Shuang-Lin Dong
Xiang-Li Tian
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Yun-Wei Dong *Editors*

Aquaculture Ecology

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Foreword

Nearly 20 years ago, when I first visited the Laboratory of Aquaculture Ecology at the Ocean University of China in Qingdao, People's Republic of China, I was surprised by the name of the lab. Professor DONG Shaung-lin, director of the laboratory, explained that he and his team were studying aquaculture ecology as a branch discipline of aquaculture or applied ecology. They have conducted a series of studies on the aquaculture ecology, including the ecology of culture organism individuals, rationales of water quality regulation, ecology of aquaculture systems, interactions between aquaculture activities and environment, and ecological approaches to disease prevention.

As a member of the steering committee for the AQUA 2012 conference (the joint meeting of the WAS and the European Aquaculture Society organized once every 6 years in Europe), I proposed him for a keynote presentation about "Integrated Aquaculture in China" at this important conference in Prague. His presentation also convinced the audience of international aquaculture experts that China has explored a wide diversity of polyculture applications, both marine and freshwater, but moreover that Chinese researchers have underpinned these applications with an essential and novel understanding in the underlying biological processes of various polyculture models.

Inspired by this presentation, I was able to convince the European Aquaculture Technology and Innovation Platform (EATiP) to organize in 2013 a visit to Qingdao and other sites in the Shandong province for a group of aquaculture academics and businesspeople from several European countries. Guided by Prof. Dong, this was a real eye-opener for most participants who were not aware of the important developments in sustainable aquaculture as developed by Prof. Dong and his team. The world of aquaculture, especially in the Western world where all modern aquaculture developments are based on monoculture approaches, only recently has realized that the future of aquaculture needs to focus on a sustainable intensification, based on these new concepts as introduced by Prof. Dong and already practiced at significant industrial scale in China. These practices are now considered as a model for the first experimental demonstrations in the Western world, for example, as recommended and supported by the European Commission through its Horizon 2020 research and innovation framework program.

I have been looking forward to the publication of a textbook on aquaculture ecology. In 2017, the book *Aquaculture Ecology*, edited by Prof. Dong, was first published by China Science Press. Although written in Chinese, but with tables and figures in English, it was an important reference for the aquaculture literature. I am delighted that I can now write this foreword for the English edition of *Aquaculture Ecology* published by Springer in collaboration with China Science Press. The publication of this book marks the maturity of aquaculture ecology as a sub-discipline of applied ecology, which is very important for global aquaculture.

Aquaculture is the fastest-growing food production industry in terms of annual production growth and has become a significant contributor of essential macro- and micro-nutrients to the diets of the global population. Increasing the consumption of farmed aquatic food products over land-raised animal meat could potentially reduce the amount of land required for growing feed crops for a global population expected to reach 9.7 billion people by 2050. However, like other food production systems, aquaculture has undergone a process of intensification in recent decades, achieving high and predictable yields in the short term but potentially facing numerous challenges in the long term, such as environmental pollution, excessive resource consumption, and is furthermore affected by global climate change. These challenges will not only have an impact on the efficiency and sustainability of the aquaculture industry, but more importantly on the future of human food security. What kind of aquaculture models are beneficial for the sustainable development of the aquaculture industry is certainly worth studying!

Aquaculture ecology is the science of the interaction between commercial aquatic organisms as well as their farming activities and the environment, including the rationales of building and management of aquaculture systems. Its mission is to lