels (*Mytilidae*), scallops (*Pectinidae*), oysters (*Ostreidae*), belongs to the filtering feeders. These animals filtered suspended particulate matter (including planktonic algae, micro zooplankton, planktonic bacteria, and organic debris, etc.) in the water through cilium, gill and lip. Bivalves in natural waters distribute widely, including river, lake, saltwater lake and estuary, and various kinds of shallow sea and deep sea habitats, but the coastal water environment is regarded as the most important habitat with the big amount of variety and quantity.

Bivalves generally has a strong ability to filter water and play an important role on nutrient dynamics and energy ecology in coastal waters ecosystem through a high filtration and feeding rate, absorption, excretion, defecation and growth and other physiological activities.

To evaluate the ecological effects of bivalve shellfish, it is necessary to study the physiological and ecological characteristics of water filtration rate (clearance rate), feeding rate, absorption efficiency, and scope of growth. At present, traditional research methods are well used to determine the physiological and ecological parameters of bivalves.

(1) Clearance rate and filtration rate/feeding rate

The still water system method for measuring the filtration/clearance rate is also known as Coughlan method. Its calculation formula is as follows:

$$CR = (\mathrm{Ln}\ ct - \mathrm{ln}\ co)/t * V/N$$

In the formula, Co and Ct are the initial concentration and the concentration at t time respectively, V is the experimental water volume, and N is the number of experimental individuals.

The calculation formula of flowing system is as follows:

$$CR = (C1-C2)/C1 * F/N$$

In the formula, C1 and C2 are the food concentration in the water flowing into and out of the experimental box respectively, and N is the number of experiment individuals. The two methods above are involved in measuring the clearance ability of shellfish on suspended particles in water.

The product of Clearance rate (CR) and total suspended particulate concentration (TPM) is the filter feeding rate of shellfish (filtration rate, FR).

When there is no pseudofeces (rejection rate, RR) appearing in the measuring box, the filter rate is usually regarded as ingestion rate (IR). When there is pseudofeces, IR= FR-RR

In addition, there are other methods for determination of bivalves' filtration rate used in the laboratory, methods such as suction, impeller, thermistor, video observation and so on. Due to control difficulty, these methods are rarely used now.

Under laboratory conditions, the simple still water and flow water tank method can eliminate the variability of seawater velocity which may occur in natural conditions. Results show that the flow rate of water could affect the feeding and growth of bivalves. In coastal waters, the changes in tidal currents and winds can lead to changes in the quantity and quality of suspended matter in the short term, and then affect the feeding activities of shellfish.

(2) Absorption efficiency

The absorption efficiency (AE) is one of the important basic parameters for study of shellfish energy. In an area with high number of bivalves, shellfish absorption rate is also an important parameter of ocean ecosystem dynamics, its value directly influences the energy flow and material cycle of the sea area. The absorption rate of bivalves is affected by a variety of factors, including feed quality, feed concentration and shellfish feeding rate, temperature, salinity and individual size.

The ratio method proposed by Conover in 1966 for determining the absorption of shellfish is based on the content of organic matter in food and feces (Ashing method determination), and calculated by the following formula:

$$AE = (f-e) / / (1-) e*f*100 = (1- e/f) / (1-e)*100$$

In the formula, f and e are the percentage of organic matter in feeds and feces respectively.

The application of this method is that the shellfish assimilate the organic matter only, and there is no obvious assimilation effect on inorganic substances. In practice, it just collects representative feces, no need to collect all the feces.

(3) Energy parameters

Energy flow is one of the basic functions of the ecosystem. The physiological energy of the bivalve shellfish has been studied extensively in the past decades by determining the feeding rate and the absorption efficiency of bivalves.

According to the biological energy principle:

$$C = F+U+R+P$$

In the formula, C is feeding energy, F is fecal energy, U is excretion energy, R is metabolism energy, P is growth energy.

Set A to absorb energy, which represents the part of the feeding energy absorbed by the organism, then: $A = C-F$.

The concept and parameter of scope for growth (SFG), used to predict the surplus energy for growth and reproduction, has been widely used in invertebrates, especially marine bivalve for physiological ecology studies. SFG is defined as the difference between the energy consumed by animals and the energy consumed and lost, i.e., $SFG = A-(R+U)$.

SFG has proved to be a useful concept for evaluating the effects of environmental stress, growth efficiency and the differences in physiological responses of different populations.

The main advantage of SFG is that the growth performance of bivalve shellfish requires long-term study, while SFG can be estimated in short-term experiments.
The other two energy budget parameters are K_1 (total growth efficiency), K_2 (net growth efficiency), which is defined as:

$$K_1 = P/C = SFG/C$$
$$K_2 = P/A = SFG/A$$

Due to feeding conditions being standardized and strict control of experiment conditions, the filtration rate and absorption rate of shellfish are widely studied under laboratory conditions.

2.3.2 Determining feeding physio-ecology of bivalves by bio-deposition method

In recent years, more researchers are applying the bio-deposition method for determining shellfish physiological ecology parameters, which include clearance rate, feeding rate, absorption rate and the scope for growth.

The principle of bio-deposition method is to assume that the shellfish does not absorb inorganic substances, that is, ash content in the fecal pellet can be used as quantitative tracer of shellfish filtered material. Cranford *et al*. pointed out that the ash content in the study of feeding and digestion of suspended filter-feeding shellfish is the appropriate inert tracer. Navarro *et al.* conducted a series of experiments on the physiological energy of *Mytilus galloprovincialis*. In these experiments, the feeding rate was indirectly estimated based on the bio-deposition rate. Prins et al. used similar methods to estimate the clearance rate of mussel (*M. edulis*) and cockle (*Cerastoderma edule*) in laboratory conditions. In the two cases above, results obtained are equivalent to the conventional method. At present, there are sufficient reasons to explain that bio-deposition is an effective tool for quantifying the food processing rate in bivalves.

2.3.2.1 Calculation methods of parameters

Based on the principle of determining the clearance rate of filter-feeding bivalves by bio-deposition:

$$IFR = IBD \qquad (1)$$
$$CR = IFR/PIM = IBD/PIM \qquad (2)$$

IFR: filtration rate of inorganic matter filtration; IBD: the filtration rate of inorganic matter bio-deposition; PIM: particulate inorganic matter concentration in the water filtrated by bivalves.

The total filtration rate (FR) can be expressed as:

$$FR = CR \bullet TPM = IBD \bullet TPM/PIM \qquad (3)$$

In the formula, TPM is the total particulate matter concentration in seawater filtered by shellfish. When the concentration of particulate matter is high enough to cause pseudo-feces production, then the feeding rate (IR) is:

$$IR = FR-RR \qquad (4)$$

In the formula, RR is the rate at which shellfish rejects to feed on the filtered food, meaning the excretion rate of pseudofeces. The filtration rate (OFR) of shellfish for particulate organic matter (POM) or particulate organic carbon (POC), particle organic nitrogen (PON) and particle phosphorus (PP) can be expressed as:

$$OFR = IBD \bullet r \qquad (5)$$

In the formula, r is the ratio of POM or POC, or PON, or PP and PIM in seawater. The calculation to determine the absorption of organic matter by shellfish is:

$$AR = OFR\text{-}OBD = IBD \bullet r - OBD \qquad (6)$$

$$AE = AR/OIR = AR/(OFR\text{-}ORR) = AR/(IBD \bullet r\text{-}ORR) \times 100.$$

If ORR = 0, then

$$AE = AR/OFR = (1\text{-}OBD/\ IBD \bullet r)*100 \qquad (7)$$

OIR: shellfish feeding rate of organic matter; OBD: bio-deposition rate of the organic matter; ORR: excretion rate of pseudo-feces of organic matter; r: ratio of POM (or POC, PON PP) and the PIM;

From the formula (5), we can see that the determination of absorption rate can be done by determining the total biogenic sediment organic discharge rate (OBD), no need to estimate the organic matter content in feces and pseudo-feces separately. But it is necessary to measure the discharge rate ORR of organic matter in pseudo-feces when calculating AE.

If shellfish physiological ecology research is done at sea, since the water particles change over time, the collection of water samples need to be done several times during the experiment, to observe the changes in water particles.

In biological deposition, based on the combination of bivalve metabolic energy (usually by measuring oxygen consumption rate to estimate) and discharge can (usually by determination of NH_4-N excretion rate to estimate), the research method of bivalve energy budget can be made, including SFG, K1 and K2, etc.

2.3.2.2 Comparison between bio-deposition and traditional methods

The bio-deposition method has been proven to be an effective method for the determination of physiological and ecological parameters of bivalves, especially in *situ* and when the food concentration is over the boundary of pseudo-feces excretion. When the food concentration exceeds the limit of the production of pseudo-feces, the conventional method for determining shellfish absorption proposed by Conover is not suitable.

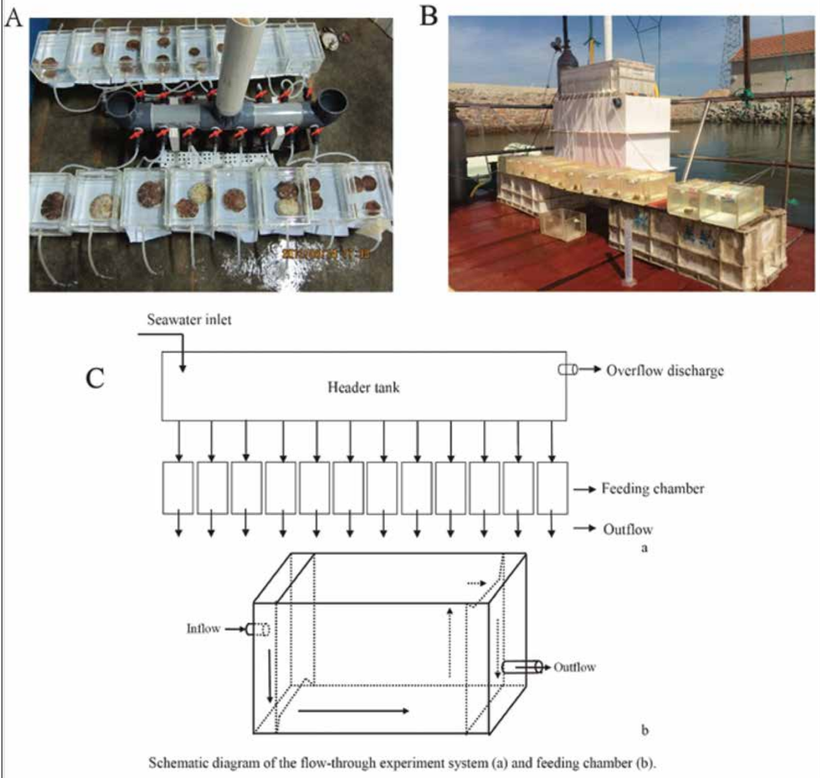
Biological deposition method requires the quantitative collection of biogenic sediment of bivalves produced in a certain time. The other sediment which is not produced by shellfish sediment must be identified carefully and removed.

Compared with traditional methods, the bio-deposition method is carried out in situ in the case of natural particles and water supply to determine the parameters of bivalve physiological ecology. Therefore, it is more accurate to measure the feeding and absorption of shellfish, which helps to accurately evaluate the role of bivalve shellfish in the energy flow and material circulation of the coastal ecosystem.

Disadvantages of the biodeposition method is that it is time consuming and involves heavy work, and it is also affected and restricted by environmental conditions.

2.3.2.3 A brief introduction of measuring the filtration rate of scallop (*Chlamys falleri*) in *situ*

The measuring device is located on the coast of the given carrying capacity assessment area. The natural seawater is pumped into the water head tank with small water pumps, and the water level is maintained at a stable level. First, the seawater in the water head tank flows to the controller device, then the seawater passes through the fine pipe into the water filtration rate measurement tank in stable flowing rate. During the measurement period, the average flowing rate of seawater into each measuring chamber is controlled at 300 ml/min to 500 ml/min (Figure 2-4).



Schematic diagram of the flow-through experiment system (a) and feeding chamber (b).

FIG. 2-4 The photo (A, B) and schematic diagram (C) of the filtration rate measurement device in situ for bivalves.

Zhikong scallops were collected for the experiment from aquaculture cages in the carrying capacity assessment area. After cleaning fouling organisms and sediments on the shell, the scallops were divided into eight groups according to size, which include seven groups (each group containing four scallops with similar sizes) and a control group. Flume experiments are operated in running water at least for 3-6 days for scallops to adapt to the experiment conditions. During this time, the sediment and feces on the chamber bottom is flushed out daily by siphoning hose.

The water flowing rate in chamber outlet, the concentration of Chl a and POM in both inlet and outlet of chamber was sampled every 6 hours to determine the variation of Chl a and POM affected by the feeding of scallops in each chamber. Feces excreted by scallops was carefully collected after 24 hours. Feces samples was suction-filtered using GF/C glass fiber filter paper and then put into a dryer under a temperature of -20^{o}C storage for analysis.

The regression analysis of the filtration rate of seven groups of different sizes of scallops showed that the water filtration rate and individual weight and shell height had a better power function regression relationship.

Among them, the relationship between water filtration rate and individual dry tissue weight was: $FR=2.9142W^{0.3762}$, $R^2=0.9392$; The regression equation between the filtration rate and the height of the fan shell was: $FR=0.4943L^{1.0392}$, $R^2=0.9151$. There was no significant relationship between the assimilation rate of scallops and the individual sizes of scallops. The average daily defecation of scallops of different sizes was 30 mg – 120 mg, and the absorption rate was 56.64% – 62.80%, with an average of 60.70%.

2.3.3 Evaluation of filter-feeding shellfish capacity.

2.3.3.1 Dynamic carrying capacity estimation model for assessing filter-feeding shellfish in open sea

The model for assessing filter-feeder shellfish production carrying capacity in open water mainly based on the supply of POM in the assessment area transported by current, filter-feeder organisms species and biomass, farming shellfish feeding physio-ecology instantaneous changes, and so on (Figure 2-5).

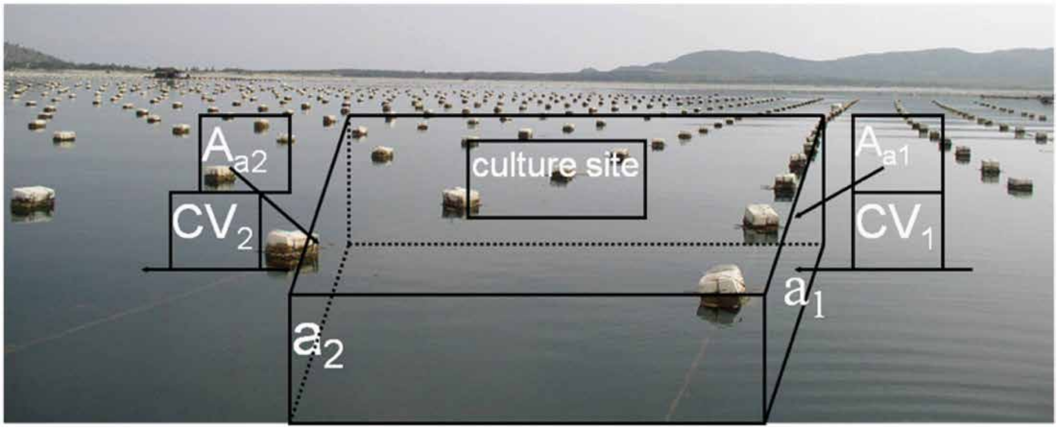


FIG. 2-5 Assessment model of carrying capacity for filter feeding shellfish in open water.

The Assessing model is as follows:

$$CC \leq \frac{\left((\overline{COP})_i \times S \times D + \left[(\overline{COP})_{a1} \times CV_{a1} \times A_{a1} - (\overline{COP})_{a2} \times CV_{a2} \times A_{a2} \right] \times T \right) - \sum_{i}^{n} \sum_{j=1}^{m} FR_{fi} \times B_{ij} \times T_i}{FR\,(COP,w)_{bi} \times T_i}$$

S: area (m^2); D: water depth (m); T_i; The time (h) of the high tide (or low tide) to i; CV_{a1}: The average velocity of current in the time of a1 point in time T (m/h); CV_{a2}:The average velocity of the current at a2 point in time T (m/h); A_{a1}: The sectional area (m^2) of the a1 point; A_{a2}: The section area (m^2) of the a2 point; $(\overline{COP})_i$: particle organic matter (POM) or chlorophyll a concentration (mg/m^3) in aquaculture waters at time i; FR_{fi}: the individual feeding rate (mg/h/ind) of the filter-feeding animals; FR_{bi}: the individual feeding rate of the filter-feeding shellfish (mg/h/DWg); B_{ij}: the total biomass (ind) of the j species in aquaculture waters at I time; m: number of fouling filter-feeding animals; W: tissue dry weight of shellfish (g).

Comparing with other models, this model fully considers the tides, velocity, distribution of food and food supplement and consumption inside and outside the aquaculture water, and is suitable for carrying capacity assessment at any time for any types (including closed waters, open water) of waters and filter-feeding animals.

2.3.3.2 Assessment model of carrying capacity for filter-feeding bivalves in sheltered waters.

The food of filter-feeding shellfish is mainly composed of phytoplankton and organic detritus, bay phytoplankton and organic detritus. The level of primary productivity has determined food quality and quantity of filter-feeding animals, and then determines the g carrying capacity for filter-feeding bivalves in sheltered waters. Because the water depth in the bay is relatively shallow, some of the organic detritus in seabed sedimentary can be re-suspended into the water column by wind and waves. This resulted when the concentration of the POM sampled in rough conditions is much higher than in calm seas and resulted in bigger data error used for assessing carrying capacity.

In contrast, the number and concentration of phytoplankton represented by chlorophyll a are more stable than POM and not susceptible to physical factors such as wind and waves. Therefore, the flowing water method *in situ* or simulated *in situ* flowing water method is recommended to measure the clearance, filtration and feeding rates of filter-feeding animals in shallow waters. In this way, the filtration and feeding rates can be obtained based on natural environment conditions and natural food composition.

The model of production carrying capacity of Sungo Bay for scallop is:

$$\boxed{CC = \frac{P - k\ \mathrm{Chl\ a} \sum_{j}^{m} (FR_j \times B_j)}{k \times \mathrm{Chl\ a} \times FR_S}}$$

CC : the production carrying capacity of scallop (ind/m^2);
P : primary production (mg C/m^2/d);
K : the ratio of organic carbon and chlorophyll a in phytoplankton (40:1).
FR_j : filtration rate of different filter-feeding fouling organisms (m^3/ind/d);
Chl a: average concentration of chlorophyll a (mg/m^3);
FRs : filtration rate of scallop (m^3/ind/d);
B : the density of different filter-feeding fouling animals (ind/m);
j : the type of filter feeding fouling animals.

2.3.4 Case study – Assessment of production carrying capacity of Sungo Bay for scallop

2.3.4.1 Survey station setting and investigation project.

The survey station setting is same for Figure 1-3. A total of 23 sampling stations and 6 current observation stations were set up inside and outside the bay.

The investigation items include: NH_4-N, NO_3-N, NO_2-N, PO_4-P, COD, pH, water temperature, salinity, chlorophyll a, concentration of suspended particulate organic (POM) and total suspended particle concentration (TPM).

2.3.4.2 Sampling and determination of water samples.

Survey ship was guided by Global Positioning System (GPS), and conducted monthly surveys except during winter (Nov-Feb).

Water samples were gathered by using Nansen bottles. When water depth was deeper than 5 m, 2 water samples were sampled from upper layer and lower layer. Otherwise, only surface sample was sampled. The determination of chlorophyll a was carried out according to the analysis method recommended by Parsons. Water samples first filter with 10 mesh screen cloth to remove zooplankton and bigger algae, and then suction filtered with 0.45 um aperture of acetate fiber microporous membrane for chlorophyll a analysis by spectrophotometer.

2.3.4.3 Determination of filter water rate and food intake.

The filtration rates of scallop were measured in September and November 1993, May 1994, and April-May in 1995 under the conditions of simulated flowing water method in situ. The filtration rate is calculated by the following formula:

$$FR = V \frac{P_{cp} - P_{ex}}{P_{cp}} \qquad (1)$$

FR: the filtration rate (L/h);P_{cp}: Average chlorophyll (ug/L) or POM (mg/L) concentration in the inlet of chamber; P_{ex}: The average chlorophyll (ug/L) or POM concentration (mg/L) in the outlet of chamber. V:flow rate (L/h).

The formula for calculating the food intake of scallop and fouling filter-feeding animals is as follows:

$$F_{demand} = k \times C_{Chl\ a} \times FR \times 10^{-12} \qquad (2)$$

F_{demand} : food intake (t C/ind/d);
K : the ratio of organic carbon and chl a in phytoplankton (40:1).
FR : amount of water filtered by animals in 24h a (L/d);
C_{Chla} : chlorophyll a concentration in the bay (μg/L).

2.3.4.4 Determination of primary productivity.

C14 method is used to determine phytoplankton assimilation coefficient, the transparency of each position is measured with a transparent plate at the same time. The simplified formula proposed by Cadee and Hegeman is used to calculate the primary productivity in photic zone of the bay.

$$P = \frac{1}{2} PP \times E \times D \qquad (3)$$

In the formula, P is the daily primary productivity of the site (mg C/m^2•d), PP is the potential productivity of surface water samples (mg C/(m^3•h)), E is depth of photic zone (m), and D is the length of day from sunrise to sunset (h).

2.3.4.5 Density of farmed scallops and fouling filter-feeding organisms.

According to the data provided by the local authority, the total number of Zhikong scallop *Chlamys farreri* farmed in Sungo Bay was 2 billion in 1995. Among them, the numbers of scallop with shell height of 3–4 cm, 4–5 cm and >5 cm were 8.0, 6.4, and 560 million respectively with density of 50 ind./m^2.

The main filter-feeder fouling organisms in Sungo Bay were sea squirts (*Ciona intestinalis, Styela clava*), blue mussel (*Mytilus galloprovincialis*) and clam (*Modiolus comptus*). Among them, most of blue mussels and clams were growing on longline and float, while sea squirts mainly growing on lantern net with big biomass. The method for estimating the biomass and density of fouling filter-feeding animals is as follows: taking 20 float, 2 m raft rope and 20 scallops each survey in random, counting the number of seasonal dominated filter-feeding animals described above, taking the average density and biomass, and then determining the average biomass according to the total farming area, the length or surface of farming equipment.

2.3.4.6 The organic carbon supply produced by primary productivity of the bay in different seasons.

The calculation formula of the primary production capacity of Sungo Bay is as follows:

$$F_S = \sum_{i=1}^{n} (P_i \text{ x } T_i \text{ x } S) \text{ x } 10^{-9})$$

In the formula, F_S is total supply of organic carbon (t), P_i is primary productivity (mgm^2•d), T_i is sampling interval (d), S is the area of water area (m^2) and n is the sampling frequency respectively.

2.3.4.7 The seasonal variation of the filtration rate and the food intake of Zhikong scallops in different size groups in Sungo Bay.

Table 2-8 show seasonal variations of filtration and feeding rates of scallop in Sungo Bay varying greatly due to different specifications and seasons. The filtration rate and feeding rate were positively correlated with the size of scallops. Due to factors such as reproduction, the seasonal variation of scallop's filtration rate and feeding rate was relatively complicated. In general, the filtering rate rose with the rise of temperature. In addition to the stage of the breeding season, the ingesting rate was basically consistent with that of the filtering rate.

Table 2-8 The seasonal variation of water filtration and feeding rates of scallop in Sungo Bay.

Date (dd/mm)	Chl a (ug/L)	Filtration rate (L/ind/)			Ingesting rate (ug Chl a/ind/d)		
		3-4cm	4-5cm	5-6cm	3-4cm	4-5cm	5-6cm
20/01	412	025	042	080	2,472	4,153	7,910
28/03	524	070	108	248	8,803	13,582	31,188
25/04	231	159	239	313	8,815	13,215	17,353
28/05	214	164	225	358	8,423	11,556	18,337
09/07	688	226	320	446	37,317	52,838	73,644
24/08	409	286	414	524	28,074	40,638	51,436
25/09	362	276	405	515	23,979	35,186	44,743
14/10	169	196	290	416	7,950	11,762	16,873
15/11	095	025	072	230	1,026	1,642	5,244

2.3.4.8 Seasonal variations of biomass, filtration rates and feeding rate of main filter-feeding fouling animals in the bay.

The average biomass of main filter-feeders fouling organisms and the total stock shown in Table 2-9. From Table 2-9, we can see that sea squirts were the largest fouling species in the bay, and their total current stock was about 1x than the scallops. The second largest fouling animal was mussel.

Table 2-9 The average biomass in different seasons of the main filter-feeding animals in Sungo Bay.

Species	Mussel (M. edulis)	Modiolus sp	Small Styela sp	Ciona sp	Big Styela sp
Area (hm^2)	4,000	4,000	4,000	4,000	4,000
Biomass (ind/hm^2)	67,500	7,500	1,000,000	1,000,000	167,500
Total (million)	270	30	4,000	4,000	670

In Sungo Bay, blue mussel and big sea squirts *Styela clava* were growing year-round on the surface of longline ropes and floats, while the biomass of Ciona intestinalis, small *Styela clava*, clam *Modiolus comptus* was very small in winter and spring. Therefore, the food intake of such animals was only calculated after May.

The water clearance of main fouling animals shown in Table 2-10.

Table 2-10 Seasonal variation of filtration rate of main filter-feeding animals (L/h•ind) in Sungo Bay.

Month	*Mussel (M. edulis)*	*Ciona sp*	*Modiolus sp*	*Small Styela sp*	*Big Styela sp*
January	0.20		0.05		0.01
May	4.39	0.73	4.01	0.36	3.19
September	1.80	1.13	1.70		
November	0.63	0.35	0.16	0.18	0.02

According to the above formula (2) and the average biomass, filtration rate of filter-feeders fouling organisms, chlorophyll a concentration, calculation results of unit area's daily food intake (g C/hm^2/ d) of Sungo Bay's filter-feeders fouling organisms (g C/ hm^2/d) is shown in Table 2-11.

Table 2-11 Seasonal variation of daily food intake (g C/hm^2/d) of main filter-feeding in Sungo Bay.

Date (dd/mm)	Chl a (mg/m^3)		Ingestion ration (g C/hm^2/d)				SUBTOTAL
		Mytilus edulis	*Modiolus sp*	*Styela sp*		*Ciona sp*	
				Young	Adult		
20/01	4.12	53.25	1.50		6.75		61.50
28/03	5.24	68.25	2.25		8.25		78.00
25/04	2.14	94.50	3.00		7.50		104.25
28/05	2.26	87.00	2.25		6.75		96.75
09/07	6.88	280.50	8.25	1,188.75	22.50	2,311.50	3,811.50
24/08	4.09	167.25	4.50	706.50	13.50	1,374.00	2,265.75
25/09	3.62	147.75	4.50	625.50	12.00	1,216.50	2005.50
14/10	1.69	69.00	2.25	291.75	5.25	567.75	936.00
15/11	**0.95**	**39.00**	**0.75**	**164.25**	**3.00**	**319.50**	**526.50**

2.3.4.9 The supply of organic carbon of Sungo Bay for filter-feeding animals.

According to the assimilation coefficient and chlorophyll a concentration in different seasons, the annual change of organic carbon in the primary productivity of Sungo Bay is shown in Table 2-12. From the data in the table, the change of primary production in the bay can be seen that it was closely related to the changes of feeding habits of farmed and wild animals, water temperature and chlorophyll a concentration.

Table 2-12 Annual change of organic carbon in primary productivity of phytoplankton in Sungo Bay.

Date (dd/mm)	Chl a (mg/m^3)	Area ($1x10^8 m^2$)	PP (mg $C/m^2/d$)	UADPP (kg $C/hm^2/d$)	DPP (t C/d)
20/01	4.12	1.33	179.47	1.79	23.93
28/03	5.24	1.33	134.69	1.79	17.96
25/04	2.14	1.33	62.86	1.34	9.05
28/05	2.26	1.33	231.63	0.63	32.25
09/07	6.88	1.33	1,419.68	2.32	189.29
24/08	4.09	1.33	974.61	14.20	137.89
25/09	3.62	1.33	963.55	9.74	126.70
14/10	1.69	1.33	206.03	9.63	27.47
15/11	0.95	1.33	179.32	2.06	23.91

PP: Primary production; DPP: Daily primary production; UADPP: Daily primary production of unit area

2.3.4.10 Production carrying capacity of Sungo bay for Zhikong scallops in different seasons.

According to the formula (5) and the above-listed ingesting rate, biomass, filtration rate, primary production of farmed scallop and fouling organisms, the unit area production carrying capacity and total production carrying capacity of Sungo Bay for Zhikong scallops of different size groups was listed in Table 2-13 and 2-14 respectively.

Table 2-13 Unit area carrying capacity of Zhikong scallops in Sungo Bay (ind./m^2).

Date (dd/mm)	DPP (t C/d)	Ingestion of FO (t C/d)	Ingestion of scallop (t C/d)			Unit Carrying capacity (ind./m^2)		
			3-4 cm	4-5 cm	5-6 cm	3-4 cm	4-5 cm	5-6 cm
20/01	23.93	0.25	988.8	1,661.2	3,164.2	167	99	52
28/03	17.96	0.31	3,521.2	5,432.8	9,306.4	46	30	17
25/04	9.05	0.42	3,526.0	5,300.0	6,941.2	19	12	10
28/05	32.25	0.39	3,369.2	4,622.4	7,354.8	85	62	39
09/07	189.29	15.25	14,926.8	21,135.2	29,457.6	67	47	34
24/08	137.89	9.06	11,229.6	16,255.2	20,574.4	76	52	41
25/09	126.70	8.02	9,591.6	14,074.4	17,897.2	85	58	46
14/10	27.47	3.74	3,180.0	4,704.8	6,749.2	18	12	8
15/11	23.91	2.11	410.4	656.8	2,097.6	283	177	55
Mean	**65.38**	**4.39**	**5,638**	**8,204**	**11,504**	**94**	**61**	**34**

Table 2-14 The total aquaculture capacity of Zhikong scallops in Sungo Bay.

Date (dd/mm)	DPP (t C/d)	Ingestion of FO (t C/d)	Ingestion of scallop (t C/d)			Theoretical CC (million)			Limited CC (million)		
			3-4 cm	4-5 cm	5-6 cm	3-4 cm	4-5 cm	5-6 cm	3-4 cm	4-5 cm	5-6 cm
20/01	23.93	0.25	988.8	1,661.2	3,164.2	240	143	75	180	107	56
28/03	17.96	0.31	3,521.2	5,432.8	9,306.4	50	33	19	38	25	14
25/04	9.05	0.42	3,526.0	5,300.0	6,941.2	25	16	12	19	12	9
28/05	32.25	0.39	3,369.2	4,622.4	7,354.8	95	69	43	71	52	32
09/07	189.29	15.25	14,926.8	21,135.2	29,457.6	117	82	59	88	62	44
24/08	137.89	9.06	11,229.6	16,255.2	20,574.4	115	79	63	86	59	47
25/09	126.70	8.02	9,591.6	14,074.4	17,897.2	124	84	66	93	63	50
14/10	27.47	3.74	3,180.0	4,704.8	6,749.2	75	50	35	56	38	26
15/11	23.91	2.11	410.4	656.8	2,097.6	531	332	104	398	249	78
Mean	**65.38**	**4.39**	**5,638**	**8,204**	**11,504.0**	**152**	**99**	**53**	**114**	**74**	**40**

FO: Fouling organisms; CC: Carrying capacity; DPP: Daily primary production

According to the assimilation coefficient and chlorophyll a concentration in different seasons, the annual change of organic carbon in the primary productivity of Sungo Bay is shown in Table 2-12. From the data in the table, the change of primary production in the bay can be seen that it was closely related to the changes of feeding habits of farmed and wild animals, water temperature and chlorophyll a concentration.

2.3.4.11 Estimation method of breeding capacity and source of error.

The results of Bacher et al (2003) showed that the effect of benthos on the growth of raft culture filter-feeding animals was negligible, compared to the effect of aquaculture density on the growth of aquaculture species. To simplify the estimation model, the effect of benthic filter-feeding organisms on farmed carrying capacity was not considered in this research.

Most zooplankton can feed on phytoplankton directly, which is one of the key factors affecting primary production. In this study, the data of chlorophyll a or POM was considered since it was already fed by zooplankton, hence the special analysis of zooplankton on the influence of primary production was not included in the assessment.

The aquaculture carrying capacity of the bay was estimated by comparing the difference between the organic carbon supply produced by primary production and the demand for organic carbon. Compared with the POM method, this method is simple in operation, and the data is less affected by the weather changes.

Aquaculture capacity can be divided into unit area aquaculture carrying capacity and total aquaculture carrying capacity. Estimating carrying capacity per unit area can help identify if the current aquaculture density is in the best density ranges, to adjust aquaculture density according to carrying capacity for sustainable aquaculture.

Aquaculture capacity is a dynamic index to measure aquaculture potential. Changes in various ecological environmental factors can bring about great changes in carrying capacity. Which indicates that different seasons have different carrying capacity, as listed in Table 2-14.

The estimated value of organic carbon of annual primary production of Sungo Bay is 24,000t, which is higher than that estimated by Mao Xinghua, etc., in the mid-1980s (about 8,000 t). The main reason for the difference may be that the pore diameter of the microporous filter membrane used here is 0.45 u in the determination of chlorophyll a, while the pore diameter of the microporous filter membrane used by Mao Xinghua is 0.65 u.

The estimation accuracy of aquaculture carrying capacity is influenced by many factors such as current, primary productivity, experimental conditions, etc. The deviation of any factor will cause a large error in carrying capacity estimation. Although the main feed of scallops is phytoplankton, it also feeds some organic detritus, small zooplankton bacteria and so on. This aquaculture carrying capacity estimation method and model were established mainly based on chlorophyll a. Further research should try to focus on how to quantify and determine food resources of filter-feeding organisms except for phytoplankton, and accurately determine filtration rates, feeding rates and ingesting rates for improving the production carrying capacity model.

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2.4 Environmental carrying capacity assessment & ecological regulation strategy for fish cage farming

2.4.1 Environmental impacts of fish cage culture

Cage culture is one intensive fish culture mode of mariculture, which can have high fish density. Cage culture for marine fish is promoted by increasing living standards and demand for fresh seafood with high market values. Moreover, the species of cultured marine fish is over 80 and the production of aquatic products is more than 1.30×10^6 t in the People's Republic of China (Tang et al., 2016). Cage culture has become the pillar industry of mariculture in coastal zones of PR China as advanced culture technology and mode of cage culture, during which culture species and scale increase, e.g., the production of cage culture in seawaters gets to 6.20×10^5 t in 2016. Nevertheless, cage culture is one pollution source and produces negative effects on adjacent seawaters because cage culture is one heterotrophic ecosystem based on artificial diets. Impacts of cage culture on environments of Ailian Bay, Weihai, Shandong Province, are studied (Ge et al., 2007). In the bay, the feeding behavior of fish is the most active in summer and the feeding rate of *Lateolabrax maculates* is 1.4–4.4 %, which reaches maximum in August. Feed remains rate ranges from 11.0 to 28.0 %, and reaches maximum from July to September. There are about 38.6 t dissolved oxygen (DO) consumed by L. maculates during one production period, and the oxygen consumption rate gets higher in July, August and September. Moreover, cultured fish provides an important effect on the nutrient cycle of seawaters used for cage culture. From April to December, there are about 0.8 t ammonia and 1.0-1.6 t nitrogen put into the bay through cultured L. maculates. In the floating net cage culture zones with area 2.0×10^5 m^2, the 17.2–27.5 % of nitrogen demanded by phytoplankton can be supplied by excretion of cultured fish. Further, 12.0 t particulate matters are discharged into the bay through the biodeposition of cultured L. maculates. These are great effects of cage culture on the environment, which include effects on water, sediment and organisms, etc.

2.4.1.1 Effects on water quality

There are some elements such as carbon, nitrogen and phosphorus in feed remains and wastes produced by cage culture. About 150–300 kg of feeds remained, accounting for about 30% of total food fed to cultured fish and 250–300 kg of fish feces will be produced with 1 t of rainbow trout. Some of these contaminations will be dissolved and some of them will remain solid, which can lead to high concentration of carbon, nitrogen and phosphorus, and particulate matters in the water body.

The decomposition effects of bacteria on organic matter can be promoted by carbon with high concentration and long retention time, which leads to increased chemical oxygen consumption. Moreover, the eutrophication level and the ratio of nitrogen/phosphorus can be influenced by these contaminations. Further, transparency decreases as particulate matters concentration increases, which influences the visual action of fish subsequently. The inhibited visual behavior of fish may lead to more particulate matter as concentration of feed remains increases, which may choke the respiration system. In cage culture zones, about 60–70 % of oxygen may be consumed by cultured fish directly, however, these contaminations caused by cage culture can lead to reduction of DO concentration which may be less than uncultured seawaters. If DO concentration is less than 4 mg/L, the growth rate of organisms will be inhibited. Moreover, the reduction community will become the dominant population as anaerobic bacteria becomes the dominant species in the environment with low DO concentration, and the transformed nutrients in the water body will be broken off.

2.4.1.2 Effects on sediments

These feed remains and bio-deposition of culture that cannot be decomposed by microbes and benthic accumulate in the bottom the net cage, which may lead to bottom rise. The sediment environment and population structure are altered by organic matters, phosphorus and sulfide in sediments. Thus, there is great impact of cage culture on sediment and the effects worsen as increased number of net cages, culture density, which has positive relation with production of feed remains, excretion and bio-deposition. Thus, the sediment quality has significant relation with the culture density.

Benthic anoxia may be caused by decomposition of feed remains and fish feces accumulated in the bottom of cage culture, and some matters with toxicity such as sulfide may generate during the decomposition of these contamination driven by bacteria. Moreover, sediments are rich in heavy metals in polluted areas because organic matter and other kinds of metals can form coordination compounds in sediments in cage culture zones. Further, red tide may be reduced as the release of nitrogen, phosphorus, and some kinds of trace elements such as Fe and Mn from sediment can be promoted by microbes under anoxia conditions.

2.4.1.3 Biological effects

Aquatic organisms are affected subsequently as the water body and sediment environmental quality are influenced by cage culture in seawaters. As the nutrient concentrations increase, including the imbalance of nitrogen to phosphorus ratios, there will be algae blooms in the cage culture zones, which leads to high concentration of *chl a* and turbidity, and sharp diurnal volatility of DO concentration in cage culture zones in coastal seawaters.

The sulfide and organic carbon caused by feed remains and fish feces accumulated in the bottom of the net cage have double threshold effects on the benthos. They can be nutrition sources for these organisms and the organic matters are poisonous for these organisms during their decomposition because of decreased DO oxygen concentration and increased hydrogen sulfide concentration. Thus, only the contamination-resistant organisms can live in the seawaters in the cage culture zones, which implies that the benthic community structure changes in the seawaters. The body size of these benthic organisms is usually small.

Wild fish population gets larger in the adjacent areas of cage culture zones, which are rich in food sources. The body sizes of wild fish in cage culture zones a larger than in uncultured zones. There are usually cultured fish escapes during net replacement, medicated bath and harvest, which implies that the native fish will be influenced by these cultured fish from a genetics perspective. Further, pathogenic microorganisms may be reduced by cage culture as the organic matter concentration and nutrients concentration in cage culture zones increases.

2.4.2 Advancement of studies on carrying capacity of cage culture

The study on carrying capacity was first conducted in Japan. Researchers from the People's Republic of China began to pay attention to carrying capacity as increased aquaculture scale relative early (Tang, 1996; Fang et al., 1996a, b; Yang and Zhang, 1999), with focus on autotrophic ecosystems.

Related studies on carrying capacity for cage culture are shown in Table 2-15. Based on investigations about water quality, sediment, marco-benthic and topography of 22 fish farms in Kumano-nada coast, carrying capacity has significant relations not only with organic matter load but also with the location and topography of fish farms, and carrying capacity can be estimated by embayment degree (Yokoyama et al., 2002). The calculation is simple and carrying capacity can be estimated in a short time, however, the estimation method is based on the investigation about small bays with similar environmental conditions such as terrigenous influence, tide, wind and waves. Thus, it should be cautious to determine the carrying capacity of other water areas by method.

The seasonal variation of the accumulation flux of organic carbon and the organic carbon content in the surface sediment in fish cage culture zones of Dapeng'ao Bay is analyzed (Huang et al., 2003). It is considered that the limiting factor to determine the carrying capacity of the fish farm is the organic carbon accumulation flux. If the organic carbon content in surface sediment is 1.8%, the aquaculture density becomes the carrying capacity. Thus, the carrying capacity of the fish farm in spring and summer is 650 t and 550 t, respectively. In practice, the variation of self-pollution of cage culture and self-purification ability of seawater is revealed by the method. Moreover, there is significant positive relation between carrying capacity and organic carbon content in surface sediment, however, the relation between the carrying capacity of fry and organic carbon content is not significant, which implies that the method should be improved.

The carrying capacity for fish cage culture in Gongwan Bay is evaluated by one 2-dimensional simulation model (Huang et al., 1998), during which the nitrogen and phosphorus concentrations are considered limiting factors. Nevertheless, the feed remains will accumulate in the sediment in the semi-closed bay with current velocity 10 cm/s, which leads to anoxia, and cultured fish may be negatively affected b oxygen with low concentration. The inorganic nitrogen distribution in summer in Xiangshan Bay is simulated by one 3-dimensional numerical model, and the carrying capacity for fish cage culture in the whole bay is determined, during which the limiting factor is inorganic nitrogen and the threshold values are the II or III levels of seawater quality of PR China (Ning et al., 2002). Nevertheless, the responsible relation among culture environment, benthos and cultured fish is not considered fully, which determines the self-purification ability of one given seawater. Further, nitrogen and phosphorus are considered conservation substance in the simulation to simplify the calculation process, however, there are active adsorption and desorption behaviors of total nitrogen and phosphate (Fan et al., 2004).

The coupling 3-dimensional numerical model including water and the bottom driven by hydrodynamic force, through which the carrying capacity is determined (Abo and Yokoyama, 2003; Lee et al., 2003). Moreover, the biogeochemical process in these cage culture zones are taken into account in Abo and Yokoyama (2003) during which the limiting factor is the oxygen demand of sediment, and in Lee et al. (2003) during which limiting factors include nitrogen and phosphorus load and oxygen demand of sediment.

Table 2-15 Studies on fish cage culture.

Fish species	Water area	Carrying capacity	Determination method	Limiting factor	Reference
Tilapia, channel catfish	Dahua Yantan reservoir, Guangxi	32393t, 23250t	The method of limiting factor based on material balance	P (threshold value 0.05 mg/L)	Zhang et al., 2012
Tilapia, channel catfish	Hepu reservoir, Guangxi	2686 t, 1928 t	The method of limiting factor based on material balance	P (threshold value 0.05 mg/L)	Kong et al., 2012
Epinephelus akaara, Epinephelus fario, Epinephelus awoara, Lutianus erythropterus, etc	Dapeng'ao Bay, Guangdong	650 t (spring), 550 t (autumn)	Organic carbon content in sediment	Organic carbon (threshold value 1.8 %)	Huang et al., 2003
Channel catfish, tilapia, etc	Longtan reservoir, Guizhou		The method of limiting factor based on material balance	P (threshold value 0.05 mg/L)	Xie et al., 2014
	Sandou Bay	1.07 kg/m^3	Sulfide content in sediment	Sulfide (threshold value 300 mg/Kg)	Du and Zhang, 2010
	Gongwan Bay, Guangdong	65,000 net cages	Water quality dynamics model	N (threshold value 0.3 mg/L); P (threshold value 0.02 mg/L)	Huang and Wen, 1998
Siniperca chuatsi	Fuqiaohe reservoir, Hubei		The method of limiting factor based on material balance	P (threshold value 0.0066 mg/L)	Peng et al., 2004
	Yaling Bay, Guangdong	It has relation with culture period.	Material balance/ Water quality dynamics model	N and P (threshold value of the II levels of the seawater in PR China)	Shu et al., 2005
	The Kingdom of Norway, Kongeriket Norge		MOM model	The minimum carrying capacity determined by limiting factor of NH_4, DO and benthos	Stigebrandt et al., 2004
Tilapia	The Federative Republic of Brazil		The method of limiting factor based on material balance	Phosphorus	David et al., 2015
			The method of limiting factor based on material balance	Nutrients	Middleton and Doubell, 2014; Middleton et al., 2014

The difficulty of carrying capacity evaluation for marine cage culture increases because of the complex hydrodynamic force and cage culture ecosystem. The total production control aim can be resolved by the present model used for carrying capacity assessment. Nevertheless, there are shortcomings about these models to regulate the culture structure of fish farms and to optimize culture modes. In PR China, some work about assessment carrying capacity for cage culture has been conducted, and the culture fishes include *Lateolabrax japonicus* and *Sebastes schlegeli*. Moreover, nutrients regeneration and diffusion have been considered.

2.4.2.1 Dynamic load of ammonia caused by *S. schlegeli* cultured in net cage

If the effects of culture density on fish growth and fish excretion, the dynamic ammonia load caused by one individual S. schlegeli in a production period can be expressed by

$$\left\{\begin{array}{l} g(w) \\ T \\ w_0 \\ N(w).(1-m(t)).n \end{array}\right.$$

where w_0 is the mean initial body weight of the cultured fish. And T is the water temperature which can be expressed as $T=f''(t)$, during which t is time. The fish growth can be expressed by $g(w)=f(T,w)$ and the ammonia excretion of cultured fish can be simulated by $N(w)=f'(T,w)$. Moreover, m(t) and n is the mortality rate and the number of fish, respectively.

2.4.2.2 Carrying capacity of cage culture in Sungo Bay

According to the results of simulation, responses of dissolved inorganic nitrogen ( ) to the increased fish culture scale can be expressed as,

$$\mathrm{DIN} = \left\{\begin{array}{llll} \text{April} & 23.056K + 34.353 & R^2 = 1 & n=9 \\ \text{May} & 44.603K + 22.919 & R^2 = 0.9997 & n=9 \\ \text{June} & 77.969K + 63.120 & R^2 = 0.9999 & n=9 \\ \text{July} & 111.18K + 20.193 & R^2 = 0.9993 & n=9 \\ \text{August} & 888.49K + 43.343 & R^2 = 1 & n=9 \\ \text{September} & 189.09K + 276.77 & R^2 = 1 & n=9 \\ \text{October} & 199.59K + 160.73 & R^2 = 1 & n=9 \\ \text{November} & 265.1K + 143.63 & R^2 = 1 & n=9 \\ \text{December} & 74.144K + 107.53 & & n=9 \end{array}\right.$$

where K is the amplification multiple as the initial culture density is 1 ind.m^{-3} and K can reflect the culture scale. Thus, the *DIN* concentration increases as the increased fish culture scale.

The DO concentration decreases as the increased fish culture scale, and the responses of DO to the increased fish culture scale can be expressed as

$$\mathrm{DO} = \left\{\begin{array}{llll}
\text{April} & -282.08K + 9{,}531.9 & R^2 = 1 & n=9 \\
\text{May} & -436.90K + 8{,}659.2 & R^2 = 0.9992 & n=9 \\
\text{June} & -605.13K + 8{,}659.2 & R^2 = 0.9997 & n=9 \\
\text{July} & -689.17K + 8{,}036.6 & R^2 = 0.9950 & n=9 \\
\text{August} & -2{,}188.3K + 7{,}759.6 & R^2 = 0.9994 & n=9 \\
\text{September} & -1{,}012.3K + 7{,}759.6 & R^2 = 1 & n=9 \\
\text{October} & -1{,}028.7K + 8{,}178.0 & R^2 = 1 & n=9 \\
\text{November} & -1{,}120.7K + 8{,}869.9 & R^2 = 1 & n=9 \\
\text{December} & -582.16K + 9{,}636.9 & & n=9
\end{array}\right.$$

According to the water standard of the People’s Republic of China (Table 2-16), the carrying capacity can be estimated (Table 2-17).

Table 2-16 Water standard of the People’s Republic of China (mg.m^{-3}).

Index	I	II	III	IV	V
DIN	≤200	≤300	≤400	≤500	>500
DO	>6,000	>5,000	>4,000	>3,000	≤3,000

Table 2-17 Environmental carrying capacity determined by DIN.

Index	4	5	6	7	8	9	10	11	12
I	≤7.18	≤ 3.97	≤ 1.76	≤ 1.52	≤ 0.18	≤-0.41	≤0.20	≤0.21	≤1.25
II	≤11.52	≤6.21	≤3.04	≤2.37	≤0.29	≤0.12	≤0.70	≤0.59	≤2.60
III	≤15.86	≤8.45	≤4.32	≤3.21	≤0.40	≤0.65	≤1.20	≤0.97	≤3.94
IV	≤20.20	≤10.70	≤5.60	≤4.06	≤0.51	≤1.18	≤1.70	≤1.40	≤5.29
V	>20.20	>10.70	>5.60	>4.06	>0.51	>1.18	>1.70	>1.40	>5.29

Note: The value shown in the table means one range.

Considering the effects of oxygen, the carrying capacity of one raft net cage is 484 fish individuals, and the carrying capacity of one floating net cage is about 15,600 individuals. Thus, if the area of the culture zone is given, the number of net cages can be calculated.

2.4.2.3 Carrying capacity of cage culture under bioremediation/biorestoration

The carrying capacity of the floating net cage with Ø 16 m and depth 20 m in Sungo Bay is 15600 individual of *S. schlegeli* with body weight 70 g. Moreover, the threshold value to determine the carrying capacity is the Class II water quality standards of the People's Republic of China. If *Gracilaria lemaneiformis* is used to promote the carrying capacity, the promotion effects (*Ae*) can be 0.033 ind/g, and the carrying capacity for cage culture can be promoted 10–15 % if there is 47.3-70.9 kg *G. lemaneiformis* is cultured in one floating net cage. At present, the number of cultured fish through the floating net cages in Sungo Bay is over the 28 percent of carrying capacity. Thus, 193.9–224.2 kg *G. lemaneiformis* is needed to promote the existing biomass of *S. schlegeli* 10–15 %, which means that the 209 kg *G. lemaneiformis* should be cultured in one floating net cage. Through bioremediation, the water quality may meet the Class II water quality standards PR China and carrying capacity may be promoted 10-15 %.

The carrying capacity of the raft net cage with size 5m×5m×5m in Sungo Bay is 484 individuals of *S. schlegeli* with body weight 70 g. Moreover, the threshold value to determine the carrying capacity is the Class II water quality standards of PR China. If *G. lemaneiformis* is used to promote the carrying capacity, the promotion effects (*Ae*) can be 0.033 ind/g, and the carrying capacity for cage culture can be promoted 10-15 % if there is 1.5-2.2 kg *G. lemaneiformis* cultured in one floating net cage. At present, the number of cultured fish through the floating net cages in Sungo Bay is over 3 % of carrying capacity. Thus, 2.0-2.7 kg *G. lemaneiformis* is needed to promote the existing biomass of *S. schlegeli* 10-15 %, meaning 2.4 kg *G. lemaneiformis* should be cultured in one floating net cage. By bioremediation, water quality may agree with Class II water quality standards of PR China and carrying capacity may be promoted 10-15 %.

2.4.3 Regulation strategy for fish cage culture environments

2.4.3.1 Advance of bioremediation/biorestoration technology

Bioremediation technology is one milestone for biological treatment technology, and has received recognition from the environmental protection field and has gotten attention from industry. The contaminated environment can return to the original state partly or fully by bioremediation technology which uses metabolism behavior to reduce concentration or content of toxic substances or to change these toxic substances into harmless.

Bioremediation technology study was conducted in the 1970s, and focuses on laboratory study about oil biodegradation in water, soil and ground water. The results of these basic studies have been used to govern contaminated environments with large scale from 1980s and the utilization is very successful. The United States Environmental Protection Agency uses bioremediation technology to treat the Exxon Valdez oil spill event, during which the contamination matters have been eliminated in a short period. Another successful example of utilization of bioremediation technology is the pollution control engineering in an air force base in Grayling, Michigan in 1993, where the contamination is from the ruptured pipeline of diesel storage tank. The contamination matters in deep soil and water contamination with high concentrations have been treated effectively in the bioremediation projects.

Application of bioremediation technology for aquaculture resource sustainable utilization is an important field of marine biological technology, and is the key field of environmental technology research and development. Because of higher efficiency and less energy consumption, the bioremediation technology is used widely to govern aquatic areas.

As self-pollution of mariculture worsens, especially the intensive culture mode of feeding-culture-ecosystem in land or shallow sea, bioremediation technology is being explored and applied to improve and optimize the culture environment, and to reduce the waste output. Thus, nutrition in waste discharged from culture zones can be used circularly and balance between economic development and environment protection can be obtained.

The environmental management for the cage culture zones are conducted through controlling the number of net cage and culture scale, alternate culture and shutoff culture generally, however, the utilization efficiency of the cage culture zone is low and some nutrition just like feed remains, fish feces and soluble matter are released into the water areas which leads to pollution and huge resource wastes. These culture modes cannot be accepted by the public, scientists, farm holders and government because it costs environmental quality and safety. Integrated Multi-Trophic Aquaculture (IMTA), being environment-friendly and remarkable benefits, can be accepted by society and is constantly being explored by scientists (Troell et al., 2009). The aquaculture environment bioremediation technology based on the IMTA theory technology is also in constant development. Moreover, culture process controlling and culture environment bioremediation are realized through seaweed and shellfish cultured in the cage culture zones. The DIAEEBDSA (Development of Integrated Aquaculture for Environmentally and Economically-balanced Diversification and Social Acceptability) has been launched in Canada to remediate the cage culture zones and the results were accepted. The results of the bioremediation conducted in Canada can be considered a successful sample for bioremediation. During the bioremediation, one integrated culture ecosystem was set up, and the ratio of biomass among trout, mussels and seaweed is determined properly. Also, the characteristics of seawaters and the operating convenience are considered. By bioremediation technology, the culture environment can be kept well and economic requirements can be satisfied. Further, limited resources are effectively used in the technology because waste produced from one culture unit can be used by another culture unit through feed management optimization and promotion food stuff transformation efficiency. The SEAPURA (Species Diversification and Improvement of Aquatic Production in Seaweeds Purifying Effluents from Integrated Fish Farms) supported by The European Commission and AWI select macroalgae with high market values to purify wastes produced from fish.

During the last 20 years, bioremediation technology used for aquatic areas has advanced well. Bioremediation used in aquaculture environment has developed stepwise, during which seaweed, shellfish, and sea cucumber were used to bioremediate culture ponds and shallow seas. The impacts of cage culture on environment have been studied in PR China (Ning et al., 2002; Gao et al., 2005; Ge et al., 2007), however, there are relative few studies on bioremediation of cage culture zones. *G. lichenoides* and *G. lemaneiformis* are used in the cage culture zones of Bachimen Bay, Dongshan, Fujian Province, China (Tang et al., 2005). *G. lichenoides* can bioremediate contaminated seawaters well, promote DO concentrations, and reduce inorganic nitrogen (IN) and inorganic phosphorus (IP) concentrations. According to Zhou et al. (2006), *G. lemaneiformis* with high contents of nitrogen and phosphorus grows well around the net cage, and the nutrients adsorption rate and growth rate of this seaweed species is high. The production of *G. lemaneiformis* in these cage culture zones can be 70 tons per hectare, and 2,200 kg nitrogen and 300 kg phosphorus can be removed from the water body by this seaweed. Nevertheless, only soluble nutrition matter can be reused by the one-fold bioremediation organisms and the nutrition matter in sediments and particulate matter cannot be eliminated from culture zones.

2.4.3.2 Seasonal complementarity bioremediation technology based on seaweed in cage culture zones

Nitrogen which can be effectively absorbed by seaweed is one important excretion matter resulting from cultured organisms in cage culture zones. Thus, the seaweed can be used to bio-restorate the cage culture zones potentially. Kelp can adapt to low temperatures and the best production season for kelp ranges from September to May of the following year. Moreover, the best production season for *G. lemaneiformis* in Northern China ranges from June to October. Thus, kelp and *G. lemaneiformis* have season complementarity from the perspective of best production period. Further, nutrients can be removed by kelp and *G. lemaneiformis* effectively. All these characteristics of kelp and *G. lemaneiformis* lead to the utilization of the two species to regulate cage culture zones throughout the year. From September to May (winter and spring), kelp can be used and from June to December (summer and fall),*G. lemaneiformis* can be used.

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2.5 Carrying capacity assessment for IMTA

2.5.1 Research status of carrying capacity assessment for IMTA

There are two kinds of variation trends in the aquaculture ecosystems as increased stocking density, aquaculture scale, or utilization period of the fisheries farms. Because of excreted nutrients, food remains and fish feces, nutrient concentrations increase as stocking density and utilization period in finfish farms increases. On the other hand, DO concentration is reduced because of respiration of finfish and oxygen consumption caused by degradation of fish feces or food remains. Moreover, lots of nutrients or POM (particulate organic matter) will be consumed by aquaculture, e.g., nutrients may be assimilated by algae, and there will be nutrient shortage if the algae culture scale exceeds the carrying capacity for algae aquaculture. There will be insufficient POM supply in shellfish farms generally if the shellfish biomass or the culture scale exceeds the shellfish carrying capacity although the relationship between stocking density of shellfish and POM concentration is complex. Unlike mono-aquaculture, the IMTA aims at adequately utilizing materials in the aquaculture system by appropriately matching proportions of different organisms. Moreover, there are at least two species of target culture organisms in the IMTA ecosystem (Silva et al., 2012). For example, finfish that depends on foodstuff is the target culture organism, however, the macroalga and the fish feeding on detritus are the auxiliary organisms in the finfish-macroalgae IMTA ecosystem, during which the macroalgae will use the nutrients and the fish feeding on detritus will feed on the food remains. Thus, the carrying capacity assessment of IMTA is only conducted for the target culture organisms. Moreover, IMTA is derived from China and more production practices are conducted in China, which leads to more assessment of carrying capacity for IMTA conducted in China.

As in the previous chapters, the methods used to evaluate the carrying capacity for IMTA include physical models and numerical models. The limitation factors for carrying capacity of IMTA are those influencing physiological characteristics, water planning requirements and ecological safety of waters.

The carrying capacity of one given water is evaluated by monitoring ecological characteristics and environmental factors of IMTA which is miniaturized in one pond or enclosure that is called physical models. To reduce self-pollution of *Penaeus vannamei* culture, one IMTA composed of *Penaeus vannamei-Scatophagus argus-Ipomoea aquatica* was funded by Hu et al. (2013), and the field experiments lasting eight weeks were conducted in one pond with size 5m×3m×1.2m. In the *P. vannamei-S. argus-I. aquatica* IMTA ecosystem, the initial biomasses of *P. vannamei* and *I. aquatica* in different ponds were similar, respectively. Nevertheless, the size or biomass of *S. argus* in different ponds were different. The carrying capacity of the *P. vannamei-S. argus-I. aquatica* IMTA ecosystem was determined as the production of *P. vannamei* and that of *S. argus* became the maximum, and the utilization rate of nitrogen or phosphorus got to the maximum.

To change the status of single structure characteristics of the *P. vannamei* culture pond, the low utilization rate of feed, and the outbreak of disease caused by massive accumulation of organic matters in ponds, one *P. vannamei-Oreochromis mossambicus* IMTA ecosystem lasting 70 days in one enclosure with depth of 1.7 m and area 36 m^2 was conducted (Yu et al., 2015). During the *P. vannamei-O. mossambicus*, different ponds had similar biomass of *P. vannamei*. While, the stocking density of *O. mossambicus* was different.

The integrated pollution index of sediment of the IMTA was calculated by

$$\boxed{A = \frac{C_N}{C_{Ns}} \times \frac{C_p}{C_{Ps}} \times \frac{C_S}{C_{Ss}}}$$

where A, C_N, C_P and C_S was the integrated pollution index, the nitrogen content in sediment (mg/g), the phosphorus content in sediment (mg/g) and the sulfur content in the sediment (mg/g), respectively. Moreover, C_{Ns}, C_{Ps} and C_{Ss} was environmental standard threshold for nitrogen content in sediment (mg/g), phosphorus content in sediment (mg/g) and sulfur content in sediment (mg/g), respectively. As the stocking density of *P. vannamei* was 8.3×10^5 ind/m^2, the value of A reached the minimum if the stocking density of *O. mossambicus* with body weight 201±25 g/ind was 3320 ind/hm^2, which implied that the carrying capacity of *O. mossambicus* in the *P. vannamei-O. mossambicus* IMTA was 3320 ind/hm^2.

The physical mode is one spatial simplification of the IMTA used for production of aquatic products and the environmental or biological index can be observed directly. Nevertheless, there is significant difference between them from the perspective of production period and the experimental period.

The different communities in one ecosystem are in balance as the materials and energy transfer among different trophic layers, during which the conversion rate of materials is given. The Ecopath model, a numerical model, assumes that the ecosystem is composed of different communities with different functions and there is balance between energy output and energy input of every community. In one ecosystem with nutrition balance, the energy flow and the feeding-related species will change if biomass of one function community is improved significantly, which implies the ecological nutrition efficiency, *EF*, will change. If the *EF* of another related function community becomes into >1 as the biomass of one given culture organism is improved, the corresponding biomass is the ecosystem carrying capacity . Based on this principle, a numerical model on a mangrove - *O. mossambicus* IMTA in Zhujiang Delta, China was funded through Ecopath with Ecosim software (Xu et al., 2011) and the carrying capacity for *O. mossambicus* culture was evaluated. If the carrying capacity is evaluated by the

Ecopath model, the water exchange will not be considered and it is difficult to determine the food sources and trophic layers of one given species of organisms in the ecosystem.

An eco-dynamic model to simulate the IMTA can be constructed as the materials circulation and energy flow in the ecosystem are expressed by equations. These equations may include hydrodynamic characteristics, phytoplankton biomass, zooplankton biomass, cultured organism biomass, DO concentration, nutrients concentration, POM concentration, and so on. The responses of environmental factors to aquaculture with different stocking density or culture scale may be estimated by regulation of the initial value of cultured organism biomass. According to the relation between the responses and the cultured organism biomass, the carrying capacity can be determined. One box model about the shellfish-macroalgae IMTA in Sungo Bay, China was conducted by Nunes et al. (2003), during which the equations were related to phytoplankton biomass, dissolved inorganic nitrogen, suspended particulate matters, scallop biomass and oyster biomass. Moreover, the hydrodynamic characteristics of IMTA was simplified as water exchange period. If the culture scale of the kelp was kept constant and only the biomass of scallop or oyster was regulated, the carrying capacity of scallop and that of oyster will be the maximum output production of them, respectively.

Another box model about the same IMTA was funded by Ge et al. (2008), during which the equations included phytoplankton biomass, nutrients concentration variation, water exchange, diffusion flux of nutrients across the water-sediment interface. Moreover, the kelp culture scale kept constant in the model and the least phytoplankton biomass that could support normal growth of shellfish was 8.2 mg.m^{-3}. By regulating the initial biomass of scallop (*Chlamys farreri*) and that of oyster (*Crassostrea gigas*), the relation between carrying capacity of scallop and that of oyster was k= -0.2765y+4.6905, where K and y was expanded multiple times of existing culture scales of scallop and oyster.

Shi et al. (2010) conducted a eco-dynamic model for the IMTA in Sungo Bay, during which the equations included hydrodynamic characteristics, kelp biomass, phytoplankton biomass, dissolved inorganic nitrogen, and suspended particulate matters. Moreover, the shellfish culture scale was the same as that of the practice production in the bay. The carrying capacity of kelp culture is the maximum output production of kelp by regulating the initial values of kelp culture density.

The credibility of these models is based on the prediction accuracy of responses of environmental factors or production of cultured organisms to different culture conditions. Moreover, it needs more parameters to run these models.

2.5.2 Steps of carrying capacity assessment for IMTA

Considering the evaluation methods for determining shellfish carrying capacity, the macroalgae carrying capacity and the finfish carrying capacity, the status of carrying capacity assessment for IMTA, and the characteristics of IMTA, the steps for carrying capacity assessment for IMTA should include the following.

2.5.2.1 Determination of assessment object organisms

Unlike the monoculture ecosystem, IMTA contains more than two species of cultured organisms at the design period of the ecosystem. Some of them are the main species, while some of them are auxiliary species. According to planning of the waters and the profit expectation, the evaluation object organisms should be determined first in the assessment of carrying capacity for IMTA.

2.5.2.2 Determination of limiting environment factors

According to the physiological characteristics, the key limiting factors for determination of the carrying capacity for the object organisms may be determined. In the finfish-macroalgae IMTA, the key limiting environment factor for carrying capacity is the nutrients concentration if the finfish feeds on foodstuff and it is the object organisms. If the IMTA is composed of macroalgae and filter feeding shellfish, the key environmental factor that can limit the survival and growth of shellfish is the phytoplankton biomass, which implies that the limiting factor of the carrying capacity for shellfish culture is phytoplankton biomass if the filter feeding shellfish is the object organisms. Moreover, the threshold value of these key factors is determined by the biological tolerance of the object organisms and the planning of the waters.

2.5.2.3 Determination of methods to evaluate carrying capacity

Based on the closure degree of the waters, the key limiting factors and the production period, the methods to determine the carrying capacity are determined. If the waters used for aquaculture belongs to closed areas which are influenced by water exchange less and the food sources of all species of cultured organisms can be determined precisely, the Ecopath mode can be used to evaluate the carrying capacity for IMTA. The physical mode can be used to determine the carrying capacity for IMTA if the key limiting factors are nutrient concentrations of water body or materials contents in sediments and the production periods are relative short, because that nutrients concentrations and materials contents in sediments can respond to aquaculture relatively quickly and the difference between the experimental period of the physical mode and practice production period can be ignored. If the practice production period is relatively long and the key limiting factor is phytoplankton biomass, it is advised to use the numerical mode to evaluate the carrying capacity for IMTA, because there is time delay of responses of phytoplankton to aquaculture. Moreover, the parameters in the equations can be determined through references or experiments.

2.5.3 Case analysis for carrying capacity assessment for IMTA

2.5.3.1 Decision of carrying capacity assessment scheme for IMTA in Sungo Bay

The Sungo Bay with water area 133 km^2 and mean water depth 7.5 m located in the east of Shandong Peninsula, PR China. It adjoins to Yellow Sea. The principle cultured organisms in the bay include scallop (*C. farreri*), oyster (*C. gigas*) and kelp (*Laminaria japonica*). In the year 2000, the kelp market demand was stable and the market demand of shellfish continued to increase. Thus, it was necessary to keep the kelp culture scale at the current levels and to explore the cultivation potential of shellfish such as scallop and oyster culture in the year 2000, which meant it needed to evaluate the carrying capacity for shellfish culture in the IMTA ecosystem in the bay.

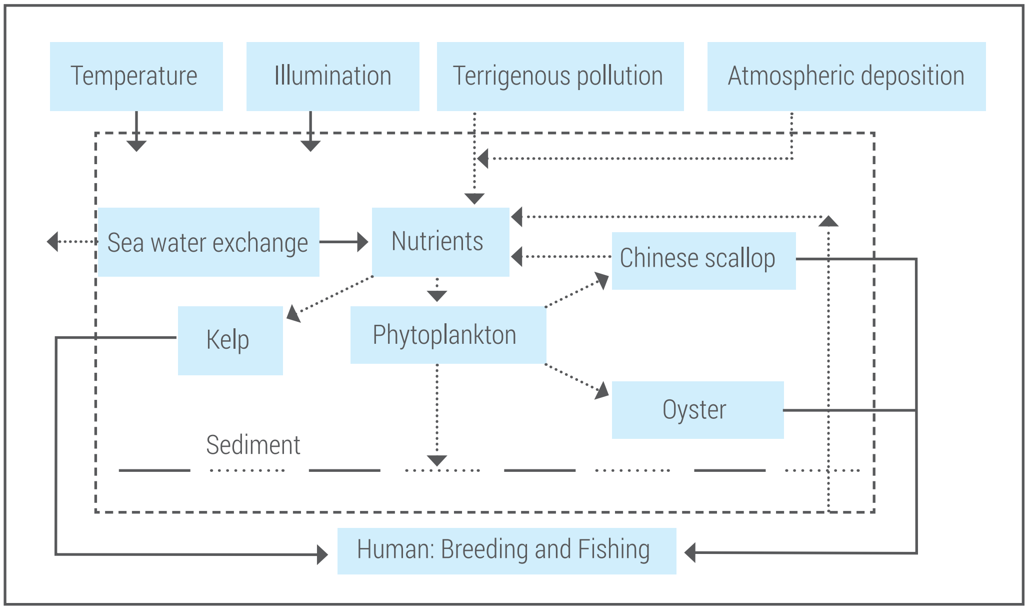
If the POM concentration is less than 900 mg.m^{-3}, the normal growth of filter feeding shellfish will be limited as the foodstuff shortage (Yang, 1998). The phytoplankton accounts for 0.91-8.0 % of the POM in Sungo Bay (Kuang et al., 1996). Thus, the least phytoplankton biomass to maintain the normal growth of filter feeding shellfish in Sungo bay should be 8.2 mg.$^{m-3}$.

Moreover, there are water exchanges between the bay and the Yellow Sea, and terrigenous pollution input into the bay. It costs about two years for the scallop or the oyster to grow to market size. And the key limiting factor to determine the carrying capacity for shellfish culture in the bay is phytoplankton biomass. Thus, the numerical model is the appropriate method to evaluate the carrying capacity for shellfish culture in the IMTA.

2.5.3.2 Implementation of carrying capacity assessment for IMTA in Sungo Bay

The aquaculture in Sungo Bay can be simplified as one IMTA ecosystem according to water characteristics (Figure 2-6), during which the kelp culture scale keeps constant.

FIG. 2-6 The IMTA in Sungo Bay.



According to the N-P-Z mode, one eco-dynamic model to simulate the IMTA in Sungo Bay is funded (Table 2-18), which includes the nutrients concentration (N), phytoplankton biomass (P). It seems that there is no zooplankton in the model, however, its effect can be replaced by Chinese scallop and oyster. The parameters in these equations are determined by results of experiments or references (Table 2-19). Moreover, the ΔDIN concentration difference between the bay and the Yellow Sea are determined by the field experiment. Furthermore, the water exchange period is based on research conducted by Zhao et al. (1996).

Table 2-18 The eco-dynamic model for IMTA in Sungo Bay.

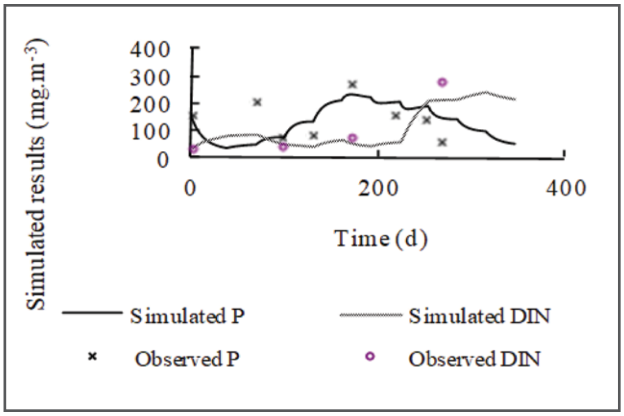
Equation	Annotation
$\frac{dP}{dt} = B_1 - B_2 - B_3 - B_4 - B_5 - B_6 - B_7$	Variation equation for phytoplankton biomass
P	Phytoplankton biomass ($mg.m^{-3}$)
$B1 = v_1(T).\mu_1(DIP, DIN).\mu_2(I).P$	Phytoplankton multiplication caused by photosynthesis
$v1\ (T) = \alpha_1 \exp (\beta_1.T)$	Effects of temperature on photosynthesis
$\mu_1\ (DIP, DIN) = \min(DIN\ (K_N + DIN)^{-1}, DIP\ (KP + DIP)^{-1})$	Effects of nutrients on photosynthesis
$\mu_2(I) = I(I_{opt})^{-1} \exp(1\text{-}I\ (I_{opt})^{-1})$	Effects of illumination on photosynthesis
$I = Ls.P_{light} / \{k_e.D_{epth}.\{1-\exp (-k_e.D_{epth})]\}$	Effective irradiance of photosynthesis
$B_2 = 0.135\exp[-0.00201\ (chl:C_P).P].B_1$	Extracellular export of phytoplankton
$B^3 = v_3\ (T).P$	Respiration of phytoplankton
$v_3\ (T) = \alpha_2 \exp (\beta_2 T)$	Effects of temperature on respiration
$B_4 = v_4\ (T).P$	Mortality rate of phytoplankton
$v_4\ (t) = \alpha_3 \exp (\beta_3 T)$	Effects of temperature on death of phytoplankton
$B_5 = w_P P\ (D_{epth})^{-1}$	Phytoplankton deposition
$B_6 = S_{den}.F_{Sc}.P$	Phytoplankton fed by Chinese scallop
$B_7 = Oy_{den}.F_{oy}.P$	Phytoplankton fed by oyster
$\frac{dDIN}{dt} = (N_m:C_m)(N:C_P)(-B_1+B_3)+B_8+B_9+B_{10}+B_{11}+B_{12}=B_{13} - Q_{DIN}$	Variation equation for dissolved inorganic nitrogen
DIN	Dissolved inorganic nitrogen concentration ($mg.m^{-3}$)
$B_8 = 0.14$	Atmospheredeposition of DIN
$B_9 = C_{rivern}.Q / (D_{epth}.A_{rea})$	Effects of terrigenous pollution on DIN
$B_{10} = F_{seddin}.\exp (k_{seddin}.T_b) / D_{epth}$	Effects of sediments on DIN
$Tb - k_T .T$	Sediment temperature
$B_{11} = S_{den}.E_{Sc}$	DIN excreted by Chinese scallop
$B_{12} = Oy_{den}.E_{oy}$	DIN excreted by oyster
$B_{13} = S_{kelp}.A_{bkelpN}$	DIN absorbed by kelp
$Q_{DIN} = \Delta DIN / T_{ex}$	Effects of water exchange on DIN
ΔDIN	DIN concentration difference between the bay and the Yellow Sea
T_{ex}	Water exchange period

Table 2-19 Meanings and values of parameters in model to simulate IMTA in Sungo Bay.

Parameter	Meaning	value	Reference
α_1	Growth rate of phytoplankton at 0°C	0.893 d^{-1}	Eppley, 1972
β_1	Temperature coefficient for growth of phytoplankton	0.063 °C^{-1}	Eppley, 1972
K_N	Half-saturation constant for DIN absorption	14 mg.m^{-3}	Franks and Chen, 1996
K_e	Optical attenuation coefficient in water	0.8 m^{-1}	Wu, 2005
I_{opt}	Optimal intensity for photosynthesis of phytoplankton	96.0 w.m^{-2}	Yu et al., 1999
P_{light}	luminousness across sea-atmosphere interface	0.6	Wu, 2005
$chl:C_P$	Ratio of chlorophyll to carbon in phytoplankton	1/40	Fang et al., 1996b
α_2	Respiration rate of phytoplankton at 0°C	0.025 d^{-1}	Wu et al., 2001
β_2	Temperature coefficient for phytoplankton respiration	0.051 °C^{-1}	Wu et al., 2001
α_3	Mortality rate of phytoplankton at 0°C	0.0049 d^{-1}	Wu et al., 2001
β_3	Temperature coefficient of phytoplankton death	0.065 °C^{-1}	Wu et al., 2001
w_p	Setting speed of phytoplankton	0.173 m.d^{-1}	Wu, 2005
$N_m:C_m$	Atomic ratio of nitrogen to carbon	14:12	/
$N:C_p$	Atomic ratio of nitrogen to carbon in phytoplankton	(16/106)	Wu et al., 2001
C_{rivern}	DIN concentration of terrigenous pollution	1.7 mg.m^{-3}	Fang et al., 1996a
Q	Quantity of terrigenous pollution	20000 m^{-3}.d^{-1}	Fang et al., 1996a
A_{rea}	Water area of Sungo Bay	133 km^{2}	Fang et al., 1996a
D_{epth}	Mean water depth of Sungo Bay	8.0 m	Wu, 2005
F_{seddin}	Diffusion flux of DIN across water-sediment interface in Sungo Bay	19.18 mg.m^{-2}	Wu, 2005
k_{seddin}	Temperature coefficient of diffusion flux of DIN across water-sediment interface	0.04 °C^{-1}	Wu et al., 2001
k_T	Temperature translation coefficient of water temperature and sediment temperature	0.8-1.0	Wu et al., 2001
A_{bkelpn}	DIN absorption speed of kelp	0.0227 mg.g.d^{-1}	Fang et al., 1996a
E_{Sc}	DIN excretion speed of Chinese scallop	They are the weighted mean excretion speed, filtering speed of Chinese scallop and oyster, which are based on results of Fang et al. (1996b), Kuang et al. (1996) and Mao et al. (2006).	
E_{oy}	DIN excretion speed of oyster		
F_{Sc}	Filtering speed of Chinese scallop		
F_{oy}	Filtering speed of oyster		
S_{den}	Stocking density of cultured Chinese scallop	During the model validation, the values are those in the work of Fang et al. (1996b). Except that, the values are regulated to obtain the responses of phytoplankton biomass to shellfish stocking density.	
Oy_{den}	Stocking density of cultured oyster		

According to results of Fang et al. (1996b), Sun et al. (1996) and Song et al. (1996), the eco-dynamic model is working (run). Moreover, the initial values of phytoplankton biomass and DIN concentration are the values measured on January 20, 1994, and the kelp culture scale and shellfish culture scale are shown in Fang et al. (1996a, b) and Zhua et al. (2002). Further, the first day in the model is January 20, 1994. The outputs at the 400th day are compared with the Fang et al. (1996b) and Song et al. (1996) (Figure 2-7). The relative error of predicted phytoplankton biomass and DIN concentration is 14.05 % and -11.30 %, respectively. Moreover, the predicted phytoplankton biomass peak time is in accord with the observed one. Thus, the model can be used to simulate the IMTA in the bay.

FIG. 2-7 Comparison of simulated values and observed ones.



According to methods of Zhao et al. (2002), nine models with different initial values (Table 2-20) are simulated for 345 days (to December 31, 1994) to reduce effects of initial values, during which the kelp and shellfish culture scale is based on Fang et al. (1996 a, b) and Zhu et al. (2002). The mean outputs of the 345th day are used as the initial values to run the model to simulate the responses of environmental factors to different shellfish stocking density.

Table 2-20 Initial values of and of 9 models to reduce effects of initial values.

Model	Initial			
	P (mg.m^{-3})		*DIN* (mg.m^{-3})	
1	164.80	-	39.36	-
2	164.80	-	59.04	+50 %
3	164.80	-	19.68	-50 %
4	247.20	+50 %	39.36	-
5	247.20	+50 %	59.04	+50 %
6	247.20	+50 %	19.68	-50 %
7	82.40	-50%	39.36	-
8	82.40	-50%	59.04	+50 %
9	82.40	-50%	19.68	-50 %

Notice: - means no variation.

If the simulated phytoplankton biomass is equal to 8.2 $mg.m^{-3}$, the corresponding shellfish stocking density is the carrying capacity. According to the simulation results, the relationship between the carrying capacity for Chinese scallop culture and that of oyster culture is $k=-0.2765y +4.6905$ ($R^2=0.9999$, sample size $n=4$), where, K and y is the expand multiple of existing culture scale of scallop and oyster. Moreover, the existing culture scale of scallop and oyster in the bay is 2.0×10^9 ind and 3.9×10^7 ind, respectively. If the kelp culture scale is keep constant (kelp culture scale 3.3×10^7 m^2, stocking density 12 $ind.m^{-2}$), and the oyster culture scale is not regulated ($y=1$, oyster scale 3.9×10^7 ind and stocking density 59 $ind.m^{-2}$), the carrying capacity of Chinese scallop may be 4.4 times to the existing Chinese scallop culture scale, 8.8×10^9 ind (89 $ind.m^{-2}$). During the calculation, 75% of seawaters can be used for aquaculture. The evaluated Chinese scallop carrying capacity through the present method is less 18% of that estimated by Fang et al. (1996b). The main reason for the difference results from the threshold value of phytoplankton biomass to determine the carrying capacity. Fang et al. (1996b) assume that shellfish may eat up all the phytoplankton in the bay. Thus, the carrying capacity determined by the present model belongs to the ecological carrying capacity, and that of Fang et al. (1996b) belongs to the production carrying capacity.

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CHAPTER

3

Development and Management of IMTA

3.1 Shellfish-seaweed and shellfish-seaweed-sea cucumber IMTA

3.1.1 Biological and ecological characteristic of shellfish and seaweed in IMTA system

3.1.1.1 Shellfish

Shellfish belong to *Mollusca*, a general name for mollusks with shells. It includes seven classes, such as lamellibranchias, gastropods, cephalopods and so on. The most widely applied species of shellfish in IMTA were mainly filter-feeding shellfish, such as oysters, scallops, mussels and herbivorous shellfish, such as abalone, etc.

3.1.1.2 Oyster

There are two shells in each oyster that differ in shape. Upper shells have a rough surface and is dark gray. The upper shells are the central uplift and the lower shells which are attached to other objects, are larger and flatter, and their edges are smoother; the inner surfaces of the two shells are all white and smooth. The two shells are connected in the narrow end with an elastic ligament and the middle of the inner shell has a strong central adductor muscle. When the shell is slightly open, seawater is introduced into the shell by the wave of the cilia on the gills to filter the microalgae and organic debris. Oysters are mostly dioecious, but few are hermaphrodites. There are more than one hundred species of oyster distributed in almost all the coastal countries in the world. The production of oyster ranks first in the shellfish production. The production of oyster accounts for more than 90 percent of the total production of shellfish. The countries with more developed oysters include PR China, France, the United States of America, Japan, Republic of Korea, Mexico, New Zealand, Australia, etc. There are more than 20 species in PR China. The main species are Pacific oyster, *Crassostrea rivularis Crould*, *Ostrea plicatula*, and *Ostrea denselamellosa Lischke* etc.

3.1.1.3 Scallop

Scallops have two almost equal-sized shells and look like fans. The colors of the shell are usually purple brown, light brown, yellow brown, reddish brown, apricot yellow, and gray white. The inside of the shell is white. The muscle in the middle of the inner shell is edible. The shell surface is smooth and distributed with radiate ribs. The ribs are smooth, scaly or tumid, and may be bright red, purple, orange, yellow or white. There are eyes and short tentacles on the edge of the mantle. The tentacles can feel the change of water quality. The tentacles hang like curtain in the two shells.

Scallops feed on algae and organic debris by filtering water and collect the food particles from the cilia and move into the mouth. The scallop can be slapped intermittently by the two shells, spray water and move with counterforce. The eggs meet the sperm in the seawater and begin to fertilize and hatch. When the larvae grow to D shape larvae and they can swim in seawater. After some days of swimming in the water, it will settle on the substrate with the byssus. There are three species of scallop in China (*Chlamys farreri, Argopecten irradias, Patinopecten yessoensis*). The optimum growth temperature of the three scallops are 5–25°C, 5–28°C, 5–20°C, respectively. The suitable growth temperature of the three scallops above are 15–23°C, 15–23°C, 18–28°C, respectively.

3.1.1.3 Mussel

The mussel shell is wedged-shape and dark brown. The front of the shell is small and the back is broad and round. The shell is 6–8 cm long, length is less than two times the shell height, and is thin. The two shells are equal, symmetrical, and shell surface is lustrous purple and black. The growth pattern is fine and clear. It grows in a ring from the shell roof. The inner surface of the shell is gray and the edge is blue and has a pearly luster. The hinges are long and ligaments are dark brown, approximately equal to the reamer. The articulated teeth are not developed. The posterior adductor muscle degenerate and disappear. The foot is very small and soft. The mussels' feeding style is familiar with other bivalve mollusks. It can only obtain food passively when water flows through its body and filtered through the gills. The main food is microalgae and organic detritus, in addition to some protozoa. Mussels' byssus can help them settle on fixed substrate such as rocks or culture ropes, but some mussels can fixed on buoys or the bottom of the ship. The suitable growth temperature is 5–23°C, and the optimum growth temperature is 10–20°C.

3.1.1.5 Abalone

Abalone belong to the Mollusca gastropoda. They have a thick layer of ear-shaped calcareous shells. The shells are right-handed. The shells have three whorls and the screw suture is not deep. The spire of abalone is very small. The shell roof of the abalone is blunt and protruding. The shell surface of the abalone is dark green. The growth pattern of abalone is obvious, and the inner shell has a pearl luster. There is a row of holes on the shell. There are 4-5 shell holes in *Haliotis discus hannai* and 7-9 shell holes in *Haliotis diversicolor*. Abalone was developed and hypertrophic gastropods, large and flat. The foot is used for adherence and crawling. In the rich macroalgae reef, the abalone will not move in a wide range. Abalone lurks in the daytime and comes out to feed at night. Abalone's intake, digestibility, movement distance and speed, and respiration intensity are most active at night, and only slightly move in the daytime when the tide is fluctuating. There are obvious seasonal movements of abalone in the sea area. When the water temperature is low in winter and spring, it moves to deep water. When the water temperature rises, it gradually moves to the shallow water. The abalone is very sensitive to environmental changes. When it is frightened and attacked by the enemy, the abalone can shrink its head, antennae and tentacles quickly and cling on a rock.

3.1.1.6 Macroalgae

The macroalgae species in the integrated shellfish-seaweed culture mainly include brown algae *Saccharina japonica, Undaria pinnatifida, Sargassum thun bergii,* and *Sargassum fusiforme*, red algae *Gracilaria lemaneiformis* and *Eucheuma gelatinae*. Their biological characteristics and ecological habits vary by species. The biological characteristics and ecological habits of several macroalgae are described below:

3.1.1.7 Kelp *S. japonica*

Kelp is a species of the genus of *Saccharina, Laminariaceae, Phaeophyta*. The large kelp plants are the sporophytes, while the tiny filaments are the gametophytes.

Kelp leaves are flat and thick in the center. The growth of kelp is accomplished by intercalary growth and the meristematic cells located in the base of the leaf and stem connections. The kelp frond is brown. In asexual reproduction of kelp, the epidermal cells develop to form single-compartment sporangia. Sexual reproduction of kelp is oogamous. The distribution of kelp *S. japonica* is mainly in the cold temperate zone. It can grow even when the temperature is below 0°C, while the maximum temperature is 20°C, above which the algae is perishable. Kelp live below the dry tide line and is sessile benthic. Currently, kelp farming is not limited to its natural distribution. In China's southern waters, such as Fujian, kelp farming scale has surpassed the northern Shandong and Liaoning Provinces.

3.1.1.8 Wakame *U. pinnatifida*

U. pinnatifida is one species of *Undaria, Alariaceae,* and *Phaeophyta*. The sporophyte of wakame is large and has three parts, the sub-root, handle and leaves. In early development, *U. pinnatifida* algae is ovate or long leaf-shaped, single and then gradually splits into plumes in the growth process, with the raised ribbed structure.

Sporophyte of wakame is brown and lanceolate, with a length of 1 to 1.5 meters and width of 0.6 to 1 meter. Wakame *U. pinnatifida* can reproduce sexually and asexually. The growth of wakame is accomplished by intercalary growth with an annual period. Its life history is similar with kelp *S. japonica*, and can be divided into sporophyte and gametophyte generation. The wakame seaweed can be seen, is a sporophyte, which can grow for nearly a year. The growth time of gametophyte is very short and develop sporophyte when the environment is suitable. The distribution of wakame is mainly in temperate regions. It can tolerate high water temperature and is suitable in semi-enclosed and nutrient-rich bays. It is fixed at 1 to 4 meters below the low tide line. At present, the integrated culture of *U. pinnatifida* and shellfish is mainly in the seas of Shandong and Liaoning in China. Wakame *U. pinnatifida* requires plenty of light and is suitable for living in shallow water. 5-15ºC is the optimum temperature range for sporophyte growth, with smooth requirements for the surrounding environment trends.

3.1.1.9 *Gracilaria* species

The main cultured *Gracilaria* species in PR China are *G. lemaneiformis, G. tenuistipitata var. Liui*, *G. asiatica, G. tenuistipitata, G. blodgettii* and *G. chouae. Gracilaria species* are erect, tufted, cylindrical or flattened. Algae is light red to dark red. *Gracilaria* is widely distributed in all parts of the world, from temperate to tropical sea. Commonly, *Gracilaria* is a temperate seaweed that distributes from north to south of PR China. However, there are also many tropic and subtropical *Gracilaria* species confined to the coastal provinces of Fujian, Guangdong, Guangxi and Hainan. *Gracilaria* usually grows in intertidal or near low tide lines, with a few growing in deeper waters. In the calm, smooth flow, flat and fertile waters of the sea, *Gracilaria* grows well at an optimum temperature of 15-25ºC.

3.1.2 Requirements for site selection

Sites for farming shellfish using the longline culture system usually require reasonable shelter from waves and wind, high water quality, adequate tidal flow, depths of at least 5 m up to 20 m and ample phytoplankton food supply. The muddy sand sediment type is better to the placement of longline facilities. Further, the site should have no industrial or sewage pollution, and environmental indicators should meet the requirements of the national standard.

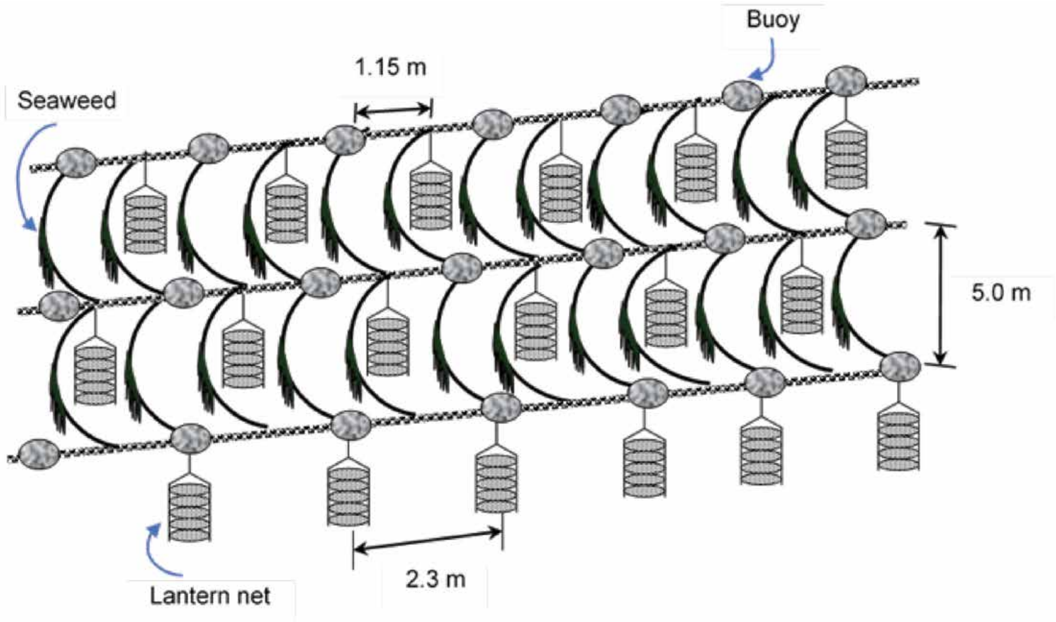
3.1.2 Establishment of the shellfish and seaweed integrated aquaculture system

3.1.3.1 Filter-feeding bivalves and seaweed integrated aquaculture system

According to the mutual benefit and biological characteristics of the filter-feeding bivalves and seaweed, *Saccharina* is the suitable bioremediation species during winter and spring, while *Gracilaria* is more suitable during summer and autumn.

Longline culture is mostly used in integrated aquaculture of filter-feeding bivalve and seaweed. The direction of the longline should be consistent with the direction of the seawater. The section of the longline holding the buoys or floats is called the backbone. Typically, the length of each backbone is 100 m with a 5 m gap between each other. A synthetic rope of 2.4 cm called a warp is attached to the edge of the backbone. The warp is generally three times the depth of the water. The warp is moored on the seabed by a heavy weight anchor or stake anchor. Buoys with 30 cm diameters are spaced appropriately to support the mass of growing bivalves on the backbone. The lantern net with scallops or oysters inside are hung on the backbone. The space between the 2 lantern nets is 2.3 m with 43 units per 100 m backbones. Horizontal kelp rope cultivation is the typical method for kelp longline culture system. Each kelp rope is combined with two short kelp ropes with the length of 2.5 m. Between two adjacent floating backbones there are 174 kelp ropes parallel. The floating backbones and kelp ropes are connected by two hanging ropes and one hanging buckle. About 40 individuals of kelp are planted on each kelp rope.

Fig. 3-1 The structure of longline system for shellfish and seaweed integrated aquaculture.



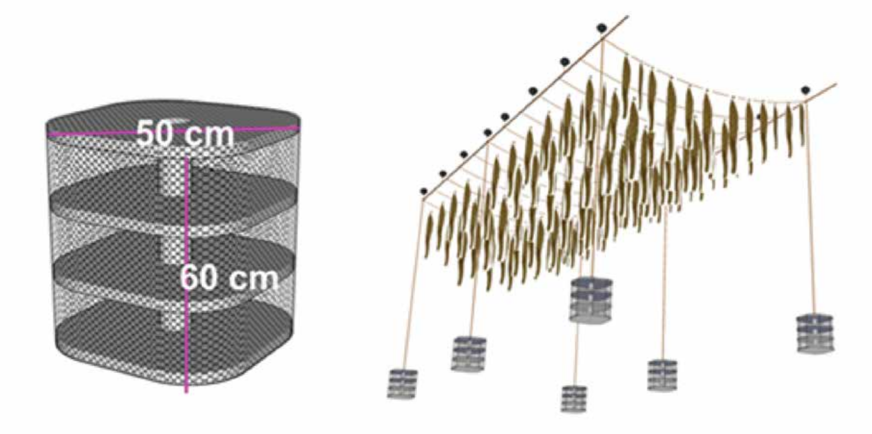
Daily management is necessary to maintain the good growth condition of the organisms, which includes the cleaning of fouling organisms, maintaining the facilities, examining the quantities of the buoys, monitoring related environmental factors. Moreover, it is important to keep records so as to trace the products through all stages of production.

3.1.3.2 Abalone, seaweed and sea cucumber integrated aquaculture system

The abalone aquaculture needs to consume considerable artificial diet (fresh or dry seaweed). The low utilization efficiency of diet leads to the deterioration of water quality which in turn affects the health of abalone, and ultimately affecting the food production function of the aquaculture system. The implementation of abalone-seaweed-sea cucumber integrated aquaculture helps reduce the negative effects caused by large-scale abalone aquaculture significantly. In this system, the seaweed serves as the food for the abalone, while the dissolved and particle wastes generated by the abalone are taken up by seaweed and sea cucumber. The dissolved oxygen provided by the seaweed can meet the requirement of the abalone and sea cucumber.

Longline culture is mostly used in the integrated aquaculture of abalone-seaweed-sea cucumber. Each aquaculture unit consists of four lines. The length of each backbone ranges from 80-100 m with a 5m gap between each other. The facilities used for abalone aquaculture is called abalone culture cage which is hung on the backbone vertically. The cages are divided into three layers and the space between the two cages is 2.5 m with 30 cages per backbone. About 280 individuals with shell length of 3.5-4 cm of abalone are cultured on each cage. Each kelp rope is combined with two short kelp ropes with a length of 2.5 m. The kelp ropes are connected with the adjacent two backbones horizontally. About 70 individuals of kelp are planted on each kelp rope. The space between the two kelp ropes ranges from 2-3 m. The sea cucumber serves as the cleaner in this system. 2-3 individuals are cultured in each layer with the initial size of about 60-80 g per individual.

Fig. 3-2 The structure of longline system for abalone-seaweed-sea cucumber integrated aquaculture.



Daily management is necessary to maintain the good growth condition of the organisms which includes the cleaning of fouling organisms, maintaining of facilities, examining the quantities of the buoys, monitoring of the related environmental factors. Moreover, it is important to keep the records so as to trace the products through all stages of production.

3.1.4 Analysis of the economic and ecological benefits

In the shellfish and seaweed integrated aquaculture system, the filter-feeding activities of bivalves will be helpful to the photosynthesis process of the seaweed by filtering particulate matter in seawater. The seaweed will benefit from the carbon dioxide and ammonia generated from the respiratory and metabolic process of the shellfish, and feedback to the shellfish by producing dissolved oxygen through photosynthesis. This mutual process is not only a good way to keep the balance of O_2 and CO_2 in the ecosystem, but also to promote the nitrogen cycle. This kind of IMTA system is the best solution to achieve remarkable economic benefits and reduce the negative pressure caused by self-pollution.

Take oyster-kelp integrated aquaculture as an example, after 6-7 months of farming, 28 individuals are harvested in each rope with an average individual wet weight of about 1.30 kg, then the total yield (wet weight) of each rope is 36.4 kg. According to the ratio of dry to wet (1:7), the total dry weight of each backbone is about 452.4 kg, so the gross income of each backbone is about 2,714.4 Yuan (Renminbi or RMB) if the price of the dry kelp is RMB 6/kg. The net income of each culture unit (4 backbones) is about 1,600 RMB if the costs of the salary for the farmers and the materials related to the aquaculture are being taken into consideration. The production of each oyster lantern net is about 12.5 kg, then the total output of each backbone is about 537.5 kg. The net income of each culture unit (4 backbones) is about 2,540 Yuan if the costs of the salary for the farmers and the materials related to the aquaculture are being taken into consideration. The net income of each oyster and kelp aquaculture unit is RMB 4,140.

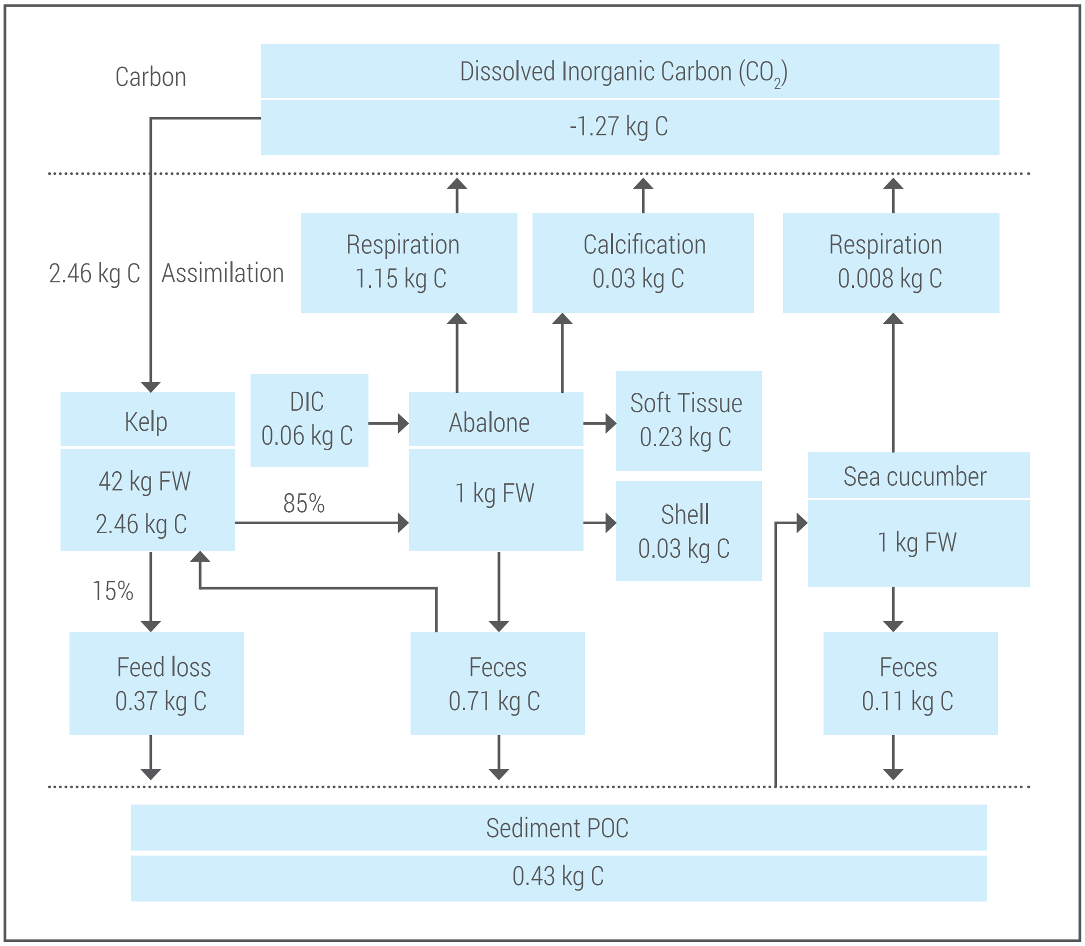
In addition to economic benefits, this kind of IMTA system has significant ecological benefits. Shellfish remove the phytoplankton and particulate organic carbon through filter feeding activities and seaweeds can transform DIC into organic carbon by photosynthesis. Thus, cultivation of seaweeds and shellfish plays an important role in carbon fixation, and therefore contributes to the improvement of the capacity of coastal ecosystems to absorb atmospheric CO_2. It is estimated that 3.79 ± 0.37 Mt C yr^{-1} are being taken up, and 1.20 ± 0.11 Mt C yr^{-1} are being removed from the coastal ecosystem by harvesting the shellfish and seaweeds in PR China.

In the abalone-seaweed-sea cucumber IMTA system, abalone is cultured in a cage and fed with seaweeds which is co-cultured on longline, while sea cucumber is co-cultured with abalone in a cage and fed on the feces and residual feed from abalone inside the cages. The dissolved inorganic nutrients (N, P and CO_2) excreted from abalone and sea cucumber are absorbed by the seaweed that also produces oxygen.

According to the four backbones of a culture unit, the integrated aquaculture system includes a total of 33,600 abalone and 12,000 kelp. Kelp culture begins from November to June of the following year. When the kelp reaches 1 meter long, it can be used to feed the abalone. The net cage of abalone should be cleaned at least once a week. This way, abalone can reach commercial size (8-10 cm) in two years. After two years growth cycle, the abalone can reach 900 kg, with an output value of more than RMB 60,000. From September to May of the following year, the average weight of the sea cucumbers could reach 150-200 g/individual. According to the price of sea cucumber (140 RMB/kg), the average economic efficiency of each cage can be increased by RMB 210. Correspondingly, each culture unit (4 backbones) of abalone and sea cucumber IMTA system can increase the output value of RMB 16,800. Taking the costs of the seeding of the sea cucumber, the net income of each backbone is RMB 3,600.

The abalone-seaweed-sea cucumber integrated aquaculture approach can also effectively remove carbon in the ocean, while increasing economic benefits. Results from the carbon budget showed that every 1 kg (wet weight) of abalone consumed about 2.15 kg of carbon, about 12 percent of which, was used for shell and soft tissue growth, 33 percent, as bio-deposition, settled down to the seabed, 55 percent was released as CO_2 by respiration and calcification process and returned to the water column. Biological carbon deposition produced by excretion and feces process was about 0.71 kg where 10 percent (0.07 kg C) of it was absorbed by the kelp and 90 percent (0.67 kg C) was served as the food sources of sea cucumber together with the feed loss from kelp (0.37 kg C). About 69 percent (0.72 kg C) was assimilated by sea cucumber, the remaining 21 percent settled down to the seabed. The 1.18 kg of dissolved CO_2 produced in the process of abalone respiration and calcification and 0.09 kg of dissolved CO_2 produced by the respiration of the cucumbers provide 52 percent inorganic carbon sources for kelp photosynthesis.

Fig. 3-3 Carbon budget in the IMTA system of kelp, abalone and sea cucumber during a farming cycle. (Tang et al., 2013)



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3.2 The Integrated Multi-Trophic Aquaculture in pond in Northern China

3.2.1 The biological characteristics and ecological habits of cultured species

The IMTA system in the northern ponds fully utilized the mutually beneficial relationship among different organisms, which not only focused on the combination of different trophic levels, but also on the utilization of different culture spaces. The functions of fish, shrimp, crab, shellfish, and other species were extremely utilized. Different biological characteristics and the ecological habits of species determined their functions in the pond in the IMTA system.

3.2.1.1 Shrimp

The main species of shrimp cultured in the northern seawater ponds are *Fenneropenaeus chinensis, Litopenaeus vannamei, Penaeus japonicas* and *Exopalaemon carinicauda* etc.

Fenneropenaeus chinensis lives in the Yellow Sea, Bohai Sea and the northern East Sea. There are a few living in the Pearl River Estuary to Yangjiang City of Guangdong Province. *Fenneropenaeus chinensis* is one of the major aquaculture species in northern ponds, which has the advantages of fast growth, adaption to a wide range of salinity and delicious meat. The optimum growth temperature is 18-25°C and the living water temperature is 8-35°C. It will stop feeding at 8°C and die below 4°C. The optimum salinity for growth is 8-25. The survival salinity is 1-40. It has a broad diet, good adaptability and preference for high protein, low fat and carbohydrate foods (Mai et al., 2009).

Litopenaeus vannamei is native along the Pacific coast of the Americas, which is a major aquaculture species in South America such as Ecuador and is one of the three major culturing shrimp species in the world. It has the advantages of strong vitality, wide adaptability, good disease resistance, rapid growth, low requirements on feed protein content, high meat yield and longer survival time without water. The optimum growth temperature is 23-32°C. The survival water temperature 9-47°C. When the temperature is below 15°C, it will stop feeding, below 8°C it will die. The optimum salinity for growth is 10-25. The survival salinity is 0-40 (Min, 2002). It is omnivorous. The demand for feed is not very strict. It can grow normally when the protein proportion in feed accounted for is more than 20 percent.

Penaeus japonicas lives in the East and South China Seas. It has a thick shell. The individual size is smaller than the two mentioned above. It can survive for a long time without seawater, which makes it is suitable for long time transport. The requirements for feed protein is high. The optimum temperature for growth is 18-28°C. The survival water temperature is 5-32°C. It will stop feeding at 8°C and die below 4°C. The optimum salinity for growth is 24-30. The survival salinity is 7-35. It likes live animal feed and the requirement for protein in feed is high, usually more than 42 percent. It is usually lurking in a sediment of 1-3 cm, inactive and non-feeding, during the day time. It will be active and feeding during the night (Yin et al., 2002).

Exopalaemon carinicauda is also known as little white shrimp. It lives along the coastal areas of China, especially in the Yellow and Bohai Seas. *Exopalaemon carinicauda* lives in shallow water near the seashore. It has a specific characteristics of adaption to wide temperature, wide salinity and wide distribution. The suitable salinity is less than 29. It can live in freshwater after domestication. *Exopalaemon carinicauda* has good adaptability to the environment. The suitable water temperature is 2-35°C. It can survive in winter by drilling holes for hibernation when the temperature is low. It is also an important byproduct with considerable yield of shrimp ponds and marine fish ponds. It is omnivorous with a lower protein content food demand. For example, dead, live, fresh, rotten animal and plant feeds, and organic debris are good food for *E. carinicauda* (Interactive Encyclopedia, 2017).

3.2.1.2 *Portunus trituberculatus*

Portunus trituberculatus are distributed in the coastal areas of China, Japan, North Korea, Malaysia, and the Red Sea. It lurks underneath the sand during the day time, and forages at night with obvious phototropism. When it stays in the sand, it slopes at 15°-45° angle with the surface only exposing eyes and antennae. It does not drill holes, so there are no facilities to escape the pond aquaculture. The crab normally stays in the sand when the water temperature is below 18°C. The suitable water temperature for *P. trituberculatus* is 8-31°C. The optimum temperature for growth is 15.5-26.0°C. The suitable salinity is 13-38. The optimum salinity for growth is 20-35. When the salinity is below 8 or above 38 it will stop any activity such as feeding. The suitable range of pH is 7.5-8.0. The dissolved oxygen should be above 2 mg/L. The chemical oxygen demand of water should not exceed 12 mg/L. The crab is omnivorous, which likes shellfish, trash fish, small shrimp, etc., also feeds on algae buds, dead marine animals and decayed aquatic plants. The diet is a little different depending on different stages of growth. The juvenile crab is omnivorous and the larger ones tend to be carnivorous. Usually, it feeds less during the day but more at night. However, when the water temperature is below 10°C or above 32°C, it will stop feeding (Cheng et al., 2012).

3.2.1.3 Shellfish

There are a lot of shellfish species in pond aquaculture in the northern China, which are mainly bivalves. Main species include *Sinonovacula constricta, Ruditapes philippinarum, Meretrix meretrix* and so on. Moreover, in the IMTA system, *Argopecten irradians* can also be cultured in ponds as an important functional unit. Due to their adaptation to buried habitat, body parts have varying degrees of change, generally with well-developed foot and water pipe. They bury themselves in the mud and sand and rely on the extension of water pipes to get in and out the seawater to feed, breath and excrete. The feeding habits of these shellfish are filtering suspended particles for food in the water. There are two types of filter feeding shellfish: the first type lacks water pipes or short water pipes, such as scallops, ingesting suspended food in seawater, the second type has longer water pipes, such as *S. constricta*, which can not only ingest suspended food in seawater, but also relies on the extension of the water pipe to get the settled food and benthic algae on the surrounding beach. They mainly feed on diatoms, protozoa and flagellates because of lack of movement. Diatoms account for about 85 percent for the *S. constricta*, showing that diatoms are the main food of shellfish. The biomass and species construction of such feed organism can greatly dependent on geographical locations and seasons, as shellfish don't strict selected the food. Therefore, the situation of diatoms in the surrounding environment determines the type and quantity of feed in the shellfish stomach. Overwintering is a limiting factor in the cultivation of shellfish in ponds. At present, the largest aquaculture area in the northern ponds is at risk mainly due to the possibility of overwintering. However, species such as *R. philippinarum, M. meretrix* and scallops are safe in the southern part of Jiangsu Province during winter with the high depth water requirements in the pond.

3.2.1.4 Fish

In the IMTA pond in the northern China, people culture small quantities of *Lateolabrax japonicus, Pagrus major, Sparus macrocephalus, Takifugu rubripes, Mugilogobius spp* and other carnivorous fish. The carnivorous fish not only eats trash fish, but also sick shrimps, thereby reducing the possibility of disease infection. The *Mugil cephalus, Liza haematochelia* and *Chanos chanos* integrated in the pond feed on benthic diatoms, organic detritus, unfed feed, and even feces of other animals in the pond. According to the biological characteristics of the main cultured species, a certain amount of fish are cultured for the purpose of utilizing space, the organic waste and controlling diseases.

3.2.1.5 Jellyfish

The cultured species of jellyfish in the northern China belong to *Coelenterata, Scyphozoa, Rhizostomeae, Rhizostomatidae, Rhopilema*. There are four cultured species: *Rhopilema esculenta, Rhopilema asamushi, Nemopilema nomurai,* and *Rhopilema hispidum*. Jellyfish are dioecious, mature in autumn, and like warm water and lower salinity. They are poor swimmers and therefore can only move with the water flow. Their life cycle is complex, which includes two different generations alternating between the asexual and sexual reproductive generations. Jellyfish generally live in a water depth of 5-40 m and mostly in 10-20 m. The suitable water temperature is generally 15-28°C in which the optimum is 24°C. The suitable salinity is generally 10-35 in which the optimum is 14-20. They are sensitive to light, thus preferring light intensity below 2400lx. They like to stay in the surface layer during early morning, evening and cloudy days. However, in the presence of too much light, strong winds or rainy days, they will sink. Therefore, the depth of ponds for culturing jellyfish should be more than 2 m. Jellyfish feed on tiny zooplankton and larvae and diatoms, such as ciliates, rotifers, copepods (Liu et al., 2010). Jellyfish are the only one of over 9,000 species in Coelenterates that can be cultured.

3.2.1.6 Deposit Feeders

Stichopus japonicus belongs to *Echinoderms, Holothuroidea, Aspidochirota, Stichopodidae*. *Stichopus japonicus* is one of the most important edible sea cucumbers, which mainly lives in the North Pacific coast including Japan, North Korea and the Russian Far East offshore. In China, they are located in the seashore of Liaoning, Hebei, Shandong and Jiangsu Province. It likes environments with slow water flow, seaweed-rich, sand and rock reef bottom. It aestivates in summer and hibernates in winter. It will evacuate its internal organs when being provoked. Regenerative ability is very high after being damaged or cut. When the water temperature is below 3°C, food intake decreases. The suitable water temperature is 5-18°C. The optimum temperature is 10-17°C. A higher temperature of 17.5-19°C has a negative impact on food intake and digestion of mature sea cucumbers. However, the juvenile ones could endure temperature higher than 20°C with a higher food intake and lower digestion and absorption rate. At 23°C, their growth is adversely affected. So sea cucumbers are rarely distributed in areas with temperature higher than 26°C. The culturing management of *Apostichopus japonicus* is relatively simple because they mainly feed on plankton, benthic diatoms, and organic debris. The natural food generally meet their requirements for growth. People can supplement some feed when the natural feed is not enough (Yang et al., 2014).

Polychaete Neanthes japonica adapts to wide salinity living in seawater, brackish water and often habitats in the estuary. It is mainly distributed in the intertidal and subtidal zones of the Yellow Sea, the Bohai Sea and the northern part of the East China Sea. It generally inhabits tidal and intertidal zones with muddy sediment and rock crevices. It hides during the day and eats at night. The main food is algae, small animals, decayed crumbs and fragments of animal and plant. It is dioecious and reaches sexual maturity nearly on its first year. The reproductive period is from April to May (Ma and Liu, 1998). As a good natural animal feed, *N. japonica* is the central part in the seawater pond food chain. Its habitat such as ecological distribution, reproduction and feeding is very suitable for culturing species to eat, especially for farming shrimps. Large living creatures bait varieties. Neanthes japonica in the sea water ponds are a good natural source for shrimp feeding as it improves energy efficiency, saves food and improves the sediment environment in the shrimp pond. It reduces the organic pollution in the pond, which significantly increases the ecological and economic benefits of the IMTA system.

3.2.2 The Requirements of ecological environment and site choice

3.2.2.1 Seawater situation

The site for building pond should be abundant of water resource, with good water exchange, no pollution, has good water quality, less suspended particles, and has access to convenient transportation. The seawater sources should meet the People's Republic of China National Standards "Fishery Water Quality Standards" (GB1607-89) requirements. Salinity is at 20-32 and pH is at 7.5-8.6.

3.2.2.2 Situation of pond

The situation of pond should be according to the cultured species. For example, the required depth for sea cucumber ponds should exceed 2 m with an artificial reef at the bottom. The pond for farming jellyfish requires a larger area (>3 hr^2) and a higher depth (>2 m). The pond for farming shrimps should be about 0.5-1.5m depth. The sediment situation is according to the species. The *Sinonovacula constricta* likes soft muddy sediment while muddy-sandy sediment is good for culturing *Ruditapes philippinarum* and *Meretrix meretrix*.

The channels for water coming in and going out should be separate to avoid pollution of farming water itself. Ponds should be without leakage and have water inlet and drainage gates. Where conditions permit, ecological ponds can be built into grade aquaculture ponds so that aquaculture water can be discharged through different aquaculture species in the graded ponds.

3.2.3 Construction of IMTA Pond System

IMTA pond system utilizes the food chain and trophic level relationship among the ecological niches in ponds. The aquaculture organisms in the pond achieve a scientific and reasonable proportion, which can realize the full utilization of time, space, food resources and other aquaculture factors. The full use of elements should achieve the best farming effect. At the same time, it can also achieve ecological regulation and disease prevention, reduce the incidence of diseases of single-species and improve the efficiency of pond farming. For example, the filter feeding fish and shellfish are used in shrimp or fish ponds to improve the use of organic particles, feces and plankton in the ponds. Animal excrement (urine) can become a rich fertilizer for seaweed to improve water quality and reduce pollutant emissions. At present, the IMTA seawater pond is dominated by fish-sea cucumber, fish-shrimp, shrimp-crab-shellfish, and fish-shrimp-crab in northern China.

3.2.3.1 IMTA pond dominated by shrimps

The seawater pond aquaculture in northern China started from the large-scale cultivation of *Fenneropenaeus chinensis* in the late 1970s. The shrimp pond modes experienced low-density farming, high-density farming, two-crop low-density farming and multi-species ecological farming. The main species were *Fenneropenaeus chinensis*, *Litopenaeus vannamei, Penaeus japonicas* and *Penaeus penicillatus* etc. The earliest seawater pond farming was to simply culture wild juvenile shrimp with fish with very low fish and shrimp yields. After the 1970s, with the improvement of artificial breeding technology and artificial feed technology for shrimp, intensive and semi-intensive mode developed rapidly. The characteristics of intensive and semi-intensive pond culture were high-density stocking artificial breeding shrimp, fed a large amount of feed, exchanged a large amount of water. The output was high, but serious pollution happened offshore. Since the 1990s, because of the outbreak and spread of epidemic diseases of shrimp, IMTA pond aquaculture was given more attention. The main types of IMTA pond in northern China are IMTA mode for culturing shrimp, IMTA mode for culturing *Portunus trituberculatus*, IMTA mode for culturing sea cucumber and multi-species IMTA mode. Following the evolutionary trajectory of shrimp farming, it can be found that different farming patterns play a decisive role in the ecological benefits of seawater ponds, while ecological benefits have a strong impact on social and economic benefits, thereby affecting the development of seawater pond aquaculture.

Disadvantages of sea ponds for monoculture shrimp

From 1978 to 1992, the shrimp aquaculture industry in China maintained rapid development. Before 1992, the annual output of shrimp in the country stabilized at about 200,000 tons and maintained a leading position in the world for several years. The export of cultured shrimp also earned foreign exchange maintaining its strong momentum, and at the same time drove the development of related industries and made tremendous contributions to the economic development of the coastal areas in China. However, there are many inherent flaws in pond single-species shrimp farming. First, single-species and high-density stocking methods over-intensify the single biological factor of shrimp and lead to the imbalance of species composition in the shrimp pond ecosystem, malformation structure of food web and low conversion efficiency of material and energy in the pond. According to statistics, the feed utilization rate is only 15% to 20% in traditional shrimp farming in China, which wastes a lot of valuable protein resources (Zhao, 2006). Second, a large number of artificial feed induces organic pollution while a large number of medication has seriously affected the growth of beneficial microorganisms in the pond. A large number of feed, metabolic waste and other organic matter, which settled at the bottom or suspended in water, cannot be effectively biodegradable. As a result, organic oxygen consumption of the water increases, and dissolved oxygen content decreases. Toxic substances such as ammonia nitrogen, nitrite and hydrogen sulfide increase. The aquatic environment of the shrimp ponds has seriously deteriorated. Third, the large amount of wastewater from the pond into the environment enhances the pollution of the aquaculture area in the sea, aggravating eutrophication and decreasing species diversity. The environment cannot deal with so much pollution resulting in frequent red tides. Fourth, the exchange of water in shrimp ponds and the sea area makes polluted seawater become the vector of virus and bacterial transmission. The combined effects of the above factors led to the almost devastating impact on the entire shrimp farming industry in China by the outbreak of the epidemic in 1993 (Liu, 2005). Therefore, the single-species culture mode has low ecological effect, poor economic and social benefits, and is not the direction of sustainable development of shrimp farming.

Polyculture mode in shrimp pond

The polyculture mode in shrimp pond is a form of production in which artificial culture of mutually beneficial species is conducted in the same pond in a quantitative relationship. This makes it suitable for all niches and nutrients in the pond corresponding to the culture species, the spatial structure and hierarchy of the biological communities in the pond ecosystem. The ecological structure of the pond can be optimized. The species diversity in the pond can be strengthened. All kinds of animals in the pond ecosystem can be connected with each other through the food network at all trophic levels, which makes full use of all kinds of natural feed resources and artificial feed in water. The polyculture mode can improve the utilization efficiency of material and energy of shrimp ponds. At the same time, the metabolites of animals are decomposed by bacteria and assimilated by photosynthetic organisms, which not only improve the primary productivity of the pond, but also promote the self-purification ability of the water environment in the pond, thus preventing pollution. The mode is good for the growth of shrimp and other aquaculture organisms to enhance growth rate and disease resistance. Every component of the system maintains a relative dynamic balance of energy and material recycle through mutual restraint, conversion, feedback and other mechanisms. The ability to self-regulate and resist foreign interference is improved. In this way, the shrimp pond ecosystem can be stabilized without water exchange. The semi-enclosed or closed aquaculture can be practiced to block the direct exchange of water between the aquaculture ponds and the offshore waters. This is of great significance to protect the coastal ecological environment and prevent the introduction of the pathogen from the sea area into the shrimp pond, which controls the large-scale occurrence and rapid spread of epidemic diseases in shrimp ponds.

Fish-shrimp polyculture

Several different habits of fish integrated in shrimp ponds could improve the ecological environment of the pond, which can have a positive effect. In shrimp ponds, a small amount of *Lateolabrax japonicus, Pagrus major, Sparus macrocephalus, Takifugu rubripes, Mugilogobius sp*p and other carnivorous fish can not only eat the small trash fish competing feed with shrimp, but also can eat sick shrimp, thereby reducing the infection chain of shrimp diseases. The *Mugil cephalus, Liza haematochelia* and *Chanos chanos* can feed on benthic diatoms, organic detritus, shrimp unfed feed, and even shrimp faeces in shrimp ponds. Tilapia, which has been domesticated with seawater, can not only effectively utilize the plankton in the shrimp ponds, but also suppress the bloom of larger algae, such as protocormophores, and promote the propagation of smaller beneficial algae, such as algae and diatoms. Fish can secrete one or several substances on the surface to inhibit shrimp virus and prevent shrimp disease. Therefore, shrimp pond with fish has a good effect on the control of water quality, promoting the regeneration of nitrogen, phosphorus and other nutrients, and blocking the spread of shrimp diseases. However, the amount of fish in shrimp ponds should be appropriate. They not only have the advantages of protecting shrimp pond ecosystems and preventing shrimp diseases, but also disadvantageously consume feed and space in shrimp ponds. Therefore, the proportion of fish in the shrimp pond should be suitable (Zhao, 2006).

Shrimp-shellfish polyculture

There is a large number of shellfish suitable for integrated culture in shrimp ponds mainly including *Sinonovacula constricta, Ruditapes philippinarum, Meretrix meretrix, Argopecten irradians, scallops*, mussels and oysters. Depending on local conditions, choosing one or more as supplementation species in the pond is acceptable. Shellfish mainly feeds on phytoplankton and suspended organic debris, which can prevent organism pollution in shrimp ponds, keep water quality stable and improve energy conversion efficiency of shrimp ponds. Buried shellfish can also utilize organic debris that sinks to the bottom, reducing the amount of organic matter in the substrate and the level of sediment contamination. In addition, they can enhance oxygen flux at the sediment water interface of shrimp ponds through movement and feeding, promoting the oxidation of organic matter in the sediment and the release of inorganic elements, and improving the utilization of nitrogen and phosphorus (Li and Cui, 1996). At present, shrimp-shellfish polyculture has shown significant ecological and economic benefits in many places.

Shrimp-sea cucumber polyculture

Sea cucumber feeds on diatoms, seaweed debris, protozoa, copepods, shrimp shell crust, organic debris, humus and bacteria at the bottom of pond. The sediment dominates the food composition because of poor feeding selectivity. It will be cleaner in the shrimp ponds playing full use of shrimp bait, the role of which is to clean the bottom. Shrimp-sea cucumber polyculture can improve the material utilization of shrimp ponds and improve the ecological environment at the bottom. At the same time, it greatly improves pond farming benefits. However, the pond must be first transformed by setting the necessary shelter and attachment reef to realize the cultivation of sea cucumber in shrimp ponds. In recent years, people have reformed the original shrimp ponds to cultivate sea cucumber in the northern region, where some have been successful. Comprehensive shrimp-sea cucumber polyculture has developed rapidly with high economic benefits. The use of shrimp ponds for shrimp-sea cucumber polyculture has great potential with good prospects.

Integrated multi-species cultivation in shrimp pond

The integrated multi-species cultivation in shrimp pond characterized by shrimp dominates with a variety of other aquatic organisms. There are fish-shrimp-shellfish polyculture, algae-shrimp-crabs polyculture, shrimp-fish-shellfish-algae polyculture and sea cucumber-shellfish-fish-shrimp polyculture, etc. in China. The results showed that fish, shellfish and seaweed utilized 26%, 14.5% and 22.44% of the nitrogen sources in feed, respectively, with only 32.8% settled in the sediments and the nitrogen released into the sea accounted for only 4.25% of the total nitrogen. The use efficiency improves more than twice compared with monoculture shrimp (about 20%). The ecological benefits are significant. Integrated multi-species cultivation takes full advantage of the complementarity of various species on spatial distribution (upper, middle, lower and lower layers) and food web structure (carnivorous, phytotrophism, omnivore and ingestion, filter feeding, licking feeding) (Hu, 2002.). It optimizes the biological community structure in the shrimp pond and improves the conversion rate of material and energy of the shrimp pond. It is more conducive to the stability of the ecological environment of the shrimp pond. The comprehensive economic benefits and ecological effects of the shrimp pond are also more significant. Therefore, this model will be the future direction of shrimp aquaculture and development trends.

In recent years, many beneficial attempts had been made to the development and improvement of the integrated culture mode of shrimp ponds, which brought good results in terms of social, ecological and economic benefits. At present, the integrated shrimp ponds has grown to more than 200,000 hectares in China. The ecological environment of shrimp ponds is improving regularly. The exchange of water between shrimp ponds and the sea area is significantly reduced. The outbreak of shrimp disease is controlled and the shrimp production is gradually rising year by year. The shrimp pond has comprehensive, strong and broad prospects for development. Continuous learning and constant practice are needed to be able to explore a comprehensive farming mode that suits the characteristics of local shrimp ponds and realize the goal of healthy, sustained and stable development of marine pond shrimp farming.

3.2.3.2 Integrated *Portunus portunus* pond culture

Shrimp-crab polyculture

Crab and shrimp are both omnivores. The crab can prey on some large bait which cannot be used by shrimp, such as conch, clams and so on. The shrimp can eat some smaller organisms that cannot be ingested by crabs. Shrimp-crab polyculture reduces the unfed feed polluting the water quality. The feed is fully utilized, reducing the cost of feed. *Portunus trituberculatus* could survive together with shrimp in the same situation. The juvenile shrimp can be harvested twice. The juvenile crab is separately cultured with the shrimp. After shrimp harvest in the middle of the cultivation period, the shrimp and crab are cultured together in the pond (Chen and He, 2008).

Crab-shrimp-shellfish polyculture

Crab-shrimp-shellfish polyculture principle: *Portunus trituberculatus* can flip the bottom of the pond and eat the snail, which could improve nutrition in the water and enhance algal bloom. The crab can feed on sick shrimp to control the spread of the virus. At the same time, the activity of crab could improve the environment at the bottom of the pond. In general, crab-shrimp-shellfish polyculture use their different physiological and ecological characteristics. The use of *Ruditapes philippinarum* filter water to fully use unfed feed of crab and shrimp, plankton to achieve the purpose of mutual symbiosis. *Portunus trituberculatus* is the dominant species in the pond and *Litopenaeus vannamei, Penaeus japonicas* and *Exopalaemon carinicauda* are the lesser, then supplemented by *Sinonovacula constricta, Ruditapes philippinarum, Meretrix meretrix* and *Argopecten irradians*. The seeds are seeding in different seasons according to different species and harvested at different times (Zhou et al 2010).

3.2.3.3 Sea cucumber pond polyculture

The pond culture has become the most important cultivation method of sea cucumber. Especially since the early 1990s, abandoned shrimp ponds have been transformed into sea cucumber ponds, which are of great significance to the restoration of the coastal pond aquaculture industry. The water quality surrounding the pond is good and allows water exchange in the pond easily. The bottom of the pond is mud-sand. The depth is more than 2m. A good dam to prevent leakage is needed. Reconstruction pond should be immersed in water twice before filling it with water. The fermented chicken manure is used to enrich benthic diatoms. Seeding should be in autumn and spring, but avoiding the water temperature below 7°C from October to November in autumn and higher than 7-8°C from March to May in spring. Cultivation period is based on the conditions of the pond and the parameters of seedlings. Harvesting big ones is the principle of harvest. Water quality management is the point, which includes monitoring salinity, temperature, pH, color, transparency. Most ponds do not need artificial feed because the natural food from the water exchange is enough for the sea cucumber. In the same period, feeding the sea cucumber could get more production. Cleaning algae in the pond is needed. In general, the harvesting cycle of sea cucumbers takes about 1.5 years (Ren, 2012).

The polyculture of shrimp-sea cucumber has proven significant benefits. After 18 months of sea cucumber cultivation, it can reach the commercial size. The body weight is generally 100-200 g. The harvest of sea cucumber should be later than the shrimp. Water needs to be drained first, and then harvest from shallow water to deep water. After harvesting, the water is immediately collected into the pool to restore the normal water level to ensure survival of the remaining sea cucumber.

3.2.3.4 Jellyfish pond polyculture

Jellyfish pond polyculture integrates jellyfish, fish, shrimp and shellfish. Fertilization improves the amount of plankton for food of jellyfish and shellfish. The unfed feed of fish and shrimp and excretion of animals promote plankton breeding. Shellfish ingests phytoplankton and also filters water to get bacteria and organic debris, which effectively purifies the water quality and improves the ecological environment of the pond.

The old ponds need to be dredged not less than 5 cm in advance, at the same time strengthening the dam and repairing the gate. The place for culturing *Sinonovacula constricta* should be built at the same time. The area is about 5% of the pond area. Small areas should have a width of 3-9 m and 50-60 cm above the bottom. A blocking net with 20 mesh surrounding the pond should be set up, which should be higher than the maximum water level 30 cm and the bottom should be left 20-30 cm in depth when the water is less. The 60 mesh inlet filter is used to allow the flow of clean sea water. After completion of the infrastructure work, water will be drained into ponds and fertilized (Mou et al., 2009).

According to the biological characteristics of different species, juvenile *Sinonovacula constricta* is generally seeding around April when the water temperature is 10-15ºC. The density is about 50 kg seedlings with shell length of 0.5-1.5 cm/667 m^2. Integrated cultured fish related parameters such as stocking time, density, specifications and etc., will be determined according to the growth characteristics of fish species. The jellyfish is seeding three times a year. The first time is in mid-May with a temperature of 15-18°C and transparency is 40 cm. The density is 80 individuals/667 m^2. The second time is in mid-June with a density of 120 ind./667 m^2. The third time is at the end of July and early August with a density of 100 ind/667 m^2. The diameter of jellyfish is above 5 cm (Mou et al., 2009).

3.2.4 Analysis of Economic and Ecological Benefits

IMTA pond integrating the biological characteristics and ecological habits of different cultured organisms takes full advantage of pond space and resources, which is making effective use of organic composition and obtaining the output at the same time. It achieves self-healing aquaculture environment. At present, compared with monoculture, IMTA pond mode can get economic benefits of output without reducing the culture density of main species, which greatly reduces the cost of monoculture (Wang and Wei, 2008). Therefore, the IMTA pond mode provides significant economic benefits.

The ecological benefits of IMTA pond mode often focus on the flow patterns of biogenic elements such as carbon, nitrogen, phosphorus and silicon. As an important source of biogenic elements in seawater, biogenic elements are important material basis for the survival of marine organisms and are of great significance to maintaining the ecological balance of the marine ecosystem and restoring the unbalanced marine ecological environment. Energy flow and material circulation are important processes in the ecosystem. It is of great significance to study the transformation rules to improve the structure and function of the system. It is also the core issue of the cultivation system. In the IMTA pond mode, artificial feed and other factors are weakened, which reinforces the material cycle and energy flow path of different organisms. Due to the high density and feeding of the main species, organic matter in the water and sediment increases, resulting in the multiplication of bacteria. In order to maintain a good environment, the function of bacteria as a decomposer is enhanced. As a result, a large amount of nutrients such as nitrogen and phosphorus is greatly increased in the water. Some of these nutrients are deposited by mineralization and some are used as nutrition for phytoplankton and benthic plants. The result of mass multiplication of these plants, on the one hand, provides food for zooplanktons and zoobenthos. The deaths of these plants increase the amount of organic matter in the water and sediment, which participate in the material circulation among different species. In addition, the growth of these phytoplankton absorbs nutrients in the water and sediment. The zooplankton or zoobenthos (shellfish, sea cucumber, polychaete, etc.) grow by ingesting these plants. Different cultured organisms have completed the circulation of matter and energy in different ways. At present, the quantitative research on energy and material of pond aquaculture is still relatively weak. Liu et al. (2002) studied the metabolism of organic carbon in plankton community in shrimp pond. Liu et al. (2002) found that the carbon-bacteria-zooplankton food chain plays an important role in organic carbon metabolism in a shrimp pond system (Liu et al., 2002). A preliminary analysis was conducted on the energy balance and flow in the shrimp pond ecosystem (Zhou and Liu, 2000). It proves that the shrimp pond has higher income than expenditure, with an average of 24.5% of the income of organic sediment at the bottom. Evidently, how to improve the input rate of material and energy output to achieve the balance of material and energy budget is an important issue to be solved in the shrimp culture ecosystem. According to the law of the biogenic elements flow, domestic scholars have created IMTA mode from the perspective of ecological environment protection and restoration. By utilizing the biological characteristics of the cultured organisms, artificial intervention has formed a stable and scientific food chain. These models and concepts are advanced in the world, which lead the development direction of related research and make great contributions to the protection and restoration of fishery industry and ecological environment.

Development of IMTA pond mode improves the quality of products and environment recovery. To promote IMTA at different trophic levels, it is needed to enhance the ecological complementarity and mutual benefit, as well as the economic and ecological benefits; it is a good way to abandon and transform some ponds, rebuild wetland ecosystems, and protect aquaculture ecosystems. By utilizing the biological characteristics of different aquaculture species and rationally collocating the aquaculture pond structure, the economic and ecological benefits of seawater pond aquaculture can be realized through the regulation of water quality and the establishment of ecological disease prevention technology. The result will promote the transformation of seawater pond aquaculture mode. The technology will establish sustainable development of aquaculture mode.

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3.3 Pond IMTA in Zhejiang Province

3.3.1 The biological characteristics and ecological habits of the major farming species in the pond IMTA system

Zhejiang breeds main integrated aquaculture species, including shrimp (crabs), shellfish, fish, often with any pair of breeding or multiple collocation farming. Farmers breed according to local conditions, and the pond's geographical location and conditions that are reasonable with breeding species, so as to make full use of water space and improve the utilization of nutrients.

3.3.1.1 Major culture shellfish of pond culture

Cockle clam *Tegillarca granosa*

Morphological characteristics and natural distribution

Tegillarca granosa belong to *Lamellibranchia, Arcoida, Arcidae* and *Tegillarca. T. granosa* are widely distributed in tropical and temperate zones, such as the coast beaches of the Indian Ocean and west Pacific. The main producers of *T. granosa* include India, Thailand, Vietnam, Malaysia, Indonesia, Japan, China and so on. It is one of the four major cultured shellfish in PR China (Wang et al., 2008), and is mainly distributed in the coastal provinces south of Shandong Peninsula. Zhejiang, Fujian and Guangdong are the major natural resource areas.

The average shell length of *T. granosa* is about 3 cm, the largest one can be 6-7 cm. Shells of *T. granosa* are usually very thick with an oval shape.

Habitat and ecological habits

T. granosa mainly live in an argillaceous or sandy-muddy intertidal flat beach as they prefer soft mudflats of inner bay or estuary with freshwater supply. *T. granosa* will usually be found between the junction of middle tidal and low tide areas. *T. granosa* mainly feed on diatoms and organic detritus. Bays with freshwater influx is more nutritious and suitable for algae breeding and a relatively calm flow is suitable for the growth of benthic diatoms, these areas can provide rich food sources for *T. granosa*. Leqing Bay in Zhejiang Province and Dongshan Bay in Fujian Province, due to their good natural environments, are famous for producing high quality *T. granosa* where they are a geographical specialty.

T. granosa can survive with water temperature from 1-35ºC, the most suitable temperature for adult T. *granosa* is between 15ºC-28ºC, and for juvenile is between 25-30ºC.

T. granosa are pene-contemporaneous animals with strong adaptability to intense environmental changes. Survival salinity range of *T. granosa* is 10-28.8 psu and the optimum salinity for juvenile growth is from 12.8-24.2 psu. T. granosa can tolerate extreme salinity for a short period through enclosure shells, but if the salinity of seawater drops sharply below 5 psu for more than 3 days, a large number of deaths would occur (Wang Wandong, 2008).

Natural resource of *T. granosa* seedlings occur mostly in relatively calm bays with abundant benthic diatoms; the buried mud layer gradually deepen with the growth of *T. granosa*, which usually just get themselves covered in order to facilitate their feeding; during winter and summer, the buried depth increases, usually at a magnitude of 4-5 cm, the deepest buried depth can be up to 10 cm.

The movement of *T. granosa* is weak. Attached spat less than 1 mm moves vertically; Juveniles of 2-5 mm actively moves horizontally; Adult *T. granosa* only slightly move vertically in the mud, the horizontal movement is greatly reduced.

Food and feeding

T. granosa are filter-feeding animals, food is composed mainly of benthic diatoms and supplied by planktonic diatoms and organic debris. As they don’t have water pipes, the feeding and breathing is completed by the collaborative work of the mantle and gill cilia to pump water through rear edge of the shell. *T. granosa* are able to adapt to strong turbid seawater, muddy dirt in the water can be filtered and discharged in the form of pseudo-feces. Within the suitable temperature range, *T. granosa* take more food with higher temperature and lead to faster growth.

Growth and reproduction

T. granosa grows during its entire life-span but is a slow-growing shellfish, with annual growth less than 30% (Yu Zhongjie et al., 2002). Generally, they grow to product specifications after 2-3 years. The culture period is similar to the Clamidae family such as *Meretrix meretrix, Gomphina aequilatera* and *Mercenaria mercenaria*, but much slower than that of oysters, scallops and pinctadas. Most shellfish showed the asynchronous growth of shell length and weight during the growth process. However, the growth of *T. granosa* showed a synchronous phenomenon of shell growth and weight gain.

During the breeding season from April to September, the clam weight increases rapidly as well as the shell length.

T. granosa are dioecious. Their gonads are distributed around the digestive gland when matured, where male and female can be distinguished according to the soft tissue color (female is orange, male is light yellow). *T. granosa* are oviparous shellfish and generally take two years to reach sexual maturity. The reproduction cycle of *T. granosa* is one year and the natural breeding season along China's coastal areas are different. On the coast of Shandong Province, it is from July to August, and the peak period is from the end of July to the beginning of August. On the coast of Zhejiang Province, it is from June to August, and the peak period is from late June to early July. At the southern part of Fujian Province, it is from late August to October, high reproduction period is September. On the Guangdong coast, it is from August to December, peak period is from September to November.

Razor clam *Sinonovacula constricta*

Morphological characteristics and natural distribution

Razor clam *Sinonovacula constricta*, belong to *Lamellibranchia, Veneroida, Pharellidae*, and *Sinonovacula*. Razor clams are widely distributed in the coastal areas of China, Japan, North Korea and other Asian countries. In China, they can be found in the north in Liaoning and Shandong Provinces, and in the far south in Guangdong and Fujian Provinces.

Clam shells of *S. constricta* are symmetrically rectangular, thin and crisp, and they cannot close their shells completely. The posterior edge of the shell has a brownish-black spindle-shaped ligament that connects the two shells. The shell surface is covered by tawny thin skin. There is a micro-concave oblique ditch that extends from the top of the shell to the ventral rim, which explains its Chinese name *Yicheng*.

Habitat and ecological habits

Razor clams are buried shellfish and prefer habitats that are soft muddy or sandy-muddy sediments between the low and middle tide regions of inner bays or estuaries with less storms. Razor clams live in a cave, where the entrance is perpendicular to the surface, cave depth of adult razor clams can be up to 50-70 cm. They can move vertically in the cave with the tidal cycle.

Razor clams can survive in an environment with wide temperature and salinity range. Suitable seawater temperature for razor clams is from 0-39°C and the optimum temperature is between 15-30°C. Suitable salinity for razor clams is between 4-29 psu, and the optimum salinity is from 16-26 psu.

Food and feeding

The razor clams feed on *Chlamydomonas* in the seawater, pelagic diatoms with weak movement and benthic diatoms are the major components of their diet. Organic detritus and microbes are also bait for razor clams. Razor clams generate flows with gill cilia motions, pipe water in and get filtered through the gill, particles with appropriate sizes will be transported into the digestive tube. The feeding activity of the razor clams is limited by the tide as they can only feed when the cave has been submerged.

Growth and reproduction

Razor clams are fast-growing species. Cultured razor clams usually reach commercial size (body length 4-5 cm) within one year. After one year, the body length growth rate significantly decreases and the tissue growth rate increases. Razor clams grow slow in winter but fast in summer. The shell grows fastest during May-July and the tissue grows fastest during July-September.

Razor clams are dioecious, sexual maturity usually takes one year. Gender cannot be told from appearance. When sexually matured, the female gonad is beige and the male gonad is milky white. Sex ratio of razor clams is nearly 1:1. Mature season for razor clams differs from regionally. In China, the razor clams mature earlier in the north than in the south. Reproduction season of razor clams in Liaoning Coast is from June–August, in Shandong Coast from August–October and peaks in September. On the coast of Zhejiang Province, reproduction period of razor clams is from September–November, and peaks in October.

Clam *Cyclina sinensis*

Morphological characteristics and natural distribution

Cyclina sinensis belong to *Lamellibranchia, Heterodonta, Veneroida, Veneridae* and *Mactra. C. sinensis* are widely distributed in the coastal areas of China, south of the Honshu Island of Japan and the coast of the Korean peninsula. *C. sinensis* live in the intertidal zone with muddy or sandy-muddy sediment, and they usually gather at the high tidal zones close to freshwater input.

Clam shells of *C. sinensis* are symmetrical in shape and close to circle. Their shells are thin and solid. Shell head is protruding and the tip bends forward. The concentric growth pattern of the shell is obvious and without radiating ribs.

Habitat and ecological habits

Cyclina sinensis are strong adaptive species with low demand for the substrate. They can survive in coarse, silt and muddy sands. The submerging depth of the clam is related to the individual size, season and bottom quality. The burial depth of the seedlings is shallow and gets deeper for adult clams. Larger size individuals can bury as deep as 15 cm under the surface.

Cyclina sinensis have strong adaptability to water temperature and salinity. Suitable temperature is from 0-30ºC, and 22-30ºC is the optimum growth temperature. The suitable salinity of the clam is from 15 psu-30 psu, and the optimum salt concentration is 20-25 psu.

Food and feeding

Chlamydomonas, especially diatoms, make up the major diet of *Cyclina sinensis*. Other than that, the clams also filter organic debris, micro zooplankton and microorganisms from seawater. In winter, the clams seldom feed. And in spring, as the temperature increases, their food intake gradually increases and growth accelerates.

Growth and reproduction

The growth rate of *Cyclina sinensis* is closely related to seasons, individual sizes and living environment. They grow faster at juvenile stag, slowing down as they grow bigger. One-year old clams can be as large as 2.5 cm in length and may reach 3 cm for two-year old clams.

Cyclina sinensis are dioecious and usually mature no more than one year. When the gonads of the clams mature, the color of the testis can be milky white or milky yellow, and the ovarian color is usually pink. The reproduction season for *Cyclina sinensis* near the Zhejiang and Jiangsu Coasts is from June-September, and most vigorous during mid-July – mid-August when the temperature is high.

3.3.1.2 Pond cultured shrimp and crabs

Penaeus Vannamei

Morphological characteristics and natural distribution

Shrimp *Penaeus vannamei* belong to *Crustacea, Decapoda, Penaeidae, Penaeus*. The natural distribution of the shrimp is along the Mexico-Peru Coast, especially in Ecuador.

Penaeus vannamei have thin shells, the general body color is blue-green or light blue-gray, and there are no stripes on the shrimp; the forehead of the shrimp slightly bent down; croaker is short, and the length of the croaker is about 1/3 of the abdomen; first to third leg of the foot is well developed; there is a ditch on the central section of the tail but there is no marginal thorn.

Habitat and ecological habits

Penaeus vannamei naturally inhabits in the muddy sediment, and usually live in the coastal water within 72 m deep. The living temperature is from 25-32ºC and salinity is from 28-34 psu, suitable pH should be 8.0±0.3. Adult shrimps live close to shore and juveniles usually gather near the estuaries with abundant food. Cultured shrimps usually stay at the bottom of the pond during daytime and become active in the evening.

Penaeus vannamei have strong adaptability as they can survive out of water for more than 24 hours as long as their body is wet. They can survive in a wide range of salinity from 0-45 psu and the suitable range is from 10-25 psu. The shrimp can stand quite a high water temperature of 43.5ºC, but they stop feeding if the water temperature falls below 18ºC. Moreover, the shrimp also survives a long time under low oxygen, where the lower limit of oxygen concentration is $1.2*10^{-6}$, and starvation, where they can survive around 30 days without feeding.

Food and feeding

Penaeus vannamei are omnivorous and close to biodynamic. Mostly small crustaceans or chimeris and other organisms are in their natural diet. In the culture environment, organic debris is also part of their feed but the curing rate of feed is high. The shrimp does not demand high feed protein, usually about 20% of protein content are sufficient for normal growth.

Growth and reproduction

Penaeus vannamei will go through several times of exuviation and seedling during their growth. When the water temperature reaches 28ºC, they exuviate every 30-40 hours and the new shell becomes hard in a few hours. Adult shrimp usually exuviate every 20 hours and the new shell gets hard in 1-2 days. When water temperature stabilizes between 25-32ºC and the other conditions are suitable, the juvenile shrimp can grow to 15-20 grams within 70-80 days of culture period.

The shrimps' seminal vesicle is open, and they mate after gonadal maturity of male and female shrimp. Fertilized ovum usually generates a few hours after the mating and spawning time is often during 9 pm-3 am.

Exopalaemon carinicauda

Morphological characteristics and natural distribution

Shrimp *Exopalaemon carinicauda* belong to *Crustacea, Decapoda, Palaemonidae, Exopalaemon*. They are widely distributed along the Chinese and Korean Coasts, in the low salinity waters, and production is enormous in the Yellow and Bohai seas. The shrimp are seafood with high protein, lower fat and abundant dietary element.

Body length of *Exopalaemon carinicauda* is 5–9 cm, with slender forehead, basal 1/3 of the forehead are with chicken coronal uplift, upper and lower edges are serrated, the upper edge usually has 6–9 teeth, and the lower edge has 3–6 teeth. The tail end of the shrimp is sharp-barbed. The body of the shrimp is transparent, with microstrip blue or red spots. When shrimp die, they turn white.

Habitat and ecological habits

Shrimp *Exopalaemon carinicauda* usually live in brackish water near shallow seas, coastal zones or estuaries with muddy-sandy sediment. The shrimp can adapt to a water environment with temperature from 0-28°C and salinity from 4-35 psu, the optimum temperature and salinity for growth are 27-29.6°C and 22-28 psu, respectively. With gradual desalination, the shrimp can live in pure freshwater. The shrimp can survive in a pH environment of 4.8-10.5 and the suitable pH is 7.9-8.6. They can maintain activity at an oxygen concentration as low as 1 mg/L, but will float and move to shore when oxygen concentration falls below 0.8 mg/L.

Food and feeding

Shrimp *Exopalaemon carinicauda* is omnivorous. Juvenile shrimp mainly feed on phytoplankton and organic debris; adult shrimp feed on phytoplankton, zooplankton and organic debris. In a pond culture environment, they can feed on vegetative bait, animal bait, artificial bait or their mixtures. The shrimp grow faster when fed on the mixtures of artificial and animal bait compared to the mono-feeding with vegetative bait.

Growth and reproduction

Reproduction season of shrimp Exopalaemon carinicauda is usually very long, from March–November along the southern coast of China and from April-October in the north. Peak breeding period is from May-August. The shrimp mate when female spawn. Spawn amounts are linearly correlated to shrimp size. An individual shrimp is able to produce 440-6,000 eggs. Due to different environment conditions, incubation period can last from 10-21 days. Incubated eggs will exuviate after 48-54 hours and grow to second stage larvae. After 2-3 days, the larvae will exuviate again and transform to third stage larvae. After about 15 days with 6 exuviations, the larvae are transformed into post larvae. The post larvae will transform to adult (4-6 cm) with sufficient feed, and most adult shrimp are matured and able to spawn. Spawned shrimp can spawn multiple times during the culture period, usually three days after the former one with sufficient feed and appropriate environment.

During the pond culture in Zhejiang, the culture shrimp *Exopalaemon carinicauda* will not be all harvested. Some parent shrimp will be selected and kept cultured in the pond until they spawn. With the shrimp's fast growth, farmers can harvest 2-3 times each year. Such pond self-spawning technique is one of the characteristics of Zhejiang seawater pond culture.

Portunus trituberculatus

Morphological characteristics and natural distribution

Crab *Portunus trituberculatus* belong to *Crusacea, Decapoda, Portunidae* and *Portunus*. The crabs are widely distributed on the coast of China, Japan, South Korea, Malaysian Islands and the Red Sea.

The body of the crab is made up of the head and chest, abdomen and appendages. The breast palate of the crab is spindle-shaped, slightly elevated and the surface are scattered with small particles. Chela of the crab is usually well-developed. The long section of the chela is prismatic in shape.

Habitat and ecological habits

According to the different seasons and individual sizes, crab P*ortunus trituberculatus* usually live in different regions. The crabs have a habit of reproductive migratory and overwintering migratory. They usually migrate in groups. During spring and summer (April-September). They usually spawn in shallow seas (3-5 m), especially in harbors or estuaries. In winter, they will migrate to 10-30 m region for overwintering. The crab usually lurks at the bottom during daytime and feeds during the night. The crabs are able to stay under the sand, but they are not able to drill caves. When cultured in the pond, they have no need for anti-escaping facilities. The living temperature for the crab is 8-31ºC and the optimum is 15.5-26.0ºC, living salinity is 13-38 psu and the optimum range is 20-35. The suitable pH for the crabs is from 7.8 to 8.6.

Food and feeding

Crab *Portunus trituberculatus* are omnivorous and they mainly feed on small fish, shrimp, shellfish and so on. In addition, they also feed on animal carcass and seaweed. The crab use chew foot to catch food, and use the first and second jaw foot to guard to prevent food loss. *Portunus tritubercularis* usually inhabit at a depth of 10-30 m muddy seabed. To avoid predators, they often hide in the vicinity of some obstacles or latent sand.

Growth and reproduction

Crab *Portunus trituberculatus* are dioecious. The female crab is larger in size. The general life expectancy of the crab is 2 years, rarely more than 3 years. The spawning population consists mainly of crabs aged 1 to 2 years old. Females die immediately after oviposition. Some males die 2 or 3 days after mating. The mating season varies by region and age. In Bohai Sea, the peak mating time for 2-year old crabs is from July to August and for 1-year old crabs is from September to October. In the East China Sea, the mating period is from July to November and peaks from September to October. When mating, the male crabs inject the sperm into the female crab's sperm capsule. Eggs begin with a pale yellow color, with the growing of embryo the color becomes orange, brown, and eventually becomes black gray, black. Eggs have about 20 days development (in Bohai Sea) before they finally transform into zoea, and then scattered for hatching. During a spawning period, *Portunus trituberculatus* can ovulate 1 to 3 times.

Scylla serrata

Morphological characteristics and natural distribution

Crab *Scylla serrata* belong to *Crustacea, Decapoda, Portunidae* and *Scylla*. The crabs are distributed mainly at the warm coast along India and west Pacific ocean, including Japan, China, Southeast Asia, India, East Africa, South Africa, Austrialia and etc. In China, the major natural habitat for the crab is on the coast region of the southeast.

Crab *Scylla serrata* is named after the color of its forehead and chest which is muddy green. The body consists of a forehead and chest and the abdomen. They are all covered by the carapace.

Habitat and ecological habits

Crab *Scylla serrata* live in the shallow sea and the intertidal zone, usually in the mud and sand sediment with seaweed or under the mangrove with shelter. They usually stay in the cave during daytime and start feed in the evening. Under the pond culture environment, the crabs also feed during daytime. The crabs have the habit of storing food for overwintering. In case of danger, they can exfoliate their limbs to escape.

Crab *Scylla serrata* are able to adapt to a range of saline water, survival salinity is 5-32 psu and the optimum is 12-16 psu. When salinity is below 5 psu, the crab will drill and stay in caves to get through the harsh environment. The crab can get used to different temperatures at different regions. At north of Guangdong Coast, they can live in a temperature of 5–35°C and the optimum temperature is 18–25°C; along the coast of Guangxi Province, the living temperature is 14–30°C and the optimum is 20-26°C.

Food and feeding

Crab *Scylla serrata* mainly feed on small fish, shrimp and scallops and other small animal carcasses. They also eat seaweed and organic debris under the condition of starvation.

Growth and reproduction

Crab *Scylla serrata* will go through several exuviations during their growth. Individual size will get larger after each exuviation as the shell size will increase by 0.3-1.0 cm in length and 0.4-1.2 cm in width. At Guangxi Coast, the crabs mainly exuviate during April-June and September-November in the morning or evening of the spring tides. Each exuviation needs about 10-15 minutes, exuviation need a longer time or even fail if the crabs are frightened. Crabs die if they fail to exuviate. After five months of culture, crabs with initial weight of about 50 g are able to grow to 200 g; crabs with initial weight of about 100-150 g grow to above 300 g after three months of culture time.

3.3.1.3 Pond cultured fish

Mugil cephalus

Morphological characteristics and natural distribution

Mugil cephalus belong to *Osteichthyes, Mugiliformes, Mugilidae* and *Mugil*. They are widely distributed globally, including the Pacific, Indian Ocean, Atlantic, Mediterranean and the Black Sea, mainly in the temperate, tropic and subtropic coastal zones. In China, *Mugil cephalus* can be found south in the Hainan Island, and in the north in Bohai Sea, especially in brackish water bays.

Mugil cephalus have a fusiform body; the former part is cylindrical and the rear part is flat. The fish have a blunt snout, big and wide eyes, no side line and caudal fin fork. There is a black plaque on the fish fin base.

Habitat and ecological habits

Mugil cephalus are tropical, temperate pelagic fish. Their natural habitat is widely along the coastal shallow seas, inner bays and estuaries with brackish water and sufficient food. They can live in the water with temperature from 3-35°C, and the optimum temperature for growth is 12–32°C . *Mugil cephalus* are able to survive in seawater, brackish water and pure freshwater. From the economic point of view, brackish culture pond is more suitable, with high growth rate, high yield and high quality of the fish.

Food and feeding

Mugil cephalus are omnivorous fish; they filter the plankton and scrape the organisms that settle on the mud sediment as food. Their diet includes diatoms, organic debris, filamentous algae, copepods, polychaetes and also some small shrimp and molluscs.

Growth and reproduction

The growth rate of *Mugil cephalus* varies in different regions and different water systems. Cultured fish, especially cultured in brackish water ponds, usually grow faster than those in natural seawater. In spring, juvenile fish could grow to 0.5-0.6 kg; some individuals can reach 0.7 kg, at the end of the year.

Mugil cephalus are dioecious as there is no significant difference in appearance during non-reproductive seasons. Sexually mature age is closely related to environmental temperature. Higher temperature leads to earlier maturity. Male fish mature at 2-3 years old and females at 3-5 years old. The mature body length will be 300-500 mm. In Guangdong and Fujian Provinces, the spawning period is from November to January of the following year, and *Mugil cephalus* usually spawn at night.

Sparus macrocephalus

Morphological characteristics and natural distribution

Sparus macrocephalus belong to Pe*rciformes, Sparidae* and *Acanthopagrus*, and are widely distributed along the coastal regions of Japan, North Korea and China.

The fish body is flat and has a long oval shape, with a big head and a blunt tip. The back of the fish is narrow and the inclination is large. The dorsal spine is hard. The color of the fish is blue-gray, with silver reflections. There are 7 black horizontal stripes along the body side.

Habitat and ecological habits

Sparus macrocephalus are shallow water fish. Their natural habitat is usually muddy sand bottom or rocky sea area within 50 m depth along the coast. During spring and summer they will stay close to shore, and when water temperature decreases during fall and winter they will move offshore. Generally, *Sparus macrocephalus* do not make long distance migrations.

Sparus macrocephalus can get used to a wide range of salinity, and after gradual desalination, they can be cultured in freshwater. They can also live in the water with temperature from 3.4-35.5°C, and the optimum temperature is 12-28°C. At south Zhejiang Province and Fujian Province, the temperature is high enough for safe overwintering.

Food and feeding

Sparus macrocephalus are omnivorous fish that mainly feed on clams, fish and shrimps. They also eat nereis, small crabs and benthic animals. Under pond aquaculture conditions, the major diet for *Sparus macrocephalus* are orchid clams and small goby. Artificial bait is generally made up of trash fish and feed.

Growth and reproduction

Sparus macrocephalus have a fast growth rate. Under natural conditions, their body length can grow from 10 mm to 100 mm during June to November. Cultured fish, as there is abundant feed, grow faster from 10 mm to about 120 mm after a 5-month culture period where body weight can be more than 50 grams.

Sparus macrocephalus are transsexual fish. Adult fish with body length around 150-295 mm are typical hermaphrodite stage, and the male gonads mature first. When body length reaches above 300 mm, individuals will divide into male or females. Reproduction season of *Sparus macrocephalus* is during the end of April to end of May, where the water temperature should be 14-20°C. Generally, a 2-3-year-old fish with 1 kg weight can reach sexual maturity. *Sparus macrocephalus* spawn in batches, where each spawn generates 30,000-100,000 eggs. Fecundity is related to individual age and size. Usually, 1 kg weight fish about 3 years old would spawn 2-3 million eggs during the reproduction season, while 4-5-year-old fish would spawn 4 million.

3.3.2 Site selection and ecological environment requirement

3.3.2.1 Site selection

Location of the culture pond is important. The environment, power supplement as well as the transportation conditions should be seriously considered. The pond should be built close to sea, with sufficient water exchange and less waves. Culture pond should be far from industries, agriculture and residential areas. Water quality of the regions should satisfy the marine aquaculture water quality standards.

The pond should be built at open and flat terrain that is suitable for design and construction but also easy to manage and cost effective.

3.3.2.2 Power and oxygen equipment

Power system
Power system should be safe, reliable, high quality and cost effective.

Oxygen system
In recent years, artificial aeration has been widely used in aquaculture and is an indispensable part of pond aquaculture system. As the density of cultured organisms continues to increase, artificial aeration is the main means of maintaining dissolved oxygen concentration in the pond water.

At present, the pond aquaculture artificial aeration is mostly through an aerator and a microporous oxygen pipe. The former uses the waterwheel to rotate and agitate the water column to achieve the purpose of oxygenation. The latter uses micropores to inject air into the water body to increase the concentration of dissolved oxygen in the water column.

3.3.3 Pond IMTA construction

Integrated multi-trophic aquaculture, which has merits such as high resource utilization, environmental protection, diverse product and disease prevention, etc., is a sustainable and environment-friendly culture mode. IMTA applied the ecological principles, made full use of, according to different biological niches, trophic level, diet and other differences, to regulate the culture ecosystem in the material cycle and energy flow, thereby enhancing the efficiency of materials and energy in the ecosystem to optimizing available resources.

The construction of IMTA system in Zhejiang Province is characterized by local conditions. Local culture species and introduced species are organically integrated. Based on factors such as culture time, space and local climatic characteristics, an IMTA system with distinctive local features is gradually formed.

3.3.3.1 Mutual culture organism combination

The principle of integrated culture is the reuse of farming waste. The main principle of IMTA is to change the waste discharged from one kind of cultured organism into food for another culture organism (nutrition).

Mutual benefit of culture organisms or culture systems: aquaculture organisms can be divided into feeding species (fish, shrimp, crabs, etc.) and acquired aquaculture species (filter feeding shellfish, large seaweeds, etc.). In the shrimp-shellfish polyculture system, waste feed and shrimp feces, after a variety of physical and chemical effects, are decomposed into a variety of nutrients which are absorbed by phytoplankton through photosynthesis. These phytoplankton are filtered by shellfish to achieve the purpose of waste material re-circulation.

Space collocation: first, the pond is simply divided into three parts — water, sediment surface and sediment. In order to make full use of the culture space, each part of the pond will be used to culture selected organisms according to their characteristics. Fish, shrimp and caged shellfish can be cultured in the water; bottom surface can be used for crab culture and buried habitat shellfish can be cultured in the sediment.

3.3.3.2 Construction of IMTA ponds

Net fencing

Net fencing is to separate some cross-affecting culture organisms physically, while the waste materials in the water can still be exchanged during the culture period for nutrient re-circulation.

Using the cockle clam *Tegillarca granosa*, shrimp *Penaeus vannamei* and crab *Scylla serrata* IMTA as an example, clam culture area should be within 25-30% of the pond area, with a culture density of about 300 ind./m^2, and the area will be fenced by net to prevent crab predation.

Circular ditch

Circular ditch mode is suitable for culture of buried shellfish, such as *Tegillarca granosa, Sinonovacula constricta* and *Cyclina sinensis*, integrated with shrimp, crab and fish. The pond, according to the area, will be divided into several rectangular sections. A ditch will be dug around each section with ditch depth of 50-80 cm. The spare mud and earth will be placed in the center of each section as culture sediment for shellfish. The ditch can be used for shrimp, crab and fish culture.

Bottom net

Bottom net culture is mainly used for clam *Sinonovacula constricta* culture, as such clams stay deeper in the sediment and the labor cost for harvest is high. The net will be placed 40 cm below the sediment surface. When harvest starts, each farmer can harvest 150-250 kg clams. Clam recapture rate can be as high as 98%, and the water body can be used for integrated culture of shrimp and fish.

3.3.4 Economic and ecological analysis

3.3.4.1 Economic benefit

The factors affecting the culture economic benefits include two aspects, one is the production of aquatic products, the risk of aquaculture; second is the market price of aquatic products, the market risk. Integrated aquaculture has a certain complementarity as its diverse culture products, which reduced the culture risk compare to monoculture. Different culture species effectively improve feed utilization and reduce farming costs. The market risk faced by farmers is the effect of the uncertainty of the future market price of aquatic products. Due to the differences in culture time and environmental conditions, cultured species can be adjusted flexibly according to market conditions.

3.3.4.2 Ecological benefit

IMTA can effectively improve the efficiency of pond culture ecosystem. In shrimp-fish-shellfish polyculture experiments, the polyculture of Chinese shrimp, Taiwan red Tilapia, clam *Sinonovacula constricta* and bay scallops with different proportions showed that all the polyculture combinations were better than monoculture. The shrimp-fish-shellfish polyculture showed the best efficiency: yield increased by 28%, nitrogen utilization increased by 85% (Li De Shang, 2002). In the polyculture experiment of Shrimp *Penaeus vannamei* and tilapia with different densities and specifications, the survival rate was 14.7% higher than that of the monoculture group and the yield of shrimp increased by 5.8% with suitable size and density of integrated Tilapia.

The nitrogen and phosphorus utilization efficiency in diets of polyculture group were significantly higher than that of monoculture group (Yuan, 2010). Net fencing the shrimp and tilapia in the same pool also yielded similar results (Muangkeow, 2007). Some studies have found that large algae can absorb nutrients produced by aquaculture organisms, which effectively reduces the water eutrophication and purifies the water body.

Gracilaria cultured around salmon cages grew significantly faster than those far from fish cages (Maria, 2009). Good results have also been achieved with seaweed cultured around fish cages (Hirata, 1993). IMTA can also play a role in disease prevention and control. *Tetraodontidae* can be cultured in shrimp ponds, where ill shrimp can be eaten to prevent the large-scale spread diseases and reduce economic losses (Chen, 2000).

3.3.5 Excretion characters of fish

Nitrogen excretion from the farming fish is discharged directly to the water body and affects the quality of the sea water. The nitrogen excretion of finfishes, such as sea bass *Lateolabrax japonicus* and large yellow croaker *Pseudosciaena crocea*, are mainly ammonia and urea, which are excreted mainly by gills, and a small amount of these are excreted with urine. In most cases, nitrogen is the most important excretion, and ammonia accounts for 80-98% of total excreted nitrogen. There are 4,000 fish cages in Nansha Island and 1,000 fish weighing 250 kg are stocked in every cage. The annual output of fish amounts to 1,000 t, about 75% and 25% of which are sea bass and yellow croaker, respectively. Based on the excretion rate of sea bass and yellow croaker in different seasons measured by Ning Xiuren et al. (2002) (Table 3-1) and the amount of fish stocks, it can be calculated that the nitrogen emissions of farming fish in spring, summer, autumn and winter were 4.62t, 15.59t, 8.96t and 2.81t, respectively.

Table 3-1 The nitrogen excretion rate and total diurnal excretion amount from farming fish in different seasons in Xiangshan Bay.

	Sea bass			**Yellow croaker**		
	NER* ***(μg/g•h)***	**Yield (t)**	**TNitrogen (kg/d)**	***NER**** ***(μg/g•h)***	**Yield (t)**	**TNitrogen (kg/d)**
Spring	0.994	330	7.87	15.08	120	43.43
Summer	7.58	480	87.32	21.06	170	85.92
Autumn	1.702	660	26.96	13.76	220	72.65
Winter	0.011	750	0.20	5.17	250	31.02

* Data from Ning Xiuren et al. (2002); NER: nitrogen excretion rate; TN: total nitrogen excreted by farming fish.

3.3.5.1 Research foundation based on seaweed bioremediation technology

Seaweeds are known as the most promising biological purifiers. During photosynthesis, they can not only use CO_2 to release oxygen, but also use dissolved inorganic nitrogen and phosphorus, which purify the surrounding waters. Compared to phytoplankton, seaweeds are easier to harvest, which can effectively remove nitrogen, phosphorus and other nutrients in the seawater. In addition to serving as food for abalone and sea urchin, the macroalgae can also be used as an important algal chemical raw material and human food to transform low value products into nutritious and economically valuable products. Therefore, based on seaweed bioremediation technology, the following can be made: full use of the nutrients and energy in the system, reducing of the nutritional loss and potential economic losses to the minimum, and achieving the purpose of environmental regulation and bioremediation.

Nutrition absorption kinetics of seaweed has been reported by numerous researchers. The existence of non-coupling relationship between nutrition absorption and growth of seaweed was found. Seaweeds have strong nitrogen absorption ability, under a nutrient-rich environment, most species have the ability to store extra nutrients than their own growth needs in their tissues, even if the irradiance intensity is insufficient. These stored nutrients are used for supporting fast growth once the irradiance intensity is sufficient. This kind of mechanism is quite useful in aquaculture production because when the content of nutrients in aquaculture water surges, seaweeds can react quickly and purify the water by absorbing nitrogen effectively. Fujita (1985) reported that the nitrogen pool in seaweed of *Ulva Lactuca*, *Enteromorpha sp.* and *Gracilaria tikvahiae* can maintain their growth for 6, 8 and 14 days, respectively, when cultured in a nutrient-deficient environment. Mao Yuze et al. (2008) showed that the kelp has the ability to absorb nutrients quickly. Ammonia concentration decreased from 5.1 mol/L to 2.7 mol/L in the initial 0.5 h, which means absorption rate reached 27.8 mol/gDW•h. The ammonia concentration changed slightly after 0.5 h and the absorption rate of kelp was very low (less than 1.1 mol/gDW•h). Kelp can also absorb nitrate rapidly. The nitrate concentration in the medium dropped from 44 mol/L to 33 mol/L in the first hour, however, in the following 28 hours the concentration stayed at a high level (19.7 mol/L). The highest absorption rate was 66.1 μmol/gDW•h, which appeared in the first 0.5 hour, followed by 45.3 μmol/gDW•h in the second 0.5h, and then the absorption rate decreased rapidly after 1 hour.

Seaweeds usually have high nutrients removal efficiency when they are at low nutrition level or under the condition of nutritional starvation. Palmlike red (dulse), *Palmaria mollis*, showed a different ability in absorbing abalone ammonia under different seasons, light conditions or different nutrient concentrations. In summer, the ammonia absorption rate was 17.4 and 31.3 mol TAN/g•d under darkness and 24-h irradiance, respectively. After the addition of nutrients, the ammonia absorption rate was 19.8 and 24.2 mol TAN/g•d under darkness and 24-h irradiance, respectively (Gao Aigen, 2005). The ammonia removal efficiency of the seaweed U. Lactuca varied in a day as the ammonia removal efficiency reached 96% at noon and dropped to 42% at night.

The nitrogen and phosphorus absorption capacity of seaweed is related to the ratio of N/P, temperature and intensity of irradiance. According to Xu et al. (2011), the nitrogen and phosphorus removal efficiency of kelp were 42%, 46%, 44% and 45%, 42%, 35%, respectively, under three different initial N/P ratio. Kelp showed maximum nutrient removal efficiency when N/P is 7.4. Temperature and irradiance intensity also significantly influenced nutrient absorption efficiency of kelp. N absorption efficiency reached the maximum value when temperature was 10°C and the irradiance intensity was μmol /m^2•s, while P absorption efficiency reached the maximum value when temperature was 15°C and irradiance intensity was 144 μmol/m^2•s.

3.3.5.2 Matter circle in IMTA of fish, shellfish, and seaweed

In the fish-shellfish-seaweed IMTA, seaweeds can absorb and transform the inorganic nutrients excreted by fish and shellfish, in the meantime providing oxygen for them. Bivalves can filter-feed suspended particulate matter composed of feces, residual diet and phytoplankton. In these IMTA systems, the size of particulate matter is essential in deciding the filter-feeding efficiency of shellfish and other kinds of filter-feeders. The Pacific oyster can filter-feed particulate matter less than 541 μm in diameter. Recently, the contribution of fish residue and feces to the food source of the Pacific oysters was measured by comparison between the fish-cage and non-fish-cage areas. For oysters, the conversion efficiency of organic debris generated by fish farming was about 54.4% (10.3% of them are residual deed and 44.1% are feces). The proportion of particulate escaped from the fish culture cage that was filter-fed by oyster was about 41.6%, and the oyster can assimilate 22.6% of the particulate organic matter. Bivalves play the role of circulating promoters in the system, which can not only reduce the pollution of aquaculture, but also create extra income for farmers. However, in order to achieve maximum cleaning effect, it is necessary to collocate sedimentary feeding species to the system such as sea urchin, sea worm, etc.

3.3.6 Site selection and eco-environmental conditions

The selection of cage farming sites should fully consider environmental conditions, water quality requirements, safety of cage facilities, and adaptability of farmed fish. Before determining the farming sites, the rough selection, the hydrological environment of the potential sites, and the local socioeconomic and ecological survey should be conducted.

Based on a comprehensive evaluation of the safety of cage facilities, adaptability of farmed fish, economical practicality of cage farming and planning rationality, combining the selection of types of cages and aquaculture species, the pros and cons of the potential sites will be analyzed. The target sites shall be determined after balancing these key factors.

3.3.6.1 Environmental conditions requirements

Flow condition: Flow condition is one of the key environmental factors affecting fish cage farming. The flow rate plays an extremely important role in the growth of fish. The unimpeded waterflow not only brings fresh seawater to the fish, but also takes away the residual feed and excrement of the fish. Therefore, the sites required by the fish cage farming require a proper level of flow rate to reduce self-pollution, improve water quality, and improve commercial quality of farming species. However, the flow rate should not be too strong to prevent damage to the breeding facilities and fish, which reduce aquaculture efficiency and output. The upper limit of the maximum flow rate in the farming sites mainly depends on the type of cages. For cylindrical cages and floating rope cages, the maximum flow rate in the potential sites should not exceed 0.8 m/s for the cultivation to be carried out directly. When the maximum flow rate is between 0.8-1.1 m/s, a simple diversion facility is required. If the maximum flow rate exceeds 1.1 m/s, diversion and detention facilities should be constructed so that the flow rate can be less than 0.8 m/s before cultivation. For metal cages and dish-shaped cages, the maximum flow rate in the farming sites should not exceed 1.1 m/s for cultivation to be carried out directly. When the maximum flow rate exceeds 1.1 m/s, a diversion and detention facility should be constructed so that the flow rate is less than 1.1 m/s.

Depth of water: Depth of water is also one of the key environmental factors affecting fish cage farming. The depth of water required for fish cage farming is generally 15 m to 25 m. The minimum distance from the bottom of the cage to the seabed must not be less than 5 m. This not only ensures that the cage net clothing will not be damaged under rough conditions, but is also conducive to the smooth discharge of the residual feed and excrement from the cage, reducing the impact of cage culture on the environment.

Avoiding winds: The fish cage framing sites need to have proper shelter conditions and avoid strong winds, protecting the cages from being damaged by strong winds, storm surges (especially typhoons), etc. The maximum wave height in the farming site should be less than 6 m. For sites with strong waves, it is recommended to use wave breakwaters (Sheng Zuyin et al., 2001) to effectively improve the conditions for cage aquaculture and wide farming areas.

Seabed sediment: For farming cages that require feeding, uneaten feed, feces and excrement of the cultured fish may enter the body of water and deposit on the bottom of the water and become sediment. The indicators of sulfide and organic carbon in the sediments of the farming area should be within the normal range (GB 3097-1997). Different seabed conditions have different abilities to adsorb and release sediments. Sandy sediments are the fastest to release pollutants while muddy sediments are the slowest. The flat, broad and sandy bottom is most suitable for fish cage farming.

Other conditions: Other conditions required for fish cage farming include convenient transportation, complete facilities, and unimpeded information, cold storage, electric power and water supply, convenience for seedlings, storage and transportation of feed, and sales of farmed fish. A reasonable aquaculture capacity should be calculated based on water quality, water flow, etc. in order to avoid water pollution inside and outside the cages due to the overlarge scale of the cages and their excessive density. The variety and quantity of plankton should be moderate as excessive plankton will result in biofouling to the net clothes and increase aquaculture cost. Low density of plankton will reduce the natural food source. In addition, no major sources of pollution should be near the farming area and avoid areas that deal with marine dumping, chemical, and processing plants.

3.3.6.2 Water quality requirements of fish cage farming area

The site selection of fish cages farming area also requires water quality surveys and assessments. A detailed analysis of the water quality was conducted to assess whether the water quality of the sea area complied with the national aquaculture water quality standards, whether there were no hidden pollution hazards and specific diseases, and whether it was suitable for placing seawater cages according to the data obtained from the test report or survey. The main water quality indicators in the farming area should not exceed the safety concentration required for fish culture and meet the Sea Water Quality Standard (GB 3097-1997).

Water temperature: There are certain differences in the adaptation range of different fish species to water temperature. For example, the suitable water temperature for cold water fish is 8-20°C, and the suitable water temperature for warm water fish is 15-32°C. Water temperature is directly related to the growth rate of cultured fish and survival of fish in the winter. Therefore, the water temperature should be considered when setting the cage. If the water temperature varied during cultivation, the blood and tissue components of the farmed fish will change, and the respiration and heart rate will also change, resulting in growth rate reduction. In addition, the effort spent on allowing fish to stay in suitable water temperature, like overwintering in southern warm waters and over-summering in northern cool waters will increase the additional cost.

Salinity: Salinity is one of the important environmental factors affecting the growth of fish. There are certain differences in the adaptation range of fish species to salinity. For example, salinity-insusceptible fish is suitable for salinity 10-30 psu, salinity susceptible fish is only suitable for salinity 20-30 psu. Salinity changes can result in osmotic adjustment disorder of stresses, and accordingly, affecting the physiological, growth, and immune function of farmed fish. Therefore, the salinity of the farming area should be relatively stable and select the appropriate fish species. In order to reduce the influence of various factors on seawater salinity fluctuations, farming area should be far from the coastline and avoid the entrance of nearby rivers.

Dissolved Oxygen (DO): Minimum DO level required in the surface and subsurface seawater is 5 mg/L (GB 3097-1997), but DO level is not as high as possible. Both low level and extreme high level of DO can affect the growth rate of fish, survival rate and food conversion efficiency. Fish species, size, water temperature, stocking density, and culture methods can all affect the lowest DO levels requirement. In the farming process, DO reduction often causes the stress response of fish. When the fish is under stress, the body produces stress hormones, changes in blood and tissue composition, changes in respiration and heart rate, reduction or even ceasing feeding, followed by reduced body immunity, susceptibility to infection of diseases and parasites, reduced growth rates, and increased mortality. As an open system, cages are affected by factors such as temperature, salinity, algal activity, water exchange rate, and oxygen consumption of fish populations. The risk of lack of critical DO in seawater is mainly related to the excessive stocking density and high temperature. In the farming process, air pump or flow generator can be used to improve and ensure the seawater DO in cage culture area.

Chemical oxygen demand (COD): COD is one of the main factors for evaluating seawater pollution level. Although the pollutant degradation capacity of the ocean is very strong, it is also limited. The COD content in the aquaculture sea area must meet the first-grade seawater quality standard (not more than 2 mg/L), and the local sea area COD content must meet the second-grade seawater quality standard (not more than 3 mg/L) (GB 3097-1997). If the COD content in the aquaculture area exceeds the standard, the water quality will gradually deteriorate, which will seriously affect the efficiency of cage culture. In natural environments, seawater flow and light, etc., can speed up the degradation of COD. Adding shellfish and seaweed to the farming area can also be used for pollution removal by taking advantage of physiology complement between animal and plant. These seaweeds can absorb large amounts of N and P, remove pollutants, and reduce COD content, which enable fish cage farming environment to be able to self-purify and coordinate.

Inorganic nitrogen and phosphate: Red tide is one of the global oceanic hazards, and red tides often cause severe deaths to farmed fish in cages. The abundant inorganic nitrogen (IN) and phosphate (PO_4-P) in seawater can provide the nutritional basis for the occurrence of red tide, especially the amount of P content, which is the main factor that restricts the occurrence of red tide. Poor management of inorganic nutrient may cause red tide and finally affects the growth and increasing mortality of fish. The IN and PO_4-P contents in the farming area must meet the Class II seawater quality standard (GB 3097-1997). The culture area should be located in areas where the frequency of red tide blooming is very low. Once red tide blooms, cages must be placed into deeper water immediately to avoid the damage caused by red tide blooming and reduce farmed fish mortality. Farming sites should be located in areas where the concentration of $IN \leq 300 \mu g/L$ and PO_4-$P \leq 30 \mu g /L$.

Heavy metals: Heavy metals such as mercury, cadmium, lead, chromium, arsenic, copper, zinc, selenium, and nickel can affect the respiration and metabolism of farmed fish when the concentration of these heavy metals in seawater exceed a certain level. When the concentration seriously exceeds the safety level, it will surely cause mortality to the farmed fish. As a result, the content of all kinds of heavy metals in the farming areas should comply with Class I or II seawater quality standard (GB 3097-1997).

3.3.6.3 The security of cage facility

In order to further explore the areas suitable for fish cage farming and create an ideal environment for the healthy growth of farmed fish, sea cages can be installed in open waters with deeper depth and stronger waves. At the same time, seawater cage facilities installed in these waters will face more complex challenges, especially the strong winds and wave resistance ability.

The strong winds and wave resistance ability depends not only on the performance of cage facilities themselves (such as the rationality design of the structure, the durability of the netting materials, and the impact resistance of the cage frame), but also on the sea cages anchored to the sea area. Due to the adaptability of sediment and hydrometeorological characteristics, the mooring system has a great influence on the anti-wind capacity of the cage. Therefore, before determining the location of the seawater cage, the environment of potential farming area must be investigated and comprehensively analyzed. In order to ensure the long-term safety of the cage facilities during the entire aquaculture production period, the type and setup scheme of the fish cages must be determined according to their environmental characteristics.

The main environmental factors that affect the safety of cage facilities include water depth, submarine conditions, and historical variations of hydrological and meteorological environments. In particular, the water depth at the potential sites (including the average tidal range and the extreme tidal range), the type and thickness of the bottom layer should be known, and the wind, waves, average wave height, maximum wave height that dominate the area should be also be considered. The average flow velocity and the maximum flow velocity at the peak of the astronomical tide, possibility of typhoons happening and red tides blooming should also be known.

3.3.6.4 The adaptation of farming fish to cage farming

Each kind of cage farming fish requires its specific environment, including water temperature, salinity, and DO in the farming area. Therefore, the safety of the facilities and the adaptability of the farmed fish to the farming environment should be considered. This way, the natural water conditions in the selected area will be kept within the proper range required by the healthy growth of the farmed fishes.

The aquaculture environment, especially the water quality, has great influence on the growth of farmed fish. Therefore, before site selection, historical information should be collected and the important environmental factors monitored for a relatively long time to ensure the accuracy and stability of the data. For nearshore waters, attention should be paid to the potential sources of pollution and the influence of variation to salinity within the potential farming area where there is freshwater inflow and pollutant discharge. Recently, due to the substantial increase in frequency and blooming areas of red tide caused by eutrophication, the influence of red tide should also become a matter that requires close attention. At the same time, avoiding the farming environment from self-pollution should also be paid close attention in the overall design of the fish cage aquaculture industry. Proper localization and distribution of fish cages should consider the flow velocity, flow direction and the direction of dominant wind and other factors. In addition, the quantity and species of organisms that inhabit the farming area should also be investigated to evaluate self-purification ability of residual feed and fish feces.

3.3.7 Patterns of IMTA for Fish, Shellfish and Seaweed

Excess nitrogen is the main factor causing eutrophication in Xiangshan Bay (Jiang et al. 2010). In most cases, nitrogen is the most important excrement of cultured fish, ammonia nitrogen accounts for 80-98% of total nitrogen. The bioremediation patterns of cage culture based on seaweed in different sea areas were established according to the content of nitrogen (N) in dry tissue of seaweed. The content of N in dry tissue of seaweed varied greatly in different seasons and different years. The value used in this paper were the measured data from 2006 to 2010 in field.

According to seaweed kelp and *Gracilaria* growth in different seasons, alternate culture of the two species is taken to remove excess nitrogen from cage culture. Furthermore, kelp *Saccharina japonica* were cultured in summer and autumn (May-October), and *G. lemaneiformis* were cultured in winter and spring (November-May).

3.3.7.1 Bioremediation by kelp cultivation in lower temperature season

Nitrogen emissions from the fish-cage is 7.43 tons in winter and spring in Nansha Island, which is the main cage farming area in Xiangshan Bay. The nitrogen in the residual diet and feces are calculated as 1.6 times as excretion of nitrogen and ammonia nitrogen, regardless of death of sea bass *L. japonicus* and large yellow croaker *P. crocea*, the total nitrogen excrement from fish-cage farming in winter and spring are 19.32 tons. The nitrogen content is approximately 2.79% (n>100) in dry kelp tissue of Nansha Island, and the water content is about 90%. The nitrogen from fish's excretion can provide biomass of kelp of about 6,924.6 tons. The fresh production of farming kelp has an average of 56 t/hectare in Nansha Island, therefore, the kelp farming areas need to be about 123.7 ha to remove the nitrogen excrement from fish in nitrogen balance strategy. In other words, in order to balance the nitrogen coming from fish-cage cultivation, the ratio of number of cages and kelp cultivation areas should reach 1 (number) to 0.3 (hectare), which means that cultivation of 1 kg fish needs 6.3 kg kelp to keep nitrogen balanced.

3.3.7.2 Bioremediation by *Gracilaria lemaneiformis* cultivation in higher temperature season

The total nitrogen load of cage fish farming is 63.8 tons in summer and autumn (higher temperature season). The nitrogen content is 3.42% in dry tissue of *G. lemaneiformis*. The nitrogen from fishes in higher temperature season can provide biomass of the species of about 18,664 tons. The fresh production of farming *Gracilaria* is averaged at 30 t/hectare in Nansha Island as it takes 311.1 ha of the seaweed to balance the nitrogen from fish farming. In higher temperature periods, one fish cage needs 0.08 hectares of seaweed farming area to remove the nitrogen, which means 8.4 kg of G. lemaneiformis should be cultivated to uptake nitrogen excreted by 1 kg of fish.
In Sanggou Bay, average nitrogen content are 2.26% of dry kelp tissue from February to August, and 3.34% dry tissue of *G. lemaneiformis* from April to November. The ratio of dry and wet of kelp and *G. lemaneiformis* are about 0.14 and 0.125, respectively.

The main cultured fish species in Sanggou Bay are sea bass *L. japonicus* and *Sebastes schlegelii* with a farming proportion of about 1:1. Each large cage (net area is about 200 m^2, accounting for 1,600 m^2 of water area) contains about 20,000 individual sea basses (≤500g). The ammonia excrement is about 25.5 mg/ind•d of every sea bass

(443 g of average wet weight) per day. In 300 days of cultivation period, the excrement nitrogen is 114.5 kg of each fish, and the nitrogen content in residual diet and feces is 183.2 kg. The yield of each cage is about 10,000 kg, and the total annual nitrogen from farming fish is 297.7 kg in each fish-cage. The average yield of kelp is 8.4 kg/m^2 in the fish farming area in Sanggou Bay, nitrogen from fish farming can supply for 1.1 ha cultivation of kelp or 1.7 ha cultivation of *G. lemaneiformis* (4.1 kg fresh weight/m^2). To remove the nitrogen coming from per kilogram of fish production, 9.2 kg of kelp or 7.1 kg of *G. lemaneiformis* need to be cultivated.

3.3.8 Analysis of Economic and Ecological Benefits

In the late 1950s in China, studies on aquaculture of marine fishes mainly focused on Mugilidae species, including sea bass *L. japonicus*, mullet *Liza haematocheila*, greenling *Hexagrammos otakii*, sea bream, puffer, and right-eyed flounders. Since the 1980s, fish cage-culture has been carried out. In the past 20 years, cage culture has rapidly developed into a new pillar marine aquaculture industry in China. The rapid expansion of floating cage culture in coastal area has increased the employment rate and produced more aquatic products. However, due to the lack of unified management plans, the economic benefits were firstly considered in most cases, which led to the high density of fish cage-culture and shrimp farming in the coastal area, resulting in a phenomenon of exceeding the aquaculture carrying capacity and the poor water quality. All these problems have threatened the sustainable development of aquaculture in China.

Fish farming could produce a large amount of waste, including dissolved inorganic nitrogen and phosphorus. An IMTA model of macroalgae *G. lemaneiformis* and black rockfish *Sebastes schulegelii* was established, which greatly reduced the risk of water eutrophication. Laboratory studies showed that the macroalgae *G. lemaneiformis* could remove most of the nutrients in the integrated culture system as an efficient nutrient pump. The ammonia concentration in water decreased from 85.5% to 69.5% after 23 days of culture, and the inorganic phosphorus concentration decreased from 66.0 % to 26.7% after 40 days of culture. Field experiments showed that the growth rate of *G. lemaneiformis* was 11.0% per day and the carbon, nitrogen and phosphorus contents were higher than the control area, with values 28.9%, 4.17% and 0.33%, respectively. The nitrogen and phosphorus uptake rates of *G. lemaneiformis* were 10.6 and 0.38 $\mu mol \bullet g^{-1}$, respectively. The experimental results showed that *G. lemaneiformis* was a potential species of removing excess nutrients in the coastal waters. It seemed that large-scale cultivation of seaweed could effectively control the eutrophication in Chinese coastal areas. The integrated farming mode has brought about sustainable economic developments and environmental benefits for the northern coasts during high temperature season.

In northern China, the pond-based integrated farming system with shrimp *Fenneropenaeus chinensis*, tilapia *Oreochromis spp* and razor clam *Sinonovacula constricta* can significantly increase economic and ecological benefits. The total nitrogen conversion efficiency entered in the system was 23.4% and the phosphorus was 14.7%. The large amount of organic matter in the shrimp pond comes from feeding, fertilizing or indirect primary production. Some are directly dissolved or suspended in water, and some are deposited in the bottom of the pond. Most of the organic matter is wasted in the post-cultivation stage of the monoculture system because shrimp cannot feed on these organisms directly. Mixed-feeding system of filter-feeding fish, molluscs and shrimp not only increases the species diversity of the pond ecosystem and makes full use of the living space, but also increases the utilization of the above-mentioned organic materials, thereby, increasing the conversion rate of the input diet. Current studies indicated that the total conversion rates of nitrogen and phosphorus in the polyculture system increased by an average of 57.0% and 110.1% compared with monocultured shrimp system. The results of this study indicated that closed polyculture system do not only improve efficiency of shrimp aquaculture, but also reduce coastal water pollution caused by pond wastewater. Therefore, it may be an economic alternative to sustainable shrimp farming (Tian et al. 2001).

This kind of farming system is comprised of four areas: one shrimp-fish-shellfish-algae cultivating area; one microbe and microalgae breeding area; one water treatment area; and one emergency drainage canal. The biological regulation of water quality is achieved by establishing an ecological niche complementation polyculture with shrimp, tilapia, oyster, and *Gracilaria* in a closed circulation system. The results indicated that the contents of suspensions, COD value, amounts of ammoniated nitrogen and total nitrogen in the recirculating aeration system were lower than those in monoculture control ponds. The final discharged wastewater was no longer eutrophicated, and 1 kg of feed was converted to 0.667 kg shrimp, 0.037 kg tilapia, 0.738 kg oyster and 0.437 kg *Gracilaria*. The input-output ratio of monoculture and polyculture shrimp significantly decreased from 0.671 to 0.235. The use of this model not only carries out self-repair of culture environment and zero discharge of aquaculture sewage, but can also increase feed conversion rate and enhance the resistance of the disease capacity. The economic benefits are remarkable, and it has advantages of environmental protection and high efficiency (Tian et al. 2001).

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3.5 Practice of Land-based Integrated Multi-Trophic Recirculating Aquaculture Model (L-IMTRA)

3.5.1 Foreword

During the Global Fisheries Executive Conference held in 2006, the Food and Agriculture Organization (FAO) pointed out that the consumption of marine products would greatly increase under the background of rapid global population growth. Traditional fishery, however, has reached its maximum output level. The only way to meet the demands for aquatic products would be to develop aquaculture. Known as "the green revolution", aquaculture draws attention from all over the world as an important means to ease the pressure on food demand and to avoid the overexploitation of marine fishery resources.

Chinese aquaculture has developed rapidly, becoming the largest global aquatic producer for decades. However, factors restricting aquaculture and problems of traditional aquaculture model have become increasingly noticeable.

3.5.1.1 The culture carrying capacity close to ecological limit.

The traditional seawater pond farming and commercial aquaculture mostly require sufficient water exchange which largely depends on an external seawater supply. Seawater pollution greatly affects mariculture as pollutants accumulated in the aquatic products would cause quality decline.

3.5.1.2 Untreated discharged water exacerbates marine pollution.

According to the Global Environment Outlook Yearbook, farmed *Penaeus vannamei* Boone can only absorb about 22% nitrogen from the artificial formulated diet, which is a fairly low rate. Meanwhile, the nitrogen utilization rates of shellfish and fish are both under 40%. Direct aquaculture wastewater discharge will cause eutrophication, coastal pollution, and destruction of available cultivation water sources.

3.5.1.3 Large-scale intensive culture industry is likely to cause disease outbreaks.

The culture area of several major species in China, such as *Penaeus vannamei* Boone, abalone and scallops, have already occupied as much as tens of thousands of hectares in some regions. When cultured organisms exceed the local environmental capacity, it is likely to lead to large-scale disease outbreaks and considerable losses.

3.5.1.4 Available aquaculture space is shrinking.

With social and economic development, the competition of land usage between the aquatic and other industries becomes prominent in many areas. Local government intends to consider that aquaculture has generally low efficiency in land use, poor level of taxation, and weak absorptive capacity of labors. As a result, many culture regions are facing the function zoning adjustment, and tightening culture land has become an inevitable obstacle to the aquaculture development. Thus, establishing an ecological recirculating aquaculture model is imminent.

3.5.2 The main culture/planting organisms in land-based IMTA

3.5.2.1 Culture species

White shrimp Penaeus vannamei

White shrimp (*Penaeus vannamei*) belong to *Arthropoda, Crustaceans, Malacostraca, Dendrobranchiata, Penaeidae, Litopenaeus*. White shrimp are naturally distributed along the coastal areas of central and South America. Adult shrimp live in the relatively high salinity coastal waters, and newly hatched larvae live in low salinity (4-30%) regions such as estuaries or coastal lagoons.

White shrimp have a high level of adaptability as their natural habitat depth ranges from 0-72 m, and the salinity tolerance is 0.5-35%. For 2-7 cm larval shrimp, the allowed salinity range is 2-78%, and the corresponding survival water temperature range is 6-40°C. The growth temperature for the shrimp is 15-38°C, and the optimum is between 22-35°C. White shrimp can survive in high temperature (43.5°C), but their tolerance for low temperature is poor. Once the water temperature is less than 18°C, the feeding efficiency goes down. To culture white shrimp, the minimum dissolved oxygen level is 1.2 mg/L usually should be higher than 5 mg/L; The optimum pH is between 7.0-8.5, ammonia nitrogen concentration should be low in culture water. Most white shrimps can survive after long-distance transportation.

White shrimp have the advantages of growing to a large size, rapid growth, low nutritional requirements and strong disease resistance. It has strong adaptability to changes in water environment, low requirements for feed protein content, high meat output rate of more than 65%, and can also survive a long time without water. Such characteristics make them an appropriate species for intensive culture. Therefore, the land-based integrated farming system (IMTA) selects the shrimp as a main cultivation species.

Other species

Culture species could be chosen according to differences in local geography, climate and market preference. Generally, culture species should be suitable for intensive aquaculture with high economic value, e.g., turbot, grouper, black porgy, and gray mullet.

3.5.2.2 Biological purification species (Biofilters)

Bivalves

Bivalves are one of the most diverse and valuable phylum Mollusca class, and they are known for removing excess phytoplankton from water. Commonly cultured bivalves include *Tegillarca granosa, Cyclina sinensis, Meretrix Meretrix, Sinonovacula constricta, Ruditapes philippinarum*, which have high economic value and water purification ability.

Mangroves

Mangroves are the principal part of the mangrove wetland system. Mangroves grow in tropical and subtropical coast intertidal zones. There are 16 genera and 120 species such as *Rhizophora, Bruguiera, Kandelia, Ceriops*. According to previous studies, the mangrove wetland system has a rich biological resource and is one the most diverse ecosystems. Mangroves can be imported as an important purification of functional group part in IMTA.

Halophytes

Halophytes refer to the plant that can grow in saline land and accumulate salt. There are two types of halophytes, one can increase the moisture content of the body, making the stem leaf succulent to balance salt content, such as *Juncus roemerianus, Salicornia*; the other one can regulate the salt content by secreting, such as *Tamarix chinensis, Spartina anglica*. These plants can be used by soil cultivation or floating island in land-based integrated farming system (IMTA) to absorb Nitrogen and Phosphorus.

3.5.3 The Establishment of L-IMTRA

3.5.3.1 Design Concepts

Based on the Niche Complementarity Theory, L-IMTRA uses aquatic species of different trophic levels to build an ecological recirculating culture pattern, and to achieve the recirculating, efficient, ecological, safe, and energy-saving purposes by optimizing the carrying capacity and regulatory measures of the system.

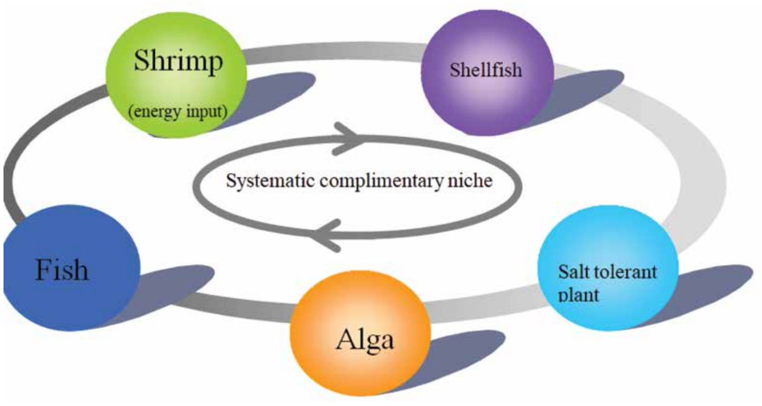


Figure 3-4 The sketch map of L-IMTRA.
(Zhejiang Mariculture Research Institute)

3.5.3.2 System composition

The construction site of L-IMTRA is located in Yongxing station at the Institute of Marine Aquaculture in Zhejiang Province. The system covers an area of 276 mu (18.4 hectares), mainly composed of five functional areas and two supporting systems. Five functional areas are high-position intensive area, larvae breeding area, shellfish culture area, artificial wetland area and ecological purifying area. Two supporting systems are the circulating canal and on-line water quality monitoring system. The specific composition and the plan view are shown in Figures 3.5 and 3.6.

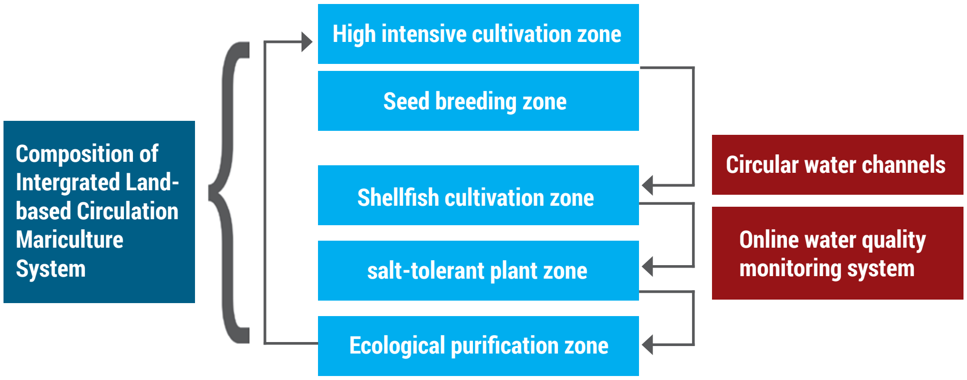


Figure 3-5 The composition of L-IMTRA. (Zhejiang Mariculture Research Institute)

Figure 3-6 The plan view of L-IMTRA. (Zhejiang Mariculture Research Institute)

水质在线监测中心: on-line water quality monitoring center; 苗种繁育区: larvae breeding area; 高位静养区: high-position intensive area; 植物栽种区: plant area; 贝类养殖区: shellfish farming area; 生态净化区: ecological purifying area; 温室: greenhouse; 辅助用房: subsidiary room; 露天高位精养池: open high-position intensive pond; 植物性饲料培养室: vegetable feed culture room; 养殖试验塘: aquaculture experimental pond; 海水蔬菜适种区: marine vegetable suitable area; 水质生态净化塘: water purification pond; 暗沉淀处理池: dark sedimentation treatment pond

High-position intensive area

High-position intensive culture area covers an area of about 1.67 hectares and is divided into D and F Districts. D District has 7 high pools, each measure 750 m^2; F District has 10 high pools, each measure 1000 m^2. High pools are oval concrete ponds with a depth of 2-2.5 m, gradually deepening from peripheries to the center. There is an insulated steel roof, a pot-type bottom, and an outfall in the middle connected with two separate circulation drains. Discharged culture water particles can enter either through the discharged-water treatment system or shellfish farming ponds according to organic content concentration.

Figure 3-7 High-position intensive Pond. (Zhejiang Mariculture Research Institute)

High-position intensive area is mainly used for intensive farm of *Penaeus vannamei* for 2-3 crops a year with an average yield of 20,000-30,000 kg/ha per crop and an average value of 1-1.5 million yuan/ha. The biological control techniques, microbial water quality control technology, bottom aeration technology and other farming techniques are applied to improve the success rate of shrimp culture and reduce the effluent discharge. Discharged water from shrimp culture mainly flows into shellfish farming areas through the circulation canals, and some with high concentrated particles are recycled after the treatment of discharged water systems. High-position intensive area is the major input area of material and energy in L-IMTRA.

Figure 3-8 Farming of *Penaeus vannamei* in high-position intensive pond. (Zhejiang Mariculture Research Institute)

Larvae Breeding Area

There are seven greenhouses in the larvae breeding area, surrounded by brick structures and shed by a steel roof. There are 260 concrete ponds of different sizes inside seven greenhouses, with a total of about 10,000 m^2 of water nursery. The water input and drainage are smooth; facilities such as water supply, electricity and heating supply are well-equipped. It is suitable for shellfish larvae breeding, *Penaeus vannamei* Boone breeding and algae cultivation.

Figure 3-9
Larvae breeding area. (Quoted from Zhejiang Mariculture Research Institute)

Seed breeding zones are mainly used to culture bivalves and white shrimp. Bivalve cultivating process includes fortified affinity, reproductive regulation, artificial oxytocin, planktonic larval breeding and temporary rear Due to similarities among different bivalves in reproductive biology, one method can be applied to the breeding of different shellfish. According to market demand and shellfish biology characteristics, the choice of cultured shellfish is flexible.

Presently, the major culture species are mud cockle, green clam, clam and Philippine clam. The annual yield of shellfish seedlings in a land-based circulating water system is about 80-10 billion individuals, with a value about RMB 3 million. The annual yield of larval shrimp is about 200 million individuals, which also worth about RMB 3 million. In addition, shellfish larvae during attachment period can be directly fed by water from shrimp culture ponds.

Figure 3-10 Larvae breeding of shrimp and shellfish.
(Zhejiang Mariculture Research Institute)

Juvenile shellfish feeding on shrimp pond water

Microalgae are the primary producers in shrimp ponds and absorb ammonia nitrogen and nitrite nitrogen that increase water quality. They also can be used as natural bait for shrimps. Phytoplankton species is diverse (more than 40). According to reports in different periods of different types of aquaculture pond, especially in the early stage, diatoms and green algae accounted for over 50% of the total biomass. Shellfish larva in floating stage, due to the limitation of mouthparts and predation ability, can only feed on directional cultivating single-cell algae. However, in the late stage, increasing waste leads to low transparency, which reduce algae quality. Therefore, discharged water can be screened by a 100-mesh sieve, and then directly used for shellfish seedling cultivation, which greatly saves resources and reduce the waste water discharge.

发明专利证书

Figure 3-11 Seawater concentrator.
(Zhejiang Mariculture Research Institute)

Reverse desalting system (RO desalination equipment)

Due to the different demands of shellfish and shrimp on salinity limitations, reverse desalting system can be used in land-based IMTA system to adjust the salinity conditions.

Reverse desalting system generates high salinity water by using RO desalination equipment and estuaries water. According to the original water concentration and output rate, the output is about 10 m^3/h-23 m^3/h, the corresponding energy consumption is lower than 0.9 KW h/m^3. Reverse desalting system with low energy consumption and high efficiency is patented.

Shellfish culture area

Covering a total area of 1.33 ha, shellfish culture area has six culture ponds altogether. The ponds are built as conventional earthen ponds with sandy bottom and 2/3 of the middle area is farming region, surrounded by a ditch, with a bottom aeration system to increase culture capacity. The main culture species are cockle clam *Tegillarca granosa*, blood clam *Anadara subcrenata*, clam *Cyclina sinensis* and hard-shell clam *Mercenaria mercenaria*. Mullet, large yellow croaker, *Siganus oramin* and other species are cultured in the surrounding area separated by nets in order to improve the economic efficiency and the purifying ability of the pond. The annual output of large-sized shellfish is 50-100 tons in the shellfish culture area.

The water discharged from the shrimp high-position pond contains large amounts of phytoplankton, food debris, shrimp manure and other organic particles which are food source for filter-feeding shellfish. Thus, when the shrimp culture water is discharged into the shellfish farming ponds through the circulating canal, phytoplankton and most debris can be directly absorbed by shellfish. The remaining part will be broken down into small organic and nutrient particles by microorganisms and phytoplankton, and then absorbed by shellfish.

Figure 3-12 Aquaculture products in the shellfish farming area.
(Zhejiang Mariculture Research Institute)

Figure 3-13 Suaeda and Salicornia planted around the aquaculture pond.
(Zhejiang Mariculture Research Institute)

Artificial wetland area

The artificial wetland system is one of the northernmost mangrove wetlands in China, covering an area of one hectare. Mangroves, mostly *kandelia candel* and a small amount of *Aegiceras corniculatum*, are planted in the wetland, and semi-mangroves (*Bruguiear gymnorrhiza, Cerbera,* vetiver, etc.) are planted on the bank. Mudskipper is raised in the mangrove wetlands to increase the substrate permeability of the mangrove areas. In addition, mudskippers can also improve the economic output of the system as an expensive aquatic product.

Water through the shellfish culture area flows into one end of the mangrove wetlands, and then flows out of the other end through the circulation canal and the extracting pump into the ecological purifying area. Microorganisms, mangroves and substrate are three key elements to the functioning of wetlands. They are able to effectively remove the organic precipitate, ammonia and phosphorus, play a role as an important purification function group in the L-IMTRA, and also a habitat for wetland animals.

Figure 3-14 Mangrove wetland area.
(Zhejiang Mariculture Research Institute)

Ecological purifying area

It is composed of two ecological purifying ponds, namely C1 and C2, covering a total area of 3.4 ha and a depth of 4 m, with mullet, large yellow croaker and *Siganus oramin* cultivated in the ponds. A marine vegetable artificial floating island is built in C1 pond, used as a dark precipitate for shading. It is also used to remove nutrients in the water through absorption by plant roots. Through culture animals of multiple trophic levels such as benthic filter-feeding shellfish, omnivorous fish and carnivorous fish, they build a stable ecosystem, enable ecological purification, and also act as reservoirs in the entire L-IMTRA system.

Figure 3-15 Ecological purifying pond
(Quoted from Zhejiang Mariculture Research Institute)

Supporting systems

Shrimp culture discharged water treatment system

The water discharged in the process of shrimp aquaculture is circulated in the system and recycled through purification. However, if the discharged water exceeds the purification capacity of the system, there is a risk of systematic collapse. Since the particle debris is the major pollutant in the water discharged from shrimp culture, a shrimp discharged water treatment system is built to intensively treat it.

The main structure of a discharged water treatment system is comprised of 4 sedimentation tanks of $63m^2 \times 4 = 252m^2$, and a bio-fermentation tank covering an area of 10 m^2. Biological stuffing is hanged inside the discharged water sedimentation tank. At the bottom of each tank, there is a pipe connected with the bio-fermentation tank. There is a high outfall and a low outfall in the high-position intensive pond. During the pollution discharge, the aggregated particles of debris in the intensive pond are drained from the low outfall to the discharged water treatment pool. After the processes of filtration, sedimentation, oxidation and biodegradation in the water treatment system, the purified discharged water can be recycled. The deposition sludge is centralized to be processed in the fermentation tank, which can be used as basic fertilizer after the fermentation.

Figure 3-16 The quadrupole tandem farming discharged water sedimentation tank in the discharged water treatment system. (Zhejiang Mariculture Research Institute)

Online water quality monitoring system

In order to improve the accuracy of regulation and processing stability of the overall L-IMTRA system and to accumulate experimental data, an online water quality monitoring system was established, which consists of a water quality-monitoring buoy and a data display terminal. The water quality-monitoring buoy is equipped with four sensors: temperature sensor, pH sensor, salinity (conductivity) and dissolved oxygen sensor. It is capable to measure five parameters: temperature, pH, salinity, conductivity and dissolved oxygen. Water quality data can be checked via mobile terminals through GPRS data transmission. The next step is to achieve real-time control of aerobics and other equipment based on monitoring data and to achieve real-time regulation of water quality.

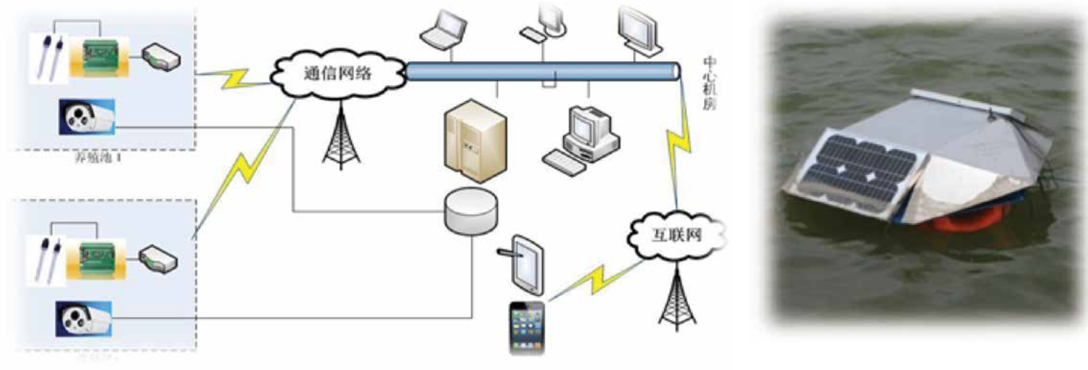


Figure 3-17 Online water quality monitoring system.
(Zhejiang Mariculture Research Institute)

3.5.4 The water circulation of L-IMTRA system

The seawater extracted through pumps from sea area is circulated in the system without external emissions. The aquaculture water discharged from the larvae breeding areas and high-position intensive area flows into each shellfish culture pond through circulating canals. After the removal and precipitation of algae and organic suspended particles (filtered by shellfish), the water flows into the wetland and finally to the ecological purifying ponds after further purification by biological, physical, chemical and other methods. After staying for some time when the zooplankton and algae in the water has been pumped into the sand filter ponds, the water flows back into the greenhouse and high-position intensive area for recycling in the shrimp culture and larvae breeding.

Through the coupling of multi-trophic levels of fish, shrimp, shellfish, algae, etc., L-IMTRA system can maximize the use of matter and energy and obtain economic benefits. Meanwhile, as aquaculture water can be recycled within the system, there is no need to pump in large amount of external waters which reduce the dependence on the external environment and alleviate the ecological impact caused by emissions. The measurement shows that the nutrient level of the aquaculture discharged water flowing back into the high-position intensive pond through circulation and sand filtration is almost equal to that of the introduced water from the sea area, from which one can see the significant purifying effect of this circulation system.

3.5.5 The Benefits of L-IMTRA

3.5.5.1 Economic benefits

Major production species:

- Commercial shellfish: cockle clam *Tegillarca granosa*, blood clam *Anadara subcrenata*, clam *Cyclina sinensis* and hard-shell clam *Mercenaria mercenaria*
- Commercial shrimp: *Penaeus vannamei* Boone
- Coastal beaches shellfish larvae: *Tegillarca granosa*, clam *Cyclina sinensis*, *Sinonovacula constricta, Moerella irideseens* and hard-shell clam *Mercenaria mercenaria*
- *Penaeus vannamei* larvae

Other production species:
Mullet, *Siganus oramin*, *Pseudosciaena crocea*, black porgy, mudskipper, and oyster.

3.5.5.2 Operational effects in 2015

Since the establishment of the L-IMTRA system in 2012, it has been running smoothly for years with significant economic benefits. The following are the economic benefits of the main production species in 2015.

Table 3-2 The benefits of L-IMTRA in 2015.

Species	Production	Production value
Penaeus vannamei Boone (commercial specification)	60 tons	RMB 2.5 million
Commercial shellfish	More than 40 tons	RMB 500,000
Shellfish larvae	5 billion	RMB 600,000
Penaeus vannamei Boone larvae	200 million	RMB 3 million

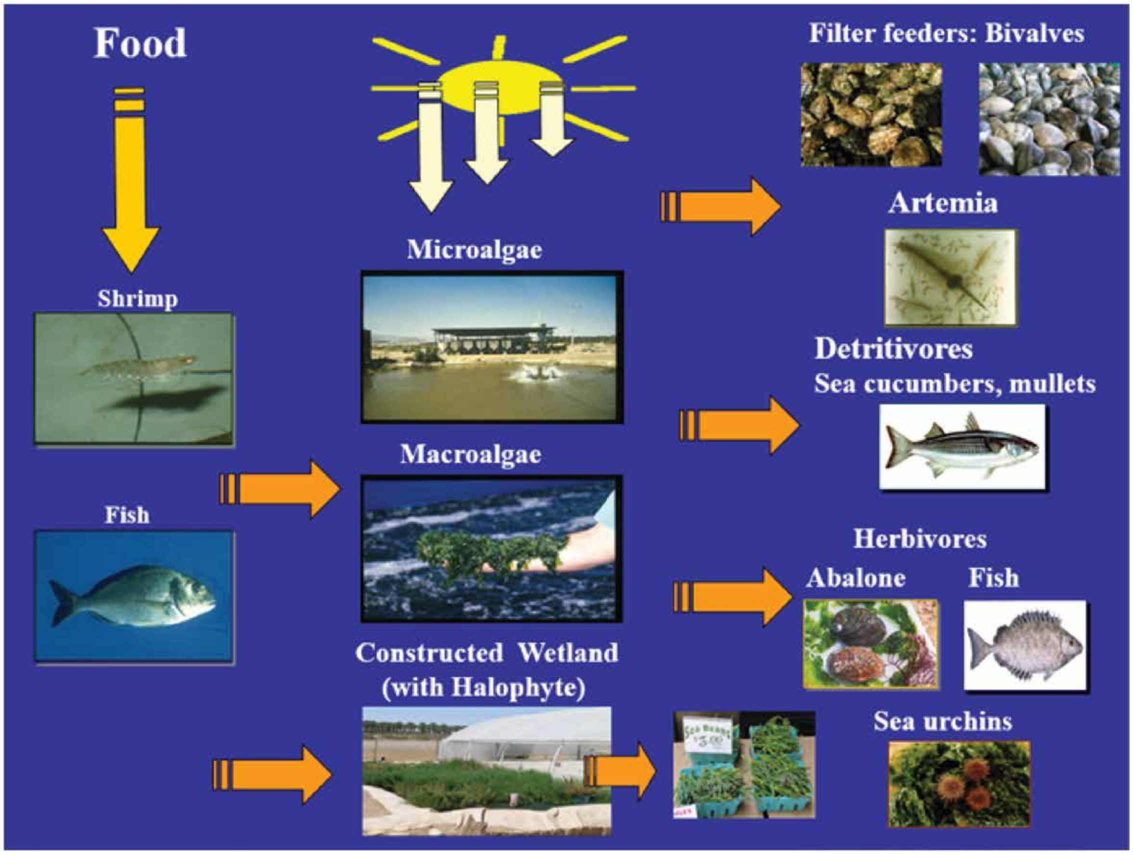
In 2015, the mariculture output value of major species exceeds RMB 6.6 million, with the cost of about 2 million yuan and profits of more than 4.6 million yuan. The total area is 18.4 hectares, therefore, the average production value is about 250,000 yuan/ha.

3.5.6 IMTA progress

Land-based IMTA system was a study by Dr. Muki Shpigel in Israel Oceanographic and Limnological Research, National Center for Mariculture. In the early 1990s, macroalgae, oysters and abalone were used for biological purification, getting rid of the excess nutrients in aquaculture. After several years of development, complete land-based ecological integrated farming system was gradually constructed in Israel, including planktonic algae, macroalgae and halophytes wetland.

Planktonic algae pathway can absorb the redundant N and P, which can also be used as bait to feed zooplankton and shellfish. Debris in water can be eaten by sea cucumber and mullet. Macroalgae pathway can absorb the redundant N and P by using *ulva, gracilaria,* which can also be feed to abalone, sea urchins and herbivorous fish. Halophytes takes advantage of halophyte wetland to purify water. All three pathways have the ability to achieve the maximization of economic and ecological benefits.

Figure 3-18 Israeli land-based IMTA.(Dr. Muki Shpigel)



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3.6 Application of Integrated Multi-tropic Aquaculture in sea ranching

Zhangzidao modern sea ranching area in the North Yellow Sea is 1,600 km^2, of which 20 km^2 inshore is coastal IMTA aquaculture area, 1,580 km^2 offshore is shellfish bottom cultured area. IMTA is a balanced ecosystem; the aquaculture area is cultured with filtered food shellfish, licking food benthic varieties, rot eating varieties and plant species together in seawater. Unlike single aquaculture, this comprehensive farming method takes biological factors, management elements and environmental quality into consideration, aiming at achieving long-term sustainable development. The aim is to improve the long-term sustainability and profitability of each breeding unit, which is not emphasized by single breed method. Shellfish cultured zone offshore mainly sows benthic shellfish seed to the sea bottom according to certain density, natural growth, rotation farming to achieve orderly development of sea ranching.

3.6.1 Biological characteristics and ecological habits of the main aquaculture species in sea ranching ecosystem

3.6.1.1 Japanese Scallop

Figure 3-19 Japanese Scallop
(Source: Zoneco Group Co. Ltd)

The Japanese scallop (Patinopecten yessoensis) belong to *Mollusca*, *mollusc phylum, Lamellibranchia, heteromyarian, Pectinidae, Pecten*. They are cold-water shellfish, distributed in southern waters of Hokkaido, Japan, north of the continent, south of the thousand islands of Russia and North Korea. Since the introduction of China by the Liaoning Marine Fisheries Research Institute in 1982, the scallop has been cultivated in the northern coastal areas such as Shandong and Liaoning Provinces in China because of its larger individual, rich nutrition, and high market value. After nearly 20 years of culture promotion, its farming has been scaled and industrialized in Bohai Sea and Northern Yellow Sea. Nearly 10 years to create billions of Chinese Renminbi (RMB) output value, the scallop has become one of the most important marine culture shellfish in northern China.

The shell of Japanese scallop is big, with maximum shell size up to 20 cm, and the weight can reach 900 g. The right shell is relatively deeper and is yellow and white; the left shell is slightly flat and smaller than the right shell, and is purple brown. The overall shell shape is nearly round. The top of the shell is located in the middle of the dorsal side, and the size of the ears of the front and back sides is equal. The anterior ear of the right shell has a shallow hole in the foot. The surface of the shell has 15-20 ribs. Below the shell top is a triangular ligament, single column. The adductor muscle is strong, located in the rear shell.

Japanese scallops are bred using in-vitro fertilization. The first reproduction age is over two years. The parent shellfish discharges the sperm and eggs into the water where they fertilize and develop. Usually, the male Japanese scallop is sensitive to external stimulus, and the spermatozoon is often preceded by spawning. As the sperm appears in the water, it can also induce spawn of the female scallop. It can spawn several times. The first spawn amount is large, as it can reach 10 to 30 million eggs.

Japanese scallops are filter-feeding shellfish and omnivorous as they feed on small phytoplankton and zooplankton, bacteria and organic debris. The phytoplankton is mainly diatoms, *Chrysophyceae* and other algae. Japanese scallops are not strictly selective in feed properties. Selection generally depends on the size and morphology of plankton and plants. The right size will be easily filtered and eaten. Japanese scallops are cold water shellfish and distributed in the hard sea bottom. The natural distribution seawater depth is at 6-60m. The range of growth temperature is 5-20°C, where 15°C is the most suitable. Growth slows down below 5°C. At 0°C, movement becomes sharp, slows down and eventually stops. When the water temperature rises to 23°C, life ability of Japanese scallops gradually weakens. They stop moving at higher than 25°C. Japanese scallops are a high salt species as the suitable salinity range is from 24-40 psu.

3.6.1.2 Oyster

Figure 3-20 Pacific Oyster (Source: Zoneco Group Co. Ltd)

The oyster breed in North Yellow Sea is the Pacific Oyster (*Crassostrea gigas*), one of the giant oysters of the Orioles oysters. The local name is oyster. Pacific Oysters are mainly distributed in South Korea, mainland China, Taiwan. They rest with the rocks in the intertidal and shallow sea, with the left shell fixed on the rock. Oysters are an important breed shellfish. In China, Pacific oysters are distributed along the coastal areas in Shandong, Liaoning, Guangdong and Fujian Provinces. It is one of the main breeds in the coastal areas of the south. The production season is from November to April of the following year.

Pacific oyster shells are large, thick and long striped. The dorsal margin is almost parallel, and the shell length is about three times its height. The large individual shell is 35 cm long and 10 cm high. There are also long oval individuals. The right shell is relatively flat and its whorled scales are wavy, sparse, less layers, and radial ribs are not obvious. The left shell is deep, the scale is large, and the shell top is small. The surface of the shell is lilac, gray, or yellowish brown. The mantle membrane has two tablets. The respiratory system is the gill. Pacific oysters have four gills and they breath mainly through these. The mantle can also exchange gases. The digestive system includes the lips, mouth, esophagus, stomach, digestive caeca, intestine, rectum and anus. The circulatory system is open and the pericardial cavity is composed of the heart, blood vessels and blood etc. Kidney tubules and renal are surrounded by the left and right funnel tubes, respectively; During the breeding season, the visceral mass has white matter or gonad. The nervous system is composed of the brain, visceral ganglia and contact nerves.

3.6.1.3 Sea cucumber

Figure 3-21 Sea cucumber (Source: Zoneco Group Co. Ltd)

Sea cucumber (*Stichopus japonicus*) belong to *Echinodermata Holothuroidea, Apodida*. Sea cucumbers are a temperate species. They inhabit in rocks or sand mud bottom, where large clustered algae and eelgrass flourish. They feed on small animals and plants, such as foraminifera, gastropods and benthic copepods, diatoms. They live mainly in the shallow waters of the North Pacific coast. The northern limit in the geographical distribution is Russia's Sakhalin, Alaska coast of the United States; the southern limit is Kagoshima in Japan, the Korean Peninsula sea, China Liaoning (Dalian), Shandong, Hebei, Jiangsu Province (Lianyungang) and other waters. In recent years, in the south of China, a new model of sea cucumber aquaculture has been created.

Sea cucumbers have a cylindrical body like a cucumber. They grow to about 20-40cm in length. Around the mouth are 20 whorled branching tentacles. Sea cucumbers have a predation function. The number of body burns, length and color vary in different living environment. The body is usually brown with different shades of markings. There are green, red, gray and white individuals. The body wall is divided into the epidermis and connective tissue of collagen fiber. There are numerous calcareous bone fragments between the two layers. The connective tissue layer is the muscle layer, which is composed of the transverse and transverse muscles. The digestive tract is a body cavity in two longitudinal bending tubes, divided into the mouth, esophagus, stomach, cloacal, and anus. The respiratory organ is called respiratory tree because of its tree-like shape. The gonadal gland is made up of a number of tubules, located on one or both sides of the mesentery, and a common tube is connected to the reproductive hole. The gonad becomes thicker during the reproductive season. The female is orange red, and the male is milky white. The quality of sea cucumber products is mainly based on the thickness and fullness of the cortex.

Sea cucumbers like to inhabit in 3-15 meters transparent water, smooth flow, no freshwater, rocks with seaweed or fine sediment seawaters. With the expansion of the foot tube and muscle, slow motion can be done on the seabed. When the water temperature reaches 20°C, they stop eating and exercising. Aestivation time is from mid-July to early October. When the seawater temperature is too high, the water quality is cloudy and is strongly stimulated, sea cucumbers' guts are often discharged from the anus. The ability to regenerate is very strong as they can regenerate after injury and discharge. The main food is diatom, brown algae and silt containing organic detritus. They reach maturity at two years old. Male and female are bred using in-vitro fertilization. Sea cucumbers are oviparous animals and reproductive period is from May to July.

Sea cucumber breeding mode mainly includes a pond, cofferdam and bottom sowing culture. The bottom sowing seed grow in natural environment in 3-5 years. The nutritional value is high.

3.6.1.4 Abalone

Figure 3-22 Abalone
(Source: Zoneco Group Co. Ltd)

Abalone (*Haliotis discus hannai Ino*) in the North Yellow Sea belong to *Mollusca, Gastropoda, prosobranchia, archaeogastropoda, haliotidae*, are mainly distributed in China's northern coast. Shandong and Liaoning Province have more output, including Weihai and Changdao of Shandong. King County and Changshan Islands of Liaoning Province have the largest production. Production season is in summer. In recent years, with the development of artificial breeding, Weihai, Changdao and Fujian have become abalone breeding bases, which are produced all year round.

The abalone foot muscle is well developed, delicate and nutritious. Dry product analysis shows it contains 40% protein, 33.7% glycogen, 0.9% fat, and contains vitamins and other trace elements. In ancient China, it is listed as seafood crown. Abalone shell is low, the spiral part is degraded and has less whorls. The top of the shell is blunt and slightly out of the shell surface but lower than the highest part of the shell. From the edge to the body whorl, the second middle whorl begins. There is a row of screw ribs with 20 protrusions and holes and at the end of the 4-5 becomes particularly large, open and tubular. Shell opening is oval, and of equal size to the body whorl. The outer lip is thin while the inner lips are thick. The foot is especially developed and hypertrophic, which is divided into the upper and lower feet. The ventral surface is flat and is suitable for attachment and crawling. The surface of the shell is dark green where growth pattern is obvious. The inner surface of the shell is silver and white with shades of green, purple, pearl etc.

The water temperature range for the abalone is 3-28°C. The optimum growth temperature range is between 15-24°C. The water salinity is above 30 psu. The activity time is generally 2-3 hours after sunset, and 2-3 hours before sunrise. Abalone inhabit in clear waters, high salinity, tidal flow, with several meters of depth with seaweed reef. They crawl slowly and once they encounter predators or become frightened the foot firmly attaches on a rock. They are nocturnal animals. Their crawl speed reaches 50 cm per minute. Abalone also feed at night and return to the cave during daytime. Abalone feed mainly on brown algae, such as kelp, seaweed, sargassum, green algae. Benthic feeding also includes some small animals, such as globigerina, hydroids, making it an omnivore. The main feeding method is to scrape food by using the tooth tongue. The feeding activities of abalone have obvious diurnal and seasonal characteristics. The seasonal feeding is mainly related to temperature and reproductive activities. Water temperature at 5°C stops them from feeding, between 8-23°C they increase food intake. Abalone in Yellow and Bohai Seas feed a lot in April to June, making them fatter. During July to August of spawning period, feeding is less, so they are thinner. Water temperature decreases food intake gradually in November. Abalone in Yellow and Bohai Seas begin to mature in the gonads at the age of three. The smallest mature abalone is 4.3 cm.

3.6.1.5 Kelp

Figure 3-23 Kelp
(Source: Zoneco Group Co. Ltd)

Kelp (*Saccharina japonica*) belongs to *Phylum Phaeophyta*, brown subclass, kelp, the kelp family, the genus kelp. There are about 50 species of kelp in the world, 20 of which can be found in Asia. The kelp belongs to the subarctic algae and is a special local species in the North Pacific. The natural distribution is in North Korea, the northern coast of northern Honshu, Japan, Hokkaido and southern coast of Russia. Aomori and Iwate Counties in Hokkaido, Japan have the most distribution of this kelp, as well as in Wonsan coastal areas. The original production of kelp in China started between 1927 – 1930. It was imported from Japan. In the 1950s, the autumn seedling method improved to summer seedling method, greatly improving the yield. In the 1960s–1970s, new varieties were obtained from the breeding and breeding of Laminaria japonica. Later on, with intensive research on the breeding technology of Kelp Gametophyte, significant progress was made in the protection of kelp, the breeding of new varieties, and the production of seedling, which has greatly promoted the development of the kelp breeding industry.

The tip of kelp leaves are gradually narrow, generally at 2-5 m length, 20-30 cm width (bottom growth kelp is small, 1-2 meters length, 15-20 cm width). The leaf edge is thin, soft, and has wavy folds. The leaf base short columnar petioles are connected with the holdfast. The fresh kelp is olive brown, while dried kelp is dark brown, dark brown with white powdery salt. Dried kelp has white powder on the surface as it contains iodine and mannitol, especially mannitol white powder attached to the surface of kelp. Kelp without any white powder is of poor quality. Secondly, kelp leaves are thick and are green, purple or yellow. Fresh yellow leaf is top grade. In addition, kelp processed after binding should be selected as clean, no mildew, sticky and without sediment impurities is preferred.

3.6.1.6 Sea urchin

Figure 3-24 *Anthocidaris crassispina*
(Source: Zoneco Group Co. Ltd)

Sea urchins have a round ball shape, like a prickly purple cactus, which is called "sea thorn ball" or "the hedgehog". There are about 850 species of sea urchins existing in the world, and about 100 species in China's coastal areas. *Anthocidaris crassispina, Strongylocentrotus intermedius, Glyptocidaris Crenularis* etc., are common in China. The coastal sea urchin species in the North Yellow Sea sea ranching are mainly *Anthocidaris crassispina*.

The sea urchin's internal organs contain one shell composed of many calcareous bone plates which is formed by a close union. The shell is covered with many dynamic spines. Each tube hole on the shell foot is one foot. At the bottom center of the mouth, there are five white teeth. One sea urchin shell has about 3,000 platelets. They live in all the world's major oceans, with the most distribution in the Indian and the Pacific Oceans. Because they like high salinity, they are very little distributed in the waters near the river and in low salinity seawater, or are not distributed at all.

Sea urchins mostly live in the sea. They inhabit in the sea reef with alga or stones in seaweed rich intertidal, and hard sediment of shallow zones. They are nocturnal animals as they hide during the day and come out by nighttime. Sea urchins make less movement with more feeding. If food is abundant, sea urchins move only 10 centimeters per day. If food is scarce, they can move more than 1 meter per day. Sea urchins move by transparent, small, numerous and sticky tube foot and thorns. When the tube foot is in motion, it is similar to a starfish as it can seize rock. Located at the bottom of the thorns is the sea urchin body lift that helps the sea urchin free movement. They can move at any time, without turning the head. When the sea urchin is inverted, its thorns and tube feet can help itself to change its orientation.

Sea urchin mouth locates in the central abdomen, surrounded by five angle teeth, and the entire masticatory organ called the "Aristotle lantern" or "Aristotle lantern". The anus of the sea urchin is in a hemispherical form at the center of the upper face (the other side of the mouth, the back of the mouth). Sea urchins feed widely, they are carnivorous and their diet include worms, mollusks or other echinaceans. The main food of *Anthocidaris crassispina* food is algae. Besides, there are sea urchins that like to eat organic debris and animal carcasses. Sea urchin especially like to eat kelp, *Undaria pinnatifida*, plankton, and sediment.

3.6.1.7 Conch

Figure 3-25 Conch
(Source: Zoneco Group Co. Ltd)

Conchs belong to the *Gastropoda, Prosobranchia, neogastropoda, Buccinidae*, warm water species. They are important economic shellfish in the northern coast of China. They are mainly distributed in China, North Korea, Japan Sea, the northeast and Hokkaido. In China, they are distributed in the Yellow, Bohai, East Seas and northeast Taiwan. The production in Bohai and the Yellow Seas is high, where the main distribution places are Dalian and Shandong coasts. Conchs are carnivorous as they feed on snails. Conch meat is fat, delicate and delicious with high protein content and a rich variety of amino acids and glycogen, plasminogen for easy digestion and absorption. Conchs have high economic and nutritional value.

Conchs are coastal shellfish as they live in sandy seabed, larvae among reefs living in intertidal habitats, sediment is mainly mud silt or silty sand. The inhabiting water depth is 10-70 m, of which 20-30 m are concentrated. The temperature range is 0-24°C, and the optimum water temperature is 8-20°C. Conchs inhabit in high salinity waters where salinity is from 30 to 33.5 psu, the optimum salinity is 31-32.5 psu. Conchs have a large reproductive capacity. Egg bags are adhered with each other to form shaped tower-type corncob eggs. Eggs are hatched in late May to early June. Conch hatching rate is very high.

3.6.2 Site selection, ecological environment requirements

Ecological environment survey assessment of the sea ranching should be done before choosing a site. Monitoring stations, time and frequency, monitoring and analysis method, sample collection and management, data recording and processing, testing and evaluation, quality assurance and quality control work on the basis of "marine monitoring specification (GB17378.4-2007, GB17378.7-2007)," "coastal water environmental monitoring standards" and “Mariculture Zone monitoring technical regulations.” The evaluation standard is mainly based on the fishery water quality standard (GB11607-1989), and the items not included in the fishery water quality standard are evaluated according to the standard value of seawater quality standard (GB3907-1997). The investigation indexes include water temperature, salinity, dissolved oxygen (DO), DO saturation, pH (pH), transparency, chlorophyll, nitrate, ammonia, phosphate, chemical oxygen demand (COD), heterotrophic bacteria, *Vibrio, Escherichia coli*, phytoplankton (a total of 16).

The water quality of IMTA aquaculture area needs Class 1 standard of water quality. Coliform group is less than or equal to 10,000/L, fecal coliform is less than or equal to 2,000/L, pH 7.8-8.5, DO>6 mg/L, chemical oxygen consumption less than 2 mg/L, inorganic nitrogen is less than 0.20 mg/L, un-ionized ammonia ≤0.020 mg/L, active phosphate ≤0.015 mg/L, heavy metal and the chemical pollutants, less than Class 1 water quality standard.

IMTA aquaculture area is related to many kinds of organisms. According to the water temperature of the upper and lower limits of the varieties, the annual sea water temperature is 1-22°C, the salinity is 29 to 31.5 psu, pH is 7.8 to 8.5, the dissolved oxygen is above 6 mg/L, and the chemical oxygen demand is below 2 mg/L. Phytoplankton is the main source of feed for filter-feeding aquatic animals. Its abundance is directly related to the output of aquatic economic animals, and its species composition is related to the food safety of products. The species of microalgae in the environment should be mainly diatom, and the harmful microalgae should be less. Phytoplankton is above 5,000/L, chlorophyll is above 0.7 mg/m^3.

3.6.3 The construction of integrated aquaculture system illustrates the biological and environmental factors affecting the construction of IMTA system, management elements, space requirements, process flow and etc.

3.6.3.1 Principle of system construction

In the North Yellow Sea, Zhangzidao Island sea ranching IMTA model is taken as an example where the basic elements of construction cultures the biological filter, biological, licking saprotroph and large algae together. Among these, macroalgae can effectively absorb the biological filter feeding, lick biological excretion of ammonia and phosphate salt, and release carbon dioxide into biomass which has potential economic benefits, at the same time lick biological feed. Nitrogen and phosphorus excretion of bivalve can promote aquaculture water phytoplankton growth, which in turn provides microalgae feed for shellfish. Shellfish farming produces feces and pseudofeces and sink to the bottom. These can become benthic organisms such as abalone and sea cucumber bait or promote seaweed growth. Animal carcasses can be fed to conchs and converted to biomass that has high economic benefits. To avoid the interference of harmful organisms and fouling organisms in the process, this kind of biological metabolites acts as a nutrient source for another organism. By this culture mode, to maximize the efficient recycling of nutrients within the system in use, reduce the pressure on the environment and culture, so that the system can accommodate the amount of food and has high productivity, make full use of the different biological nutrient cycling sure, double upgrade marine product quality and yield and promote the sustainable development of the coastal ecosystem.

3.6.3.2 Biological factors

Biological effect mainly refers to the different ecological functions of cultured or major wild organisms. Filter-feeding species refer to Japanese Scallops and oyster economic shellfish, microalgae or organic detritus as filter-feeding bait. Saprotroph mainly refers to species as conch. Large algae including kelp, *Undaria* and etc., which contributes to primary production. The predator refers to *Asterias amurensis*; fouling refers to the unplanned growth of mussels, clams and *Hiatella orientalis*.

3.6.3.3 Environmental factors

In North Yellow Sea, Zhangzi Island IMTA system sea ranching culture area sea water is clear. According to the national standard of "People's Republic of China sea water quality standard" (GB 3097-1997), sea water quality should reach the national standard class 1 water quality. The selection area is a shallow sea tide zone, the depth of water is within 15 m, and the seabed is hard bottom or sand bottom. Floating rafts should be used on the surface of the sea. There should be a distribution of sea cucumber, abalone or sea urchin in the areas. The water quality and the flow rate should also be suitable. The location of the demonstration area needs to satisfy the abovementioned biological elements and environmental conditions.

3.6.3.4 Technological process

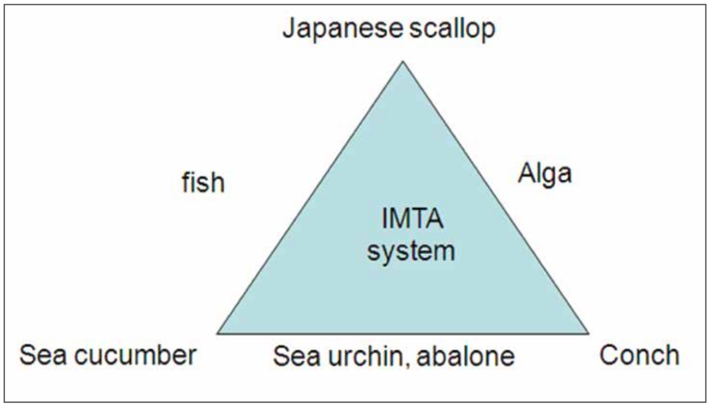

Figure 3-26 IMTA system (Source: Zoneco Group Co. Ltd)

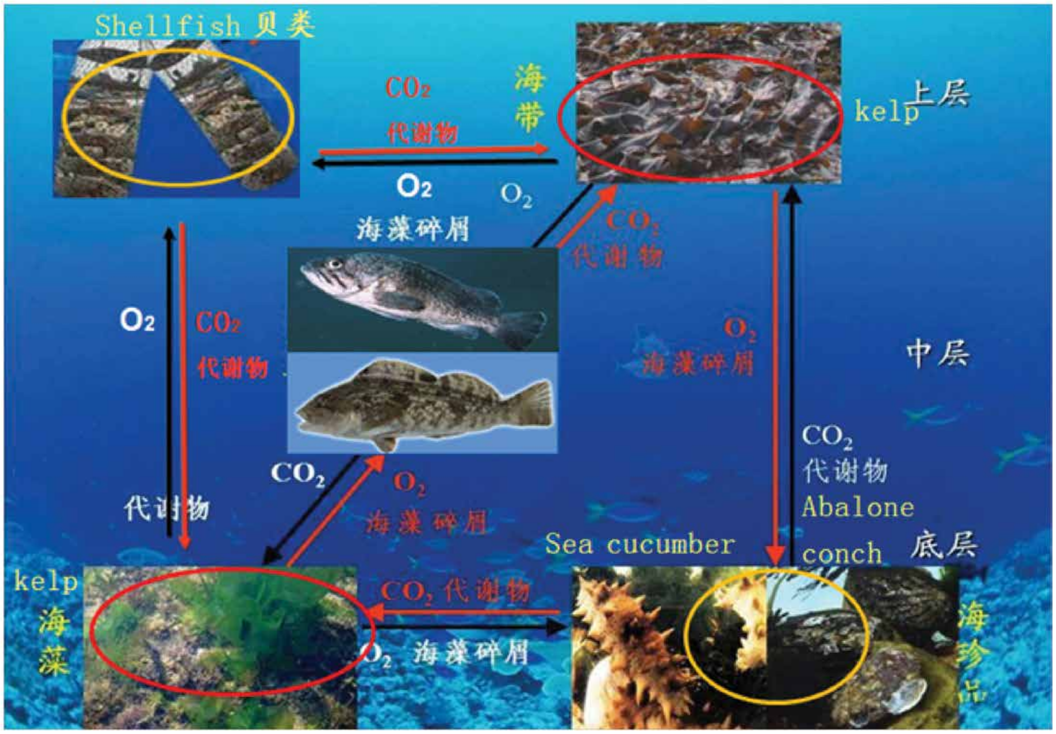

Figure 3-27 IMTA model (Source: Zoneco Group Co. Ltd)

The IMTA culture model demonstration area space should have at least 500 acres of water surface for the upper raft cultivation and breeding of Japanese Scallops and kelp. In order to have a convenient harvest, Japanese Scallops and kelp should be cultured separately. In the middle are natural fish, such as *Hexagrammos otakii, Sebastes schlegelii, Kareius bicoloratus, Kareius* etc. At the bottom are the wild sea cucumber, sea urchin, abalone, sea-bottom-sowing abalone and sea cucumber. The artificial reef or rocks should be on the sea bottom so that kelp, red algae, green algae and various types of algae will attach on the reef.

IMTA aquaculture mode combines aquaculture technology with natural conditions, including algae, shellfish breeding, and artificial reefs that can promote the growth of marine organisms to help more plants grow. By using stock enhancement culture, scallop transfer from concentrated intermediate breeding area to free growth marine area, scallop can achieve faster growth and increase weight, therefore, increasing yield and profit. The technology also helps to reduce the incidence of disease, improve biodiversity and “carbon sink” level.

3.6.3.5 Management factors

Strict environmental monitoring provides a powerful complement to innovation. Every month, the water quality and health related microorganisms are thoroughly investigated. Every quarter, growth and survival rates are supervised. Every year, carbon emissions of aquaculture are supervised. Accordingly, management of carbon emissions should be made using comprehensive methods to deal with the environmental impact of business activities. By IMTA technology, the North Yellow Sea marine ranching has been able to increase production and achieve economic diversification. At the same time, the technology also reduces waste by converting excrement of animal products into harvested crops, therefore, reducing the demand for artificial feed.

Surface aquaculture and management of scallop: in early October to mid-November, when seawater temperature is 16-18°C, the size of scallop reaches 3 to 3.5 cm. The raft culture of scallop in scallop culture cage is carried out according to 22-25 density of each layer. As the growth of the shellfish gradually becomes dense, in mid-March of the next year, the density is reduced to 15-18 per layer and replacement the cage is carried out at the same time. According to the condition of the sea area and the load of the raft, the buoyancy will be increased in time to prevent the winding of the hoisting cage and drifting system, and the responsibility system is carried out. The growth specifications and death conditions are often checked. When the natural water temperature is about 15°C from June to July, the harvest begins, and the harvest specification is 7-8cm.

Management of surface kelp aquaculture: kelp breeding area should be a safe sea area with smooth flow, less mud, less algae and relatively rich water quality. In order to make full use of the nutrients excreted by scallops, kelp culture area should not be too far away from the scallop culture area. Kelp culture starts with Japanese Scallop culture in November. Using the hanging method, open the seedling curtain, cut into 100 cm segment of seedling rope and tie it to a lower seedling rope with a stone about 150 g. Seedling rope spacing should be 25 cm horizontally. The water layer at the beginning of the sea is generally controlled in a transparent 1/5 to 1/3 meter, and in a transparent sea area, the water layer is controlled by about 1 meter in depth. After the seedlings go to sea, avoid the attached mud and algae, so that the seedlings should always be swung and washed in the water. When the seedlings reach 15-20 cm, ensure rapid growth of seedlings by separating big seedlings. In the mid-term, it is suitable for seedlings to grow 15-20 cm long. In the late stage, seedlings reach more than 20 cm long. The head stubble seedlings are generally used. Seedlings usually use a single clip form to manually clip seedlings onto the breeding rope. Seedling spacing is controlled at 8-11 cm (early seedling spacing is 11 cm, middle seedling spacing is 10 cm, and late seedling distance is 8 cm). The following year, when the natural water temperature is about 15°C, it is time for harvest, otherwise, the kelp will rot when the temperature rises.

The bottom of sea cucumber, abalone and conch management: submerge near or at the surface culture kelp and Japanese Scallop culture area, by putting artificial reef to attach algae or natural existence of reef algae, it provides an important source of food for abalone, sea cucumber. Kelp debris such as organic matter in the surface of raft culture is also a food source. Sea cucumbers are wild resources, abalone and conch have both wild and stock enhancement. Culture period usually lasts three years, farmers should periodically clean harmful organisms such as *Asterias amurensis*. When harvested, usually employ divers to harvest by picking individual sea cucumber/abalone from the sea bottom.

3.6.4 Analysis of economic and ecological benefits

3.6.4.1 Economic performance

After three years of breeding, farming demonstration area yield per unit area increased by more than 10%, comprehensive benefits increased by more than 20%, the process of demonstration zones reduced carbon emissions by more than 15%. Integrated technology radiation area of more than 500,000 acres, and demonstration will produce good economic benefits. The promotion of IMTA culture model and sea ranching brings advantages for the North Yellow Sea Zhangzidao sea ranching to reduce the negative impact of a single culture model. From 2005 to 2010, the annual growth rate of the company’s revenue reached 40%, which is much higher than the industry average level (13%). The average EBITDA (Earnings Before Interest, Taxes, Depreciation and Amortization) profit margin was 31%.

3.6.4.2 Ecological and social benefits

This IMTA offshore fisheries model can effectively use the sea water to increase the aquaculture space and improve the output capacity of the aquaculture area. The algae in the sea directly absorbed CO_2 and algae as the main food for shellfish and other marine organisms indirectly absorb CO_2, reduced greenhouse gas emissions and slowed down global warming speed, reduced the adverse effects of acid rain and other natural disasters and showed ecological significance to promote fishery energy saving and emission reduction.

The sustainability of the marine ecological environment in north Yellow Sea is ensured by optimizing traditional aquaculture technology. At the same time, by implementing various monitoring mechanisms, local fishers will be guided to improve their working standards and make more industrialized production, so as to improve their living standards and promote the development of the local fishery economy, which has good social benefits.

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CHAPTER

4

Evaluation of ecosystem service and value in different aquaculture modes

4.1 Evaluation contents and methods of ecosystem services in different aquaculture modes

4.1.1 The implication of marine ecosystem service

The definition of mariculture ecosystem and its service are based on the ecosystem and services concept which must first be studied. The ecosystem is the basic organization unit in the biosphere and the most vigorous part. The ecosystem not only provides a variety of goods for human beings, but also plays an irreplaceable role in the dynamic balance of supporting system and environment. Between the 1930s and 1940s, Tansley proposed the concept of ecosystem, "The basic concept of an ecosystem is the 'system' that is used in physics," which was a remarkable event in the development of ecology. This system includes not only the organisms, but also the entire physical components of the environment. "Our fundamental view is that organisms cannot be separated from their environment, they form the natural system with their environment". Therefore, the term mainly emphasizes the functional unity between various organisms at a given region including environmental interaction. After Tansley, many scholars have studied the ecosystem concept and proposed different opinions. The most widely used is the concept from the Convention on Biological Diversity: ecosystems are a dynamic and complex functional unit formed by the interaction of plant, animal and microbial communities with the surrounding inorganic environment (United Nations, 1992). The concept synthesizes the research achievements of the ecological system for decades, and it is very practical for the management of ecosystem.

According to the definition of ecosystem service, the mariculture ecosystem services refer to the products and services generated directly or indirectly by culture species and their environment through aquaculture activity. These services are derived from the interaction of the aquaculture species with physical and chemical components. The value depends on the aquaculture scale, functional property and the social and economic environment where the aquaculture system is located. The economic value would be expressed as a local market price when products and services are generated through the interaction of these factors. The activity of aquaculture species is controlled by many conditions, such as water environment, biogenic elements, sediment, etc., and it also has feedback effect on water environment and biogenic elements. The values of the aquaculture ecosystem are formed by the interaction of these factors.

4.1.2 Marine aquaculture ecosystem services classification

Regarding the classification of ecosystem services, different scholars have grouped and classified ecosystem services differently (functional grouping, structural grouping and descriptive grouping). Ecosystem services classification has gone from describing the service characteristics to the value of assessment, and then closely linked to human welfare and development process. Representative categories include: Costanza et al. (1997) classifying ecosystem services into 17 categories, which is currently the most influential ecosystem service classification system; In the Millennium Ecosystem Assessment (MEA) (UNDP, 2005), ecosystem services are divided into regulating service, providing service, cultural service and supporting service, and different types of services are quantified. Based on the characteristics of the mariculture ecosystem, the mariculture ecosystem service was divided into four types according to the ecosystem service classification system of MEA (2005): providing service, regulating service, supporting service and cultural service.

Providing service refers to the products or substances harvested from the ecosystems, including mariculture products (e.g., fish, shrimp, shellfish, algae, etc.), productive raw materials (e.g., daily necessities, fuel, medicine, etc.), genetic resources carried by aquaculture species, which may be one of the most valuable resources in the future.

Regulating service refers to the benefits obtained from ecosystem regulation including the absorption of CO_2 by mariculture ecosystem and various ecological processes, which will regulate regional or global climate (e.g., mariculture biological pump effect of the CO_2 fixation and subsidence). The various harmful substances that enter the marine aquaculture ecosystem are decomposed, reduced, converted and treated, which contributes to waste disposal and water purification. The biological regulation and control of harmful organisms and diseases can significantly reduce the occurrence probability of related disasters such as zooplankton and shellfish feeding on poisonous algae. The interference regulations are the capacity, attenuation and comprehensive effect of the ecosystem on various environmental fluctuations, namely algal cultivation.

Supporting service refers to mutual supporting between different ecosystem services. It includes the primary production which satisfies the energy and material requirements for various activities and processes of various aquaculture species; The material recycling process of ecosystem stability maintaining and other services; The habitat services such as living space and shelter provided by other creatures.

Cultural services refer to the non-material benefits obtained from the ecosystem through spiritual satisfaction, development of cognition, thinking, recreation and aesthetic feeling, including non-commercial contribution of mariculture ecosystems on human spirit, art creation and education, namely the cultural service (e.g., spiritual and cultural diversity, create inspiration, increase the chance of education and practice); Due to the complexity and diversity of mariculture ecosystem, producing and attracting knowledge of scientific research and supplement with potential commercial value, namely the function extension service, can improve the ability of human management knowledge.

4.1.3 The content and method of ecosystem service evaluation in different aquaculture modes

Material production refers to the aquaculture products harvested from the ecosystem, including three services: food supply, raw material supply and genetic resources, and the market price method, which is used to calculate its value.

Climate regulation refers to the benefits derived from the regulatory role of ecosystem processes, such as the absorption of CO_2 and the release of O_2 by cultured species. This includes the fixing and depositing of CO_2 by aquaculture organisms through filter activities (e.g., shellfish, etc.), and the releasing O_2 by cultured species through photosynthesis (e.g., algae, etc.). The value of released O_2 is based on the data of primary productivity of large algae, and is calculated according to the Photosynthetic Reaction Equation l. The value of fixed CO_2 is estimated by the average transaction price of CO_2 emission rights of environmental exchange or similar institutions, and the value of O_2 is estimated by the price of industrial oxygen.

Water purification refers to the transformed, transferred, absorbed and degraded harmful substances in the aquaculture ecosystem This plays a significant role in waste treating and water purifying. The value of water purification can be estimated by alternative cost method according to the treatment cost of wastewater treatment plant.

Material circulation refers to the process of transformation and circulation of the materials needed by aquaculture species throughout their life cycle, including the circulation of nutrients (e.g., N, P) and water properties. This process will provide energy and materials for the normal operation of the ecosystem and support for other functions. Because energy and material values are embodied in other service values from which human beings are not directly involved, the value of these two services is generally not recalculated to avoid duplication. However, these two service functions can be used to assess the matter quantity.

Biodiversity refers to the genetic diversity, species diversity and system diversity generated and maintained by the offshore aquaculture ecosystem, which can be measured by the species of plankton in different aquaculture modes.

Biological control function of marine ecosystem is rather complicated, mainly considering the control effect of aquaculture shellfish on red tide organisms. The value of biological control includes three parts: reducing the area of red algae bloom, economic deaths and red tide toxins; the corresponding value can be estimated by the eliminating cost of red tide unit, the market price of aquatic products, and the human health loss caused by red tide toxins.

Disturbance adjustment refers to the aquaculture facilities which help reduce the damage of storms and waves on the coasts, dams, and ponds. The value of disturbance adjustment is reflected by the reduction of economic losses caused by storms and the cost of repairing dams.

Entertainment refers to the function of leisure-fishery, sightseeing and other similar activities provided by the aquaculture system, which offers tourism options and leisure functions for local residences. Tourism values include travel expenses, travel time value and other expenses, which can be assessed by the method of travel expenses; other recreational value is estimated by a consumer's willingness to pay (WTP).

Scientific research value refers to the functions of scientific research sites and materials provided in the aquaculture area. The scientific value is reflected by the number of research projects carried out in the research area. The research value mainly considers the following two aspects: (1) The research funding and the published scientific research achievements in the research area; (2) The economic benefits arising from the promotion and application of the scientific research achievements obtained in the research area.

4.2 Measurement and evaluation of ecosystem services in different aquaculture modes

The services of mariculture ecosystems can be measured and quantified through some specific indicators. As a measurement method, the value assessment can reflect its social importance and the variation of ecosystem services in quantity. The evaluation of the ecosystem service of mariculture includes matter quantity and value quantity in different aquaculture modes.

4.2.1 Evaluation index of mariculture ecosystem services

The evaluation index of mariculture ecosystem services mainly considers the quantifiable and monetizable service elements. Providing service evaluation index considers material production; Regulating service evaluation index considers climate regulation and water quality; Supporting service evaluation index considers species diversity maintenance; Cultural service evaluation index considers scientific research service.

4.2.2 Data sources

4.2.2.1 Material Production Data

Aquaculture production can be determined according to the fishery statistics in the adjacent region and can be obtained by on-site investigation. The average market price of aquaculture products should be calculated using the wholesale price of similar seafood near the assessment sea area, and the deducted related production cost, depreciation expense, power cost and labor cost.

4.2.2.2 Climate regulation data

The amount of CO_2 absorbed by cultured algae should be calculated according to the measured dry weight of macroalgae and the photosynthesis equation. The phytoplankton primary productivity should be measured or taken from estimated data from a relevant marine survey report. Climate regulation mainly comes from the fixation of greenhouse gases (e.g., CO_2). The main sources of CO_2 from farming ecosystems in different aquaculture modes are as follows: first, the dissolved inorganic carbon is transformed to organic carbon by cultured algae (e.g., kelp) through photosynthesis. The fixed carbon could be calculated according to the production of cultured algae (dry matter), primary productivity and photosynthesis equation; second, the cultured shellfish can transform and fix carbon by feeding planktonic algae and particle organic carbon. Meanwhile, the $CaCO_3$ (shell) was formed by absorbing HCO_3- directly from sea, and the formula is $Ca^{2+}+2\ HCO_3^- = CaCO_3+CO_2+H_2O$. 1 mol of CO_2 will be released to form 1 mol of $CaCO_3$, and 2 mol of HCO_3- will be absorbed. The fixed carbon will be removed from the system by harvest of scallop; third, sedimentary animals (e.g., sea cucumber) in the IMTA mode assimilate carbon from sediment into tissue by sediment deposition. Assimilated carbon is removed from the sea by harvest and is estimated based on carbon content in the soft tissue. Breeding organisms (e.g., shellfish, algae, etc.) should be calculated based on weight, usually taken from relevant resources survey reports and statistical data; The content of carbon in soft tissues and shells, such as shellfish, should be evaluated by measurements or reference data. The unit price of CO_2 should be the average transaction price of the CO_2 emission rights of the environmental exchange or similar institutions.

4.2.2.3 Oxygen production data

The oxygen content mainly refers to the oxygen that the aquaculture species releases or consumes through photosynthesis or respiration. The main source of its positive effect is the release of oxygen, which should be calculated based on the measured value of macroalgae dry weight. The primary productivity of phytoplankton can be calculated from relevant ocean survey reports. The price of oxygen should be the price of industrial oxygen.

4.2.2.4 Water purification data

The water purification of aquaculture ecosystem is mainly to estimate the cleaning and processing capacity of cultured species in the culture cycles as well as pollutions generated. It mainly considers the handling and adjusting ability of nitrogen. The effect of removing nitrogen can be achieved through the harvest of aquaculture species. The removal effect of macroalgae on nitrogen is mainly calculated based on the proportion of nitrogen in the algae tissue. The removal effect of shellfish or other organisms on nitrogen and phosphorous is calculated by the protein content in the body or nitrate content in different tissues. The cost of water treatment is calculated according to the sewage treatment cost.

4.2.2.5 Research services evaluation data

The number of research papers can be obtained through the scientific literature retrieval engine. The unit cost of research paper can be calculated according to the marine science funds and the total number of scientific papers.

4.2.3 Ecosystem service evaluation in different aquaculture modes

4.2.3.1 Providing services

Material production

Matter quantity assessment

The matter quantity of material production should be evaluated by the annual production of the main aquaculture species in different aquaculture modes, such as algae or shellfish.

Value quantity assessment

The value of material production is calculated using the formula (1):

$$V_M = \sum(Q_{Mi} \times P_{Mi} - Q_{Mi}) \qquad (1)$$

VM - Value of material production (Y / ha / a);
Q_{Mi} - Yield of the ith aquaculture species (kg / ha / a), i = 1, 2, 3 ..., representing the main aquaculture species in different aquaculture modes;
P_{Mi} - Average market price of the ith aquaculture species.
Q_{Mi} - Cost of the ith aquaculture species (including breeding cost, breeding facility cost, management cost, etc.).

The average market price of culture organisms should be calculated by evaluating the wholesale price of similar seafood in the adjacent market.

4.2.3.2 Regulating service

Oxygen production

Matter quantity assessment

The matter quantity of oxygen production is mainly provided by aquaculture algae, which is evaluated by the amount of oxygen released through photosynthesis.

The matter quantity of oxygen production is calculated using the formula (2):

$$Q_{O2}= 1.2\times Q_{Ma} \tag{2}$$

Q_{O2} - Matter quantity of oxygen production (kg/ha/a);
Q_{Ma} - Dry matter quality of cultured algae (kg/ha/a).

Value quantity assessment

The value of oxygen production should be evaluated by alternative cost method. This is calculated using the formula (3):

$$V_{O2}= Q_{O2}\times P_{O2} \tag{3}$$

V_{O2} - Value of oxygen production (Y/ha/a);
Q_{O2} - Matter quantity of oxygen production (kg/ha/a);
P_{O2} - Unit cost of artificial production of oxygen (Y/kg).

The unit cost of artificial production of oxygen should be estimated using the average production cost of industrial oxygen production.

Climate regulation

Matter quantity assessment

The matter quantity of climate regulation is equal to the amount of CO_2 that is fixed or removed by aquaculture species in different aquaculture modes. The matter quantity of climate regulation is calculated using the formula (4):

$$Q_{CO2} = Q'_{CO2} + Q''_{CO2} + Q'''_{CO2} \qquad (4)$$

Q_{CO2} - Matter quantity of climate regulation (kg/ha/a);
Q'_{CO2} - Amount of CO_2 fixed by cultured algae (kg/ha/a);
Q''_{CO2} - Amount of CO_2 fixed by cultured shellfish (kg/ha/a);
Q'''_{CO2} - Amount of CO_2 fixed by sediment animal, such as sea cucumber (kg/ha/a).

The amount of CO_2 fixed by cultured algae is calculated using the formula (5):

$$Q'_{CO2} = Q_A \times R_A \qquad (5)$$

Q'_{CO2} - Amount of CO_2 fixed by cultured algae (kg/ha/a);
Q_A - Dry weight of cultured algae (kg/ha/a);
R_A - Carbon content of cultured algae's tissue.

The amount of CO_2 fixed by cultured shellfish is calculated using the formula (6):

$$Q''_{CO2} = Q_T \times R'_{TC} + Q_S \times R_{SC} \qquad (6)$$

Q''_{CO2} - Amount of CO_2 fixed by cultured shellfish (kg/ha/a);
Q_T - Yield of cultured shellfish's soft tissue (kg/ha/a);
Q_S - Yield of cultured shellfish's shell (kg/ha/a);
R'_{TC} - Carbon content of cultured shellfish's soft tissue;
R_{SC} - Carbon content of cultured shellfish's shell.

The amount of CO_2 fixed by sediment animal (e.g., sea cucumber) is calculated using the formula (7):

$$Q'''_{CO2} = QSC \times R''TC \qquad (7)$$

Q'''_{CO2} - Amount of CO_2 fixed by sediment animal (e.g., sea cucumber) (kg/ha/a);
Q_{SC} - Yield of sediment animal, such as sea cucumber (kg/ha/a);
R''_{TC} - Carbon content of sediment animal's soft tissue (kg/ha/a).

Matter quantity assessment

The value of climate regulation should be evaluated by alternative market price method. This is calculated using the formula (8):

$$V_{CO2}= Q_{CO2}\times P_{CO2} \qquad (8)$$

V_{CO2} - Value of climate regulation (Y/ha/a);
Q_{CO2} - Matter quantity of climate regulation (kg/ha/a);
P_{CO2} - The market price of CO_2 emission rights.

The market transaction price of the CO_2 emission rights should adopt the average transaction price of the CO_2 emission rights of China's environmental exchange or similar institutions.

Water purification

Matter quantity assessment

The Matter quantity of water purification is equal to the yield of aquaculture species multiplied by its nitrogen content in different aquaculture modes. Matter quantity assessment of water purification is calculated using the formula (9):

$$Q_{WT}= Q_{Mi}\times R_N \qquad (9)$$

Q_{WT} - Matter quantity of water purification (kg/ha/a);
Q_{Mi} - Yield of the ith aquaculture species (kg/ha/a), i = 1, 2, 3 ..., representing the main aquaculture species in different aquaculture modes;
R_N - Nitrogen content of aquaculture species' body.

Value quantity assessment

The value of water purification should be assessed using the alternative cost method. This is calculated using the formula (10):

$$V_{WT}=Q_{WT}\times P_j \qquad (10)$$

V_{WT} - Value of water purification (Y/ha/a);
Q_{WT} - Matter quantity of water purification (kg/ha/a);
P_j - Unit price of manually dealing N.

4.2.3.3 Supporting services

Matter quantity assessment

The matter quantity of supporting services can be measured by counting the species of plankton in the study area.

Value quantity assessment

The value of species diversity maintenance can be assessed using the willingness to pay method. This refers to people's willingness to pay for the protection of the ith species or their willingness to accept compensation for the loss of the ith species. The value of species diversity maintenance was calculated using the formula (11):

$$V_{SSD}=\sum WTP_i \text{ (or } WTA_i)\times P_j \qquad (11)$$

V_{SSD} - Value of species diversity maintenance (Y/a);
WTP_i - Willingness of people to pay for the protection of the ith species (Y/P/a);
WTA_i - Willingness of people to accept compensation for the loss of the ith species (Y/P/a);
P_j - Population of the administrative area where the aquaculture is located (P).

Conditional value method can also be used to evaluate, and calculated using the formula (12):

$$V_{SSD}=D\times S \qquad (12)$$

V_{SSD} - Value of species diversity maintenance (Y/a);
D - Maintenance value of species diversity per unit area (Y/ha/a);
S - Aquaculture area being assessed sea area (ha).

4.2.3.4 Research services

Matter quantity assessment

The matter quantity of research services should be assessed using marine scientific papers, patents and projects of aquaculture area being assessed sea area, which area is used as a research area or an experimental site. The matter quantity of research services can also be calculated by relevant statistical data.

Value quantity assessment

The value of scientific research services can be assessed using the direct cost method, and calculated using the formula (13):

$$V_R=Q_R×P_R \qquad (13)$$

VR - Value of research services (Y/a);
QR - Matter quantity of research services (P/a);
PR - Research funds for each marine scientific and technological paper (Y/P).

The unit cost of scientific papers can be calculated according to the total amount of marine science and technology funds and papers.

Alternative value method can also be used to evaluate, and calculated using the formula (14):

$$V_R=E×S \qquad (14)$$

V_R - Value of research services (Y/a);
E - Research function value per unit area (Y/ha/a);
S - Aquaculture area being assessed sea area (ha).

4.3 Case Analysis - Sanggou Bay

Sanggou Bay is one of the most typical aquaculture bays in northern China, where aquaculture activities started since the 1960s. Presently, the aquaculture area extends to the outside of the bay, including more than 30 kinds of aquaculture species, and more than a dozen aquaculture modes. Among these modes, the IMTA (Integrated multi-trophic aquaculture) mode developed in recent years, using different levels of nutritious organisms to recycle and reuse nutrients in aquaculture, thus, increasing the output and reducing the impact on the environment. This kind of aquaculture mode has inestimable effect on ensuring human food safety and reducing environmental pressure. At the same time, Sanggou Bay has been chosen by domestic and foreign scholars to carry out research projects on aquaculture capacity, ecological optimization of aquaculture model, ecological regulation and environmental restoration of aquaculture waters, healthy aquaculture technology, etc. The bay has become a well-known gulf in domestic and international groups that integrate production and scientific research.

There are dozens of aquaculture modes currently implemented in Sanggou Bay, which can be divided into four types. The first is monoculture, where major species include kelp, scallop, oyster, abalone, etc. The second is polyculture, which includes polyculture of kelp, scallop, oyster, abalone, cage polyculture, etc. The third is raft culture, which includes bottom sowing mode, dominated by kelp and cage culture, bottom sowing of sea cucumber and sea urchin. The fourth is IMTA mode, which includes the integrated culture of kelp, abalone and sea cucumber. Three main aquaculture patterns in Sanggou Bay were studied, including kelp monoculture, polyculture of kelp and scallop, IMTA of kelp, abalone and sea cucumber.

4.3.1 Providing services

4.3.1.1 Material production

Matter quantity assessment

Referring to the production and operation data of fishery production, surrounding aquaculture companies and farmers in Rongcheng City, the matter quantity of material production is shown in Table 4-1:

Table 4-1 The matter quantity of material production in different aquaculture modes in Sanggou Bay.

Aquaculture mode	Aquaculture species	Yield per unit area (kg/ha/a)
Kelp monoculture	kelp	14,063
Polyculture of kelp and scallops	kelp	11,719
	scallop	5,625
IMTA of kelp, abalone and sea cucumber	kelp	15,625
	abalone	8,654
	cucumber	1,875

Value quantity assessment

The value of material production in different aquaculture modes in Sanggou Bay can be estimated using formula (1), and the estimated results are shown in Table 4-2.

Table 4-2 The value of material production in different aquaculture modes in Sanggou Bay.

Aquaculture mode	Aquaculture species	Yield per unit area (kg/ha/a)	Market price (Y/kg)	Income (Y/ha/a)	Cost (Y/ha/a)	Value (Y/ha/a)
kelp monoculture	kelp	14,063	6.0	84,375	35,156	49,219
polyculture of kelp and scallops	kelp	11,719	6.0	70,313	31,641	38,672
	scallop	5,625	4.6	25,875	5,273	20,602
	total	17,344	10.6	96,188	36,914	59,273
IMTA of kelp, abalone and sea cucumber	kelp	15,625	6.0	0	4	0
	abalone	8,654	200.0	865,384	482,716	382,668
	sea cucumber	1,875	120.0	112,500	11,250	106250
	Total	**26,154**	**326.0**	**977,884**	**493,966**	**483,918**

4.3.2 Regulating service

4.3.2.1 Oxygen production

Matter quantity assessment

The matter quantity of oxygen production in different aquaculture modes in Sanggou Bay can be estimated using formula (2), and the estimated parameters (Table 4-3) and results (Table 4-4) are as follows:

Table 4-3 Estimation parameters of oxygen production.

Parameter	Parameter value	Unit	Data source
Unit dry weight oxygen consumption rate of scallop software	1.35	mg/gdw/h	Mao, et al., 2006
Unit wet weight oxygen consumption rate of abalone	0.0587	mg/gww/h	Bi, et al., 2000
Unit wet weight oxygen consumption rate of sea cucumber	0.0167	mg/gww/h	Yuan, et al., 2006
Artificial oxygen costs	0.4	y/kg	Shi, et al., 2008

Table 4-4 The matter quantity and value of oxygen production in different aquaculture modes in Sanggou Bay.

Aquaculture mode	Produced O_2 (kg/ha/a)	Value (Y/ha/a)
Kelp monoculture	16,875	6,750
Polyculture of kelp and scallops	14,062	5,624
IMTA of kelp, abalone and sea cucumber	18,750	7,500

Value quantity assessment

The value of oxygen production in different aquaculture modes in Sanggou Bay can be estimated using formula (3), and the estimated results are shown in Table 4-4.

4.3.2.2 Climate regulation

Matter quantity assessment

The amount of carbon fixed in different aquaculture modes in Sanggou Bay can be estimated using formulas (4 to 7), and the estimated parameters (Table 4-5) and results (Table 4-6) are as follows:

Table 4-5 Carbon content of various aquaculture species.

Aquaculture species	Carbon content of algae's tissue or shellfish's soft tissue (%)	Carbon content of shell (%)	Data source
Kelp	31.2	/	Zhang, et al., 2008
Scallop	43.87	11.44	Zhou, et al., 2002
Abalone	33.00	/	Britz, et al 1996
Sea cucumber	0.3	/	Li, et al., 2006

Table 4-6 The matter quantity and value of fixed carbon in different aquaculture modes in Sanggou Bay.

Aquaculture mode	Fixed and removed carbon (kg/ha/a)	Value (Y/ha/a)
Kelp monoculture	4,388	4,809
Polyculture of kelp and scallops	4,200	4,603
IMTA of kelp, abalone and sea cucumber	12,529	1,3732

Value quantity assessment

The price of CO_2 is based on Sweden's carbon tax rate of 150 $/t C, equivalent to 1096 Y/t (based on the median price in December 2007, 1 $=7.305 Y). The value of fixed carbon in different aquaculture modes in Sanggou Bay can be estimated using formula (8), and the estimated results are shown in Table 4-6.

4.3.2.3 Water purification

Matter quantity assessment

The amount of nitrogen removed in different aquaculture modes in Sanggou Bay can be estimated using formula (9), and the estimated parameters (Table 4-7) and results (Table 4-8) are as follows:

Table 4-7 Nitrogen content of various aquaculture species.

Aquaculture species	Nitrogen content of algae's tissue or shellfish's soft tissue (%)	Data source
Kelp	1.63	Zhou, et al., 2002
Scallop	12.36	Zhang, et al., 2005
Abalone	31.00	Britz, et al. 1996
Sea cucumber	34.00	Li, et al., 2005

Table 4-8 The matter quantity and value of removed nitrogen in different aquaculture modes in Sanggou Bay.

Aquaculture mode	Removed nitrogen (kg/ha/a)	Value (Y/ha/a)
Kelp monoculture	1.63	Zhou, et al., 2002
Polyculture of kelp and scallops	12.36	Zhang, et al., 2005
IMTA of kelp, abalone and sea cucumber	31.00	Britz, et al. 1996

Value quantity assessment

The sewage treatment cost of nitrogen is 1.5 Y/kg (Zhao et al. 2007), therefore, the value of water purification in different aquaculture modes in Sanggou Bay can be estimated using formula (10), and the estimated results are shown in Table 4-8.

4.3.3 Supporting services

4.3.3.1 Matter quantity assessment

The species composition of phytoplankton in Sanggou Bay were investigated in April, July and November in 2006 and January in 2007. Ninety-two (92) species belonging to twenty-eight (28) genera of phytoplankton were identified during the surveys. Based on the field survey data in 6 bimonthly cruises in 2009-2010, a total of 61 zooplankton species from 6 cruises were identified in Sanggou Bay (Liu et al., 2015).

4.3.3.2 Value quantity assessment

Based on data availability, the value of supporting services in Sanggou Bay can be estimated using formula (12). The functional value per unit area of species diversity maintenance is 2,100 y/ha/a (Li, 2007), the area of Sanggou Bay is 13,200 ha, and the supporting service value of aquaculture area in Sanggou Bay is up to 2.77×10^6 y/a.

4.3.4 Research services

4.3.4.1 Matter quantity assessment

The matter quantity of research services in Sanggou Bay (Table 4-9) was estimated using data from China's marine statistics yearbook (2010) and China's fisheries statistics yearbook (2010).

Table 4-9 Matter quantity assessment of research services in Sanggou Bay.

Area	Total aquaculture area (ha)	Number of invention patents (item)	Total number of scientific papers published (paper)	Funding of scientific research institutions (Y)
Shandong province	782,935	411	1,619	3.69×10^9
Sanggou Bay	13,200	7	27	6.23×10^7

4.3.4.2 Value quantity assessment

Based on the data availability, research funding is used as an estimate of research value. The value of research services is up to 6.23×10^7 y/a in Sanggou bay (Table 4-9).

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CHAPTER

5

Mariculture Environmental Monitoring

The purpose of environmental monitoring is to collect and analyze regular and systematic information about the environmental condition in an area. This way, one can ensure that the carrying capacity is not exceeded and that the area can be used over a long period of time. The ecological objective of monitoring is systematic observation, measurement and calculation of the condition of the environment, emission of pollutants, or populations and species, which are necessary for the assessment of the environmental condition, and the planning of environmental protection measures (Anon., 2012). In an IMTA, context monitoring is initially given less importance as with intensive monoculture production since the production is extensive and the waste products from one organism are potentially food for another. However, since IMTA often covers large areas, it is important to perform monitoring over time.

There are two main categories of monitoring: baseline monitoring and operational monitoring. Baseline monitoring characterizes the conditions in an area before the start of an aquaculture activity. It usually includes area mapping, bathymetry, current measurement, determination of the environmental condition and identification of the impact of other sources. This way, any change in environmental conditions after the introduction of aquaculture can be compared directly to the initial situation. Operational monitoring is performed during production and the sampling usually covers an area around and a transect away from the aquaculture activity. Depending on the allowable impact, different monitoring surveys may be used, from simple, easy-to-perform surveys to sensitive and time-consuming ones. In addition to monitoring, a pilot survey may be conducted. This will provide a general overview of the environmental conditions, and is used for simple rapid assessment to give basic information for designing more detailed sampling programs.

Monitoring is commonly used in many areas with intensive fish farming, where waste from the farms in the form of waste feed and feces may impact the seabed and in the vicinity of the net pens (see examples in Anon. 2012). The aim of the monitoring is to avoid unacceptable impact on the fauna in the sediments. Biological or chemical parameters may be used, separately or together, to determine the effect. To prevent unacceptable environmental conditions, the right combination of site characteristics, production scheme and management must be found. Monitoring models are valuable tools by simulating the outcome of various scenarios. The monitoring program and the environmental quality standards (EQS) will ensure that the actual aquaculture activity does not exceed the carrying capacity of the area.

Preventing overexploitation of sites and adjacent areas and ensuring good rearing conditions for aquaculture organisms is important for the production of high quality seafood. In the future, consumers may demand documentation of both the environmental consequences of production, the quality of the product and the physical rearing conditions.

5.1 Introduction to the MOM system (Modelling–On-growing fish farms–Monitoring)

The MOM system was developed for intensive fish farming to be able to predict and control environmental impact (Ervik et al., 1997). It includes environmental impact assessment, impact monitoring and threshold levels for impact (EQS). The environmental assessment may be provided by a model and should simulate the main environmental impact of the aquaculture facility on the site. This assessment will be checked by monitoring. The EQS sets a limit for maximum allowable impact and preferably makes it possible to distinguish between different impact levels. To link the model, the monitoring program and the EQS have two terms: the degree of exploitation of the site and the level of monitoring. The degree of exploitation expresses the extent of impact compared with the carrying capacity of the site or the area. If the impact of the production is close to the carrying capacity, the degree of exploitation is high, whereas it is low if the impact is small relative to the carrying capacity. The degree of exploitation may be divided into two or more categories. For every degree of exploitation there is a level of monitoring, which determines how much monitoring is necessary to ensure that the site is not exploited beyond the limits of the category. The higher the degree of exploitation, the higher the level of monitoring, resulting in a more frequent and elaborate monitoring.

The monitoring program includes three investigations, A, B and C. These cover from very simple monitoring to detailed but time-consuming and expensive surveys. Depending on the objective, one or all three may be used. The C-investigation can pick up small changes in the environment and may be used if little impact is allowed. The B-investigation is relatively cheap and easy to perform, and may be chosen if more impact is tolerated.

The model developed for use of the MOM system consists of four sub-models: simulating the metabolism of the fish, determining the water condition in the net pens, the dispersion of the organic particles and giving an indication of whether the sediment under the farm has been overloaded with organic material (Stigebrandt et al. 2004). The model has two main applications: estimating the environmental impact of a given fish farm on the site, and estimating how a farm can be operated without overexploiting the site and the recipient. The principles of the MOM system are general, and may be applied in both intensive and extensive aquaculture areas. These require that the correlation between the source of impact and the amount of impact must be known, and that it is possible to determine threshold values for impact to be able to distinguish between various impact levels. The MOM system is flexible and allows for substitution of the model and the monitoring program, including the EQS, to accommodate the specific environmental concerns in different areas or countries. The system was designed with a model, but it is possible to use it with the monitoring program and threshold values only.

Monitoring

Several general principles for monitoring applied in the MOM system and in other monitoring programs were described in Anon. (2012):

- The effort of environmental monitoring should be proportional to the scale of impact and should focus on the long-term use of farming areas.
- Before a site is utilized for aquaculture production, baseline monitoring should be carried out.
- Monitoring should be regular and the more impact an aquaculture activity has, the more often the monitoring survey should be performed.
- Different monitoring surveys may be used in different areas: where little impact is tolerated the survey must be able to detect subtle changes, where more impact is tolerated a simpler survey may be enough to provide an adequate result.
- Threshold values for environmental impact should be set that aquaculture sites may be in use over a long time and aim to ensure favourable living conditions for the aquaculture organisms as well as to prevent unacceptable impact on the surrounding area. For official threshold values, the national pollution control authority should be contacted.
- The monitoring survey used should be suited to the task and the following considered: the aim of the monitoring; how detailed need the survey be to provide an adequate result; the level of accuracy needed for the measured variables; practicability, efficiency, time consumption and costs involved in relation to the outcome; transparency.
- Surveys comprising many parameters are less sensitive to anomalies in individual parameters and may provide a more robust result.
- The variables that make up a monitoring survey may be organized in modules and be replaced or modified as appropriate according to new knowledge, techniques or legislations.
- The results should be presented in a clearly set fashion in a report where both the overall condition of the site is presented together with a detailed overview of the primary results. If conditions vary at the aquaculture area, this should be commented upon. The report should compare the results with previous surveys, and explain the changes over time.

The MOM monitoring program consists of three monitoring investigations (A, B and C) of increasing elaboration and accuracy which are applied more frequently with increasing environmental impact (Hansen et al. 2001). The investigations were made for conditions under which benthic impact is the most serious environmental problem, but may be changed or substituted if other or better methods of measuring impact are developed.

The A-investigation is a simple sedimentation measurement which provides an indication of overfeeding or overstocking and is only relevant for intensive fish farming. The B-investigation is a chemical sediment investigation providing an indication of the condition in the sediment. This investigation utilizes several parameters in concept, in order to make the investigation more robust. It is described in detail in the next chapter. The C-investigation is a comprehensive investigation of the structure of the benthic fauna community following biological changes in the sediment. The main element is a survey of the bottom fauna communities with additional information on sediment parameters. In many countries the pollution control authorities have defined threshold values for environmental quality of coastal waters which may be applied to the C-investigation.

The scientific benefit of the more advanced faunal community method of the C-investigation is balanced against the advantage of a higher number of samples and more frequent surveys in the B-investigation. The smaller sampling gear of the B-investigation also allows sediment to be sampled from smaller boats. EQS's for environmental impact are set so that the sites may be in use over a long period of time and aim to ensure favorable living conditions for the farmed organisms as well as to prevent unacceptable impact on the surrounding area.

The B-investigation

The objective of the B-investigation is to perform simple, cost-effective monitoring of the sediment. Because it is inexpensive, and its frequency is determined by the degree of impact, the B-investigation can be carried out often to provide an ongoing check of the sediment. This enables measures to be put into effect to avoid undesirable trends or prevent undesirable occurrences.

The B-investigation was developed to monitor the impact of fish farming waste (feces and waste feed) on the sediment under the net cages of salmon farms. However, the changes in the sediment condition is not limited to the release of these waste products but will reflect other types of organic material such as feces and pseudo feces from mussels and other shellfish, macroalgae debris, but also includes sewage and surface runoff. Organic material that settles on the seabed is either utilized by the benthic fauna or mineralized by sediment bacteria. If the sedimentation of organic material increases, this may initially lead to an increase in the benthic fauna and the bacterial activity, but it also increases the oxygen demand in the seabed. Eventually, this may lead to oxygen deficiency in the sediment, and other bacteria groups, which can live without oxygen, taking over the mineralization. Some of these, sulphate-reducing bacteria, produce hydrogen sulphide which is toxic and which in turn also utilise oxygen to produce sulphate. The benthic fauna shifts towards opportunistic species, which can tolerate deteriorating sediment conditions. If organic material continues to accumulate, the sediment will turn azoic and anoxic lowering the redox potential and eventually the pH. The changes in the sediment can either be tracked by following the change in the benthic fauna community or by measuring the sediment chemistry. Fauna community studies will provide a detailed picture of the changes and small variations can be picked up. However, it requires large sampling equipment and the identification of the fauna is expensive and time-consuming. If only small changes are accepted, this type of survey is often preferred and it is part of the MOM monitoring program as the C-investigation. An easier and cheaper way to determine the condition in the sediment is to measure the chemistry such as the redox potential and sulphide concentration or pH (Schaanning and Hansen 2005). In the B-investigation, the redox potential and pH are measured in the sediment and together with other visual observations. These are used to determine the sediment condition. The sediment parameters are divided into three groups: (1) biological parameter (presence or absence of animals larger than 1 mm in the sediment); (2) chemical parameters (pH and redox potential); and (3) sensory parameters (qualitative determination of outgassing, smell, consistency, colour of the sediment, grab volume and thickness of the layer of deposits). All the parameters in the three groups change according to organic input to the sediment. A scoring system has been developed and the higher the score, the more affected the sediment is by organic material. The use of several parameters makes the evaluation more robust and the results are less sensitive to variation in any one parameter. EQS values have been established for each group, rather than for individual parameters.

The upper threshold for allowable sediment impact (the division between acceptable and unacceptable sedimentary conditions) is set at the highest level of accumulation of organic material that will not lead to the extinction of the benthic fauna. The carrying capacity is then the maximum fish production that will allow benthic fauna to survive in the sediment. When the sediment turns azoic, the carrying capacity is considered to be exceeded. The more impact there is, the higher the degree of exploitation at a site and the more monitoring is required. Because the survey is repeated regularly at intervals determined by the extent of the environmental impact, trends in the environmental impact can be followed closely.

The B-investigation was developed to monitor impact of fish farming waste but the investigation can be used for all types of organic material which easily decompose. When using the B-investigation in areas with much less organic effluent than intensive fish farming, it is important to consider whether the variables in the B-investigation are sensitive enough to detect unwanted impact. If this is not the case, the variables can be substituted with more sensitive ones, such as additional fauna analysis. An example of the use of the B-investigation in an area with seaweed and shellfish farming to determine if the production was within the benthic carrying capacity is presented in Zhang et al. 2009.

Sampling

Crucial for all monitoring is where the sampling stations are placed. They must be positioned with regard to local bathymetric and hydrodynamic conditions and considering which type of aquaculture technology is used. A general plan for sampling stations when using the

B-investigation at fish farm sites has been developed as part of a standard for performing the B- and C-investigation (Anon. 2007). When sampling at fish farm sites, the area is divided into two impact zones: the local impact zone where some impact is expected and the intermediate impact zone where only small effects are accepted. The B-investigation is primarily used in the local impact zone. Sampling stations are distributed evenly in this area to cover the various sediment conditions. If the result of the investigation shows unacceptable conditions, the number of samples may be increased to verify the result. When sampling in other areas, specific sampling plans must be made. An example of a sampling plan in an area with production of seaweed and shellfish is presented in Zhang et al. 2009.

The sampling is performed using light equipment operated from a small craft. Samples are collected by a small gravity core sampler with transparent corers or a modified van Veen grab (>200 cm^2). The sediment is measured, and scores are allocated for the three groups of parameters right after the sample is collected.

Sample treatment

After the sediment is sampled, it is examined according to the description below:

Group 1 parameter

This parameter is linked to the to the environmental quality objective, which states that a viable macrofauna must be present in the sediment.

The sediment is sieved through a 1 mm mesh sieve and the presence of animals yields a score of 0, and the absence a score of 1. If a sample contains little sediment, fauna may not have been collected even if the bottom condition is good. This is often the case where there is hard bottom with little accumulation of organic material. The condition of such a sample may still be acceptable if the results of the other two groups of parameters show either condition 1, 2 or 3. If a full sample does not contain fauna, the sediment condition is unacceptable, which will also be revealed by the other two groups of parameters.

Group 2 parameters

The Group 2 parameters are based on direct measurements of pH and redox potential by electrodes inserted in the sediment immediately after sampling in transparent corers or grab (Schaanning and Hansen 2005). Changes in these parameters are largely controlled by three major decomposition processes in marine sediments, oxygen respiration, sulphate reduction and methane production. Redox potential is a common parameter for the description of oxygen deficiency in organically-enriched sediments. It has also been used to assess environmental impacts of fish farming and for developing benthic enrichment index, though it may be difficult to attain stable readings from the electrodes in some sediments, especially when there is little impact. When the sediment gets more impacted by organic material and it becomes more important to be able to distinguish between sediment conditions, the redox potential usually becomes more stable. pH has been less used in sediment investigations, but is useful when sediments receive high input of organic material. pH may fall below 7.0 in anoxic sediments where there is methane production and appears to be a reliable parameter for predicting the risk of gas ebullition (Schaanning and Hansen 2005).

pH and redox potential are measured at 2 cm depth intervals in the core sample. If cores cannot be collected, the electrodes may be inserted directly into the grab sample and a measurement performed at 1 cm depth. Measurements of pH and redox potential from Norwegian fish farms sediments have showed a relationship between the two parameters which is the basis for five different impact categories (Schaanning and Hansen 2005). When pH and redox potential are measured, they are compared to the figure and allocated a score. The method gives high resolution in heavily enriched sediments where the macrobenthic community is absent or severely disturbed. A score of 0 will correspond to a well-oxygenated environment with low organic input and favourable conditions for the presence of viable benthic communities. Increasing input of organic matter will drive the sediment environment through successive stages of increasing oxygen deficits and corresponding changes in microbial communities. A score of 2 frequently represents an environment with hydrogen sulphide, which gives low redox potentials in pore water. A score of 5 represents an environment with methane gas in the sediment and low pH values. Scores of 1 or 3 are allocated to transition zones.

If measurements are made at several depths in core samples, the lowest pH and the corresponding redox potential are used to assign scores. This implies that in sediments with a redox discontinuity layer, site assessment will frequently be based on values recorded below this layer. This may result in the allocation of a lower score that might have been obtained from data recorded at depths closer to the sediment-water interface. In coarser sediment types on the other hand, sharp redox-clines may be absent or present only below the sampling depth of the light grab or core equipment. Furthermore, in sediments that have recently been enriched with organic material, the redox potential gradient may be inverted, so that the potential increases with increasing depth.

The rationale for using the minimum values is based on the following considerations: (1) the simplicity of the rule; (2) the freedom it provides with regard to sample quality and electrode design; and (3) the reduction in the variance resulting from measuring the steep gradients frequently present within the top few millimeters of the sediments.

Group 3 parameters

The Group 3 parameters are a group of sensory sediment variables which change with increasing organic enrichment: sediment colour, smell and consistency, gas ebullition, and thickness of organic material accumulated on top of the original sediment. These parameters provide useful information about the condition of the sediment and have long been included as visual observations in sediment studies. The information provided by these parameters has been standardised for use in the B-investigation by assigning scores to the sensory variables. The more affected the sediment is by organic enrichment, the higher the score. Sediments may have different colors such as grey, brown or light, which are all allocated a score of 0, but it will normally change to black (iron sulphide) if there is hydrogen sulphide in the sediment, in which case, it is allocated a score of 2. Hydrogen sulphide will also cause the sediment to smell, and depending on the intensity, a score of 0, 2 or 4 is allocated. Highly anoxic sediments may produce methane which often produces small bubbles in the sediment, a sign of very impacted sediments. If gas bubbles are absent, a score of 0 is allocated, but if they are present, it is a strong sign of unacceptable sediment conditions and it is given a score of 4. If gas bubbles are too small to be seen, the pH measurement will usually indicate if methane is being formed. The consistency of the sediment is softer in areas where sedimentation is high and if there is much organic material, therefore, firm sediment is allocated a score of 0, soft sediment a score of 2 and very soft a score of 4. If organic material is accumulated on top of the sediment, the thickness is measured and allocated a score of 0, 1 or 2.

The allocation of scores to the individual variables involves a certain degree of subjectivity. Therefore, the variables are not considered individually, but the scores from all group 3 parameters in one sample are added in order to avoid placing too much emphasis on individual observations. A mean score of zero is equivalent to undisturbed conditions while a mean score higher than 14 defines a sediment condition which is unacceptable.

Determination of site or area condition

The environmental condition of a sample is expressed by combining the conditions determined by the three groups of parameters. Group 1 only differentiates between acceptable and unacceptable conditions, whereas groups 2 and 3 determine sediment conditions. If groups 2 and 3 show different conditions, group 2 takes precedence over group 3, since redox potential and pH are measured variables.

If the samples are obtained under fish farms, an average value can be calculated, expressing the sediment condition of the site. If an area is surveyed, the presentation of the results will depend on the sampling strategy.

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5.2 The AZTI's Marine Biotic Index (AMBI)

5.2.1 Introduction of the AMBI index

Macrobenthic communities are sensitive to long-term changes in habitat and responses to the change of water and sedimentary environments quality caused by natural and human activities. It is the most important symbol of environmental quality and so it is usually used to indicate the ecological environment quality condition. As a biological indicator of marine ecological environment and the biological index of ecosystem health assessment, the biological index has been widely recognized by scientists all over the world.

The AZTI Marine Benthic Index (AMBI) (Borja et al., 2000) is one of the most widely applied indices and has been used as a metric of benthic quality in many areas. According to the environmental sensitivity of various benthic animals, AMBI approach covers five different Ecological groups (EG) and the ABMI index can be calculated using the following formula:

$$\mathrm{AMBI}=[(0\times\%\ \mathrm{EG\ I})+(1.5\times\%\ \mathrm{EG\ II})+(3\times\%\ \mathrm{EG\ III})+(4.5\times\%\ \mathrm{EG\ IV})+(6\times\%\mathrm{EG\ V})]/100$$

where:
EG I. "Sensitive species" are sensitive to organic matter enrichment. Their abundance is highest under unimpacted conditions (at lowest TOC values) and drops to zero as organic matter concentration increases.
EG II. "Indifferent species" are indifferent to organic matter enrichment. They never dominate the assemblage. They occur in low abundance over a broad range of organic matter concentrations, but are absent at very high concentrations.
EG III. "Tolerant species" are tolerant to excess organic matter enrichment. They may occur at low TOC. Their highest frequencies are stimulated by organic enrichment but they are absent at very high organic matter concentrations.
EG IV. "2nd-order opportunistic species" show a clear positive response to organic matter enrichment with maximum abundance between the maxima of Groups III and V.
EG V. "1st-order opportunistic species" show a clear positive response to excess organic matter enrichment with maximum abundance at a higher stress level induced by organic load than species of Group IV. At even higher organic matter concentrations, no foraminifera are able to survive.

The AMBI index classification and corresponding benthic community health and ecological environment quality are shown in Table 5-1.

Table 5-1 MAMBI index ecological grouping and evaluation criteria.

Biological index	Dominant biome	Benthic community health	Station disturbance level	Ecological quality status
0.0<AMBI≤0.2	I	normal	undisturbed	high
0.2<AMBI≤1.2	II	frail		
1.2<AMBI≤3.3	III	unbalanced	Mild disturbance	fine
3.3<AMBI≤4.3	IV	The transition to pollution	Moderate disturbance	moderate
4.3<AMBI≤5.0		polluted		unhealthy
5.0<AMBI≤5.5	V	Transition to heavy pollution	Severe disturbance	
5.5<AMBI≤6.0	V	Heavily polluted		very unhealthy
6.0<AMBI≤7.0	No life	No life	Extreme disturbance	

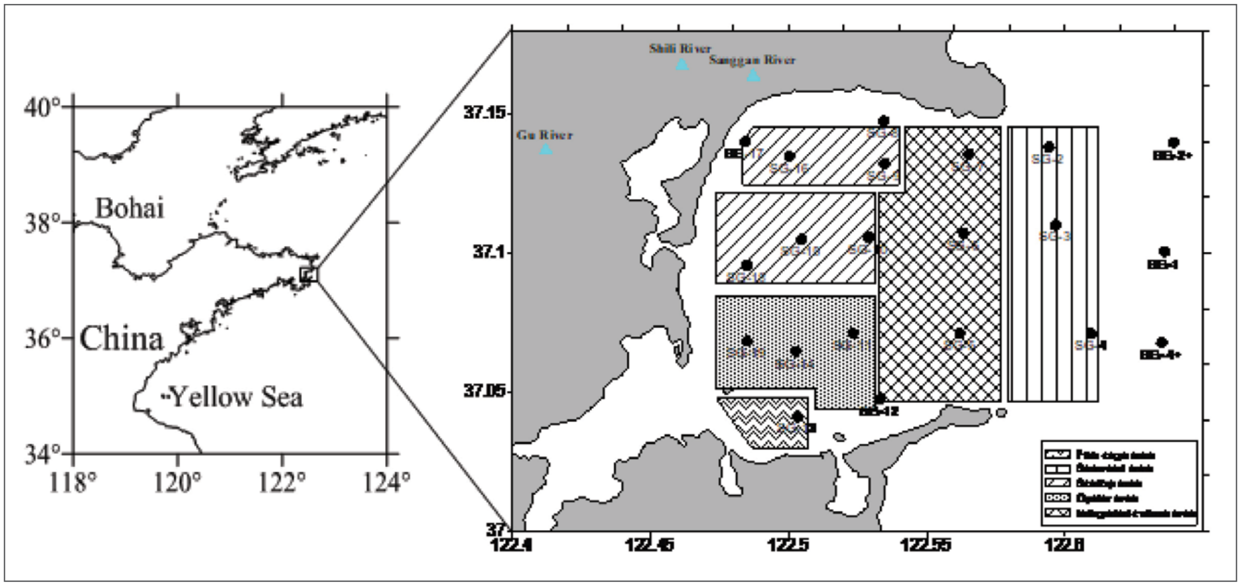
In order to meet the regulations of European Water Framework Directive (WFD) on ecological quality conditions, Borja and Muxika proposed the multivariate biological index (M-AMBI) concept which combined the AMBI, species richness (S) and the diversity index (H). The M-AMBI value ranges from 0-1, the closer to 1, the better the ecological quality.

AMBI index is used to reflect the European coastal and estuarine waters ecosystem health and ecological environment quality condition in the early stage. The Mediterranean coast is the most frequently evaluated coast, with applications in the northeast Atlantic, the west coast of the United States and the Indian Ocean. The AMBI approach can be used under different environmental pressures, such as eutrophication of water body, channel dredging and aquaculture. AMBI and M-AMBI can be calculated by the free AMBI software from the AZTI website (http://ambi.azti.es). In recent years, the index has been applied to evaluate the ecological environment quality of China's coastal waters and estuaries. Its universality and applicability have been widely recognized and certainty.

5.2.2 AMBI-based approach on the assessment of sedimentary environment quality in Sanggou Bay - a case study

A field cruise with 21 investigation stations was conducted in Sanggou Bay in April 2017 (Figure 5-1). Sediment was sampled by a bottom grab sampler of 0.05 m2. Mud was removed using a sieve with an aperture size of 0.5 mm and then biological samples were fixed with 5% formalin solution. Operation procedures in detail refer to “the Marine monitoring regulation” (GB17378.7-2007).

Figure 5-1



The results in Table 5-2 showed that there were 31 species of macrobenthos in the study area. *Polychaetes* (23 species) are the main dominant group in this area followed by 4 kinds of crustaceans, 2 kinds of molluscs and 2 kinds of echinoderms. The spatial distribution shows that the highest number of species are found in stations 5 and 18. Taking the frequency, density and biomass into consideration, the *Lumbrineris latreilli* is the dominant species in this area.

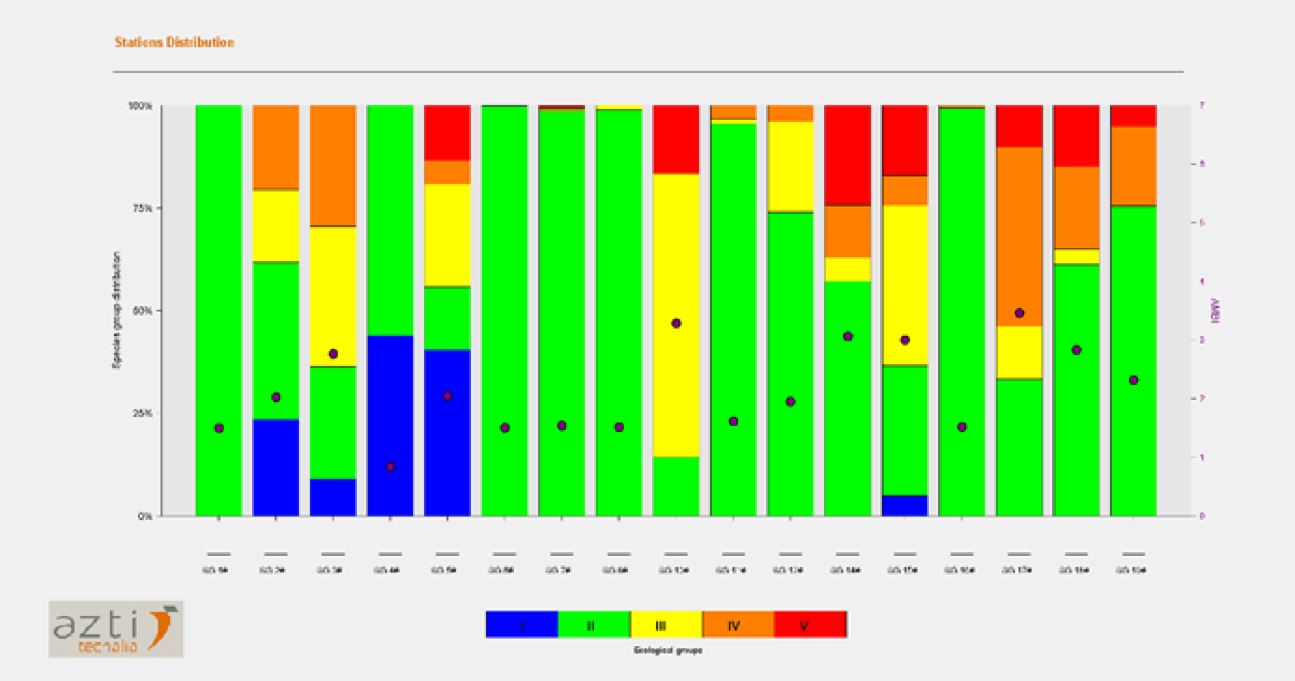
Other dominant species are *Mediomastus sp.* and *Tharyx multifilis*. The average density of macrobenthos is 108.24 ind/m^2. The polychaetes are the dominant density group as its average density occupied 90.2% (97.65 ind/m^2). The average biomass is 6.35 g/m^3. The average biomass in stations 1 and 6 is significantly higher than the other stations in the bay. Table 5-2. The species and biomass of macrobenthos in Sanggou bay in April 2017.

AMBI evaluation results showed that the AMBI value of the sedimentary environment of Sanggou Bay ranges from 0.857–3.643. The lowest AMBI value appears on station 4 where value is 1 and station disturbance level is undisturbed. The highest AMBI value appears on station 17, where value is 3 and station disturbance level is moderately disturbed. Most of the stations in the survey area were slightly disturbed. Some of the stations were moderately disturbed and undisturbed. The quality level of ecological environment in Sanggou Bay is excellent (Figure 5-2).

Table 5-2 The species and biomass of macrobenthos in Sanggou bay in April 2017.

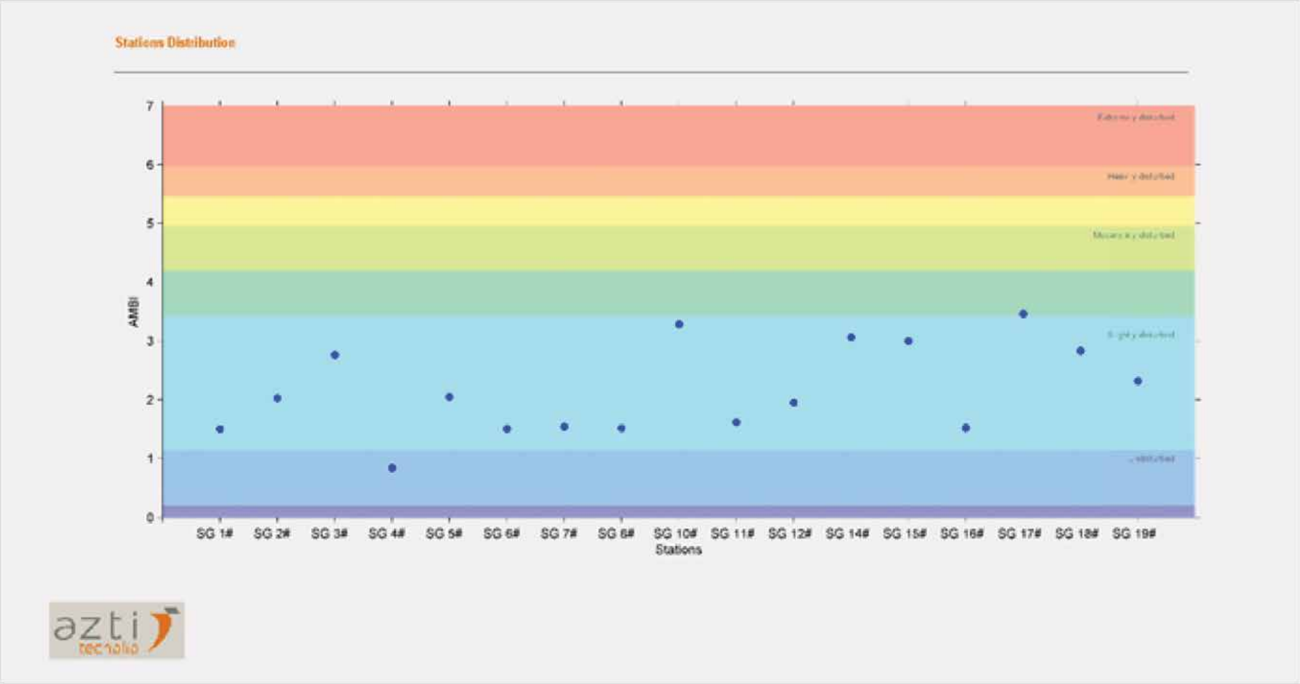
	SG1	SG2	SG3	SG4	SG5	SG6	SG7	SG8	SG10	SG11	SG12	SG14	SG15	SG16	SG17	SG18	SG19
Ampharete anobothrusiformis															0.06	0.01	
Aricidea fragilis		0.06	0.04		0.05												
Asychis gotoi						21.69											
Capitella capitata					0.07		0.04		0.07			0.17	0.07		0.04	0.12	0.03
Chaetozone setosa										0.07		0.03				0.03	
Diopatra chiliensis							11.48										
Glycera chirori	4.17	0.13															
Glycinde gurjanovae			0.05							0.03			0.07	0.03		0.05	0.03
Lumbrineris latreilli				0.08	0.04	0.34	0.16	0.13	0.06	0.24	0.37	0.16	0.06	0.04		0.17	0.06
Lumbrineris heteropoda						11.7				2.03							
Lumbrineris longiforlia		0.07	0.11			0.04									0.17	0.06	
Marphysa sanguinea	26.13																
Mediomastus sp.		0.01	0.13		0.11		0.07	0.07	0.26	0.04				0.02	0.05	0.03	
Neanthes japonica			0.02			0.02											
Nephtys oligobranchia						0.05								0.03	0.07		
Nptomastus latericeus		0.05															
Paralacydonia paradoxa			0.07	0.08													
Pista sp.																	0.07
Scoloplos armiger											0.08	0.04	0.11				
Sigambra bassi					0.03												
Sternaspis scutata					0.02			0.06	0.03				0.05				
Sthenolepsis japonica				0.07													
Tharyx multifilis			0.02			0.01	0.06			0.05	0.02	0.06	0.03	0.06		0.07	0.11
Moerella jedoensis				0.16	0.16												
Nucula kawanurai													0.02				
Ampelisca cyclops		0.02															
Ampelisca bocki				0.02													
Cirolana japonensis					0.04											0.26	0.27
Paranthura japonica											0.03						
Amphiura vadicola								11.41		1.16				10.37			
Amphioplus japonicus												0.24					

Figure 5-2 Histogram showing the results from a group of sampling stations.



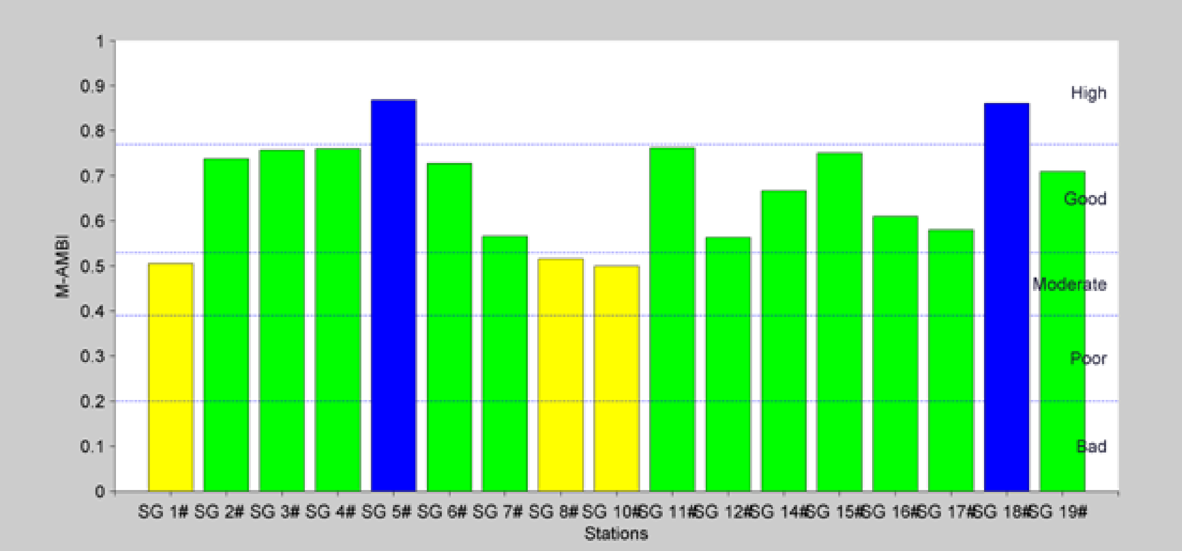
The M-AMBI evaluation results showed that 16 stations are in good and high condition, the excellent rate occupied 84.2% (Figure 5-3). Only three stations (1, 8 and 10) are at the moderate level. No station is at the poor level.

Figure 5-3 AMBI index from a group of sampling stations.



The assessment results showed that the quality of sedimentary environment in Sanggou Bay is still in good condition even if it has been developed for more than 30 years of large-scale mariculture (Figure 5-4).

Figure 5-4 M-AMBI index from a group of sampling stations.



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CHAPTER

6

Prospects and suggestions

The global climate change and its growing influence have not only aroused the attention of the scientific community, but also received the attention of the international community and governments. The convening of the Copenhagen World Climate Conference marked the arrival of a low-carbon era characterized by "low energy consumption, low pollution and low emissions." The development of low-carbon economy has become a strategic choice of all governments in response to climate change. On the other hand, under the dual influence of global climate change and human activities, the carbon cycle and carbon budget of fishery ecosystem responds abnormally. In order to actively cope with global climate change and implement sustainable aquaculture development, there is an urgent need to establish a scientific approach to recover and amplify biological carbon sinks.

Carbon sink of fisheries is a biological sink and refers to processes and mechanisms that promote the absorption of CO_2 in seawater by aquatic organisms through fishery activities, and finally remove the carbon from the waterbody by harvesting aquatic products. Carbon sink fisheries aim to reduce the amount of greenhouse gases in the atmosphere. Carbon sequestration and carbon emission reduction are the main measures. Industrial structure adjustment, culture space organization, facilities and equipment upgrade and clean energy utilization help carbon sink fisheries achieve low pollution, low energy consumption and low emissions and high carbon storage, and efficient modern fisheries. The proposal and advocacy of the fishing carbon sink has an important realistic meaning and for heading historic significance. Carbon sink fisheries make full use of aquatic organisms to strengthen the absorption of the atmospheric greenhouse gases by the seawater, and also provide high-quality protein and ensure food safety. Thus, it can be seen that the development of a carbon sink fishery and innovation in low-carbon fisheries technology are projects that have won great achievements in the contemporary era and will benefit future generations. These will help speed up the modernization of a resource-saving and environment-friendly fishery. The carbon sink fishery also promotes the national goals of energy conservation and emission reduction which is a good response to climate change.

Integrated Multi-Trophic Aquaculture (IMTA) is a good interpretation of the carbon sink fisheries and is an environmental-friendly and efficient eco-farming model. IMTA system is composed of different trophic levels: the feeding culture units (e.g., fish, shrimp) generates nutrients for non-feeding culture units (e.g., filter-feeding shellfish, macroalgae and carnivorous organisms). Excess material in the culture system is transformed into cultured organisms to achieve effective material recycling and reduce ecosystem pressure from aquaculture. At the same time, IMTA also increases the culture diversity and enhances economic benefits, which promote sustainable development of aquaculture industries.

IMTA not only promotes efficient food supplement but also provides ecological service, which is mainly made up by material production, water purification, climate regulation and air quality regulation. The ecological service provided by IMTA is much higher than monoculture aquaculture, the seruve value ratio can be up to 18:1. Using the Norwegian Monitoring On-growing Fish Farms Modeling (MOM), the monitoring and assessment of the environmental quality of Sanggou Bay in China showed that most of the sedimentary environment in the bay maintained a good state despite 30 years of extensive mariculture.

The successful case of IMTA practice in Sanggou Bay provided theoretical basis and good example for developing environment-friendly mariculture with "high efficiency, excellent quality, ecology, health and safety" and led the direction of the world's sustainable mariculture. In 2016, the Food and Agriculture Organization of the United Nations (FAO) and Network of Aquaculture Centers of Asia Pacific (NACA) promoted the IMTA model in Sanggyou Bay to the world as one of the 12 successful examples of sustainable and intensive aquaculture in the Asia-Pacific region.

Although the ecological IMTA at Sanggou Bay has made remarkable progress, there are still many challenges that it has to overcome, such as squeezed culture space, unscientific culture layout, low production efficiency per unit area and shortage of labor. Some suggestions on the future development of aquaculture industries are as follows:

1. Ecosystem-based management on mariculture. The concept of ecological management was first proposed by the British ecologist A.G.Tansey in 1935. However, different definitions and connotations about it arouse from different research objects, purposes and specialty. For example, Agee (1988) pointed out that ecosystem management refers to the regulation and control of the internal structure and function of ecosystems, input and output, so as to achieve the desired status from society. Verbay (1992) pointed out that ecosystem management refers to the elaborate utilization of ecology and economics, sociology, and management principles to manage the long-term production of ecosystems and to restore or maintain the integrity and desired status, utilization, products, values and services of ecosystems. The main purpose of ecosystem management is to ensure the ecological integrity and sustainability of ecosystems by adjusting the physical, chemical and biological processes of ecosystems (William, 2005).

2. With people's improving awareness of environmental protection, the environmental effects and management of mariculture have drawn widespread social concern. The management of

mariculture is no longer just to maximize output, but should take practical steps to focus on the ecosystem services. To implement the ecological mariculture management, we must have enough knowledge on the ecological concepts and mechanisms of the mariculature system. At the ecosystem level, mariculture is to harmonize culture activities with eco-sustainable development and to achieve the best balance between different social goals, taking into account the interactions between living things, non-living things and human beings in the ecosystem. Aquaculture at the ecosystem level places particular emphasis on proportioning among different aquaculture organisms, the balance between different culture modes, and the coordination and harmonization of aquaculture activities and environmental conditions; This is a technical means to achieve the maximization of input-output ratio of aquaculture and environmental impact of the benign. When applying ecological management: first, management activities must take into account the ecological, economic, social and institutional factors; Second, the management objectives is the mariculture activities rather than the mariculture ecosystem itself; Third, management objectives are to maintain the health and sustainable use of culture ecosystems. Through the development ecosystem management systems, it is expected to solve the key problems that restrict the sustainable development of mariculture, such as the squeezed culture space and the unscientific layout.

3. Develop standardized ecological farming. With the progress of urbanization, there is a serious shortage of aquaculture employees due to an aging trend. In order to ensure the sustainable development of aquaculture, mechanization and automation are imminent. At present, China's mariculture, especially the coastal longline farming, is extremely irregular to implement mechanical operations. Therefore, standard aquaculture is the only way to solve this contradiction. According to different culture methods, it is important to design suitable mechanized equipment and facilities for unified longline culture structure and culture density and also to develop mechanized harvesting equipment to provide automated technical support. Through the development of standardized eco-farming, many challenges such as raising costs, decreasing benefits and shortage of labor can be efficiently dealt with.

4. Establish aquaculture capacity management system. Carrying out the assessment of aquaculture carrying capacity is the basis for scientifically planning the culture scale, rationalizing culture structure and promoting modernization, as well as the prerequisite for ensuring the development of a green, low-carbon and environment-friendly aquaculture industry. Carrying capacity assessment should be included in the government's institutional management, to establish the regional farming carrying capacity assessment system and corresponding assessment center. Based on the ecosystem carrying capacity, technical specifications for aquaculture water bodies such as seawaters, tidal flats and ponds must be made to provide a scientific basis and regulatory measures for the sustainable development of modern aquaculture.

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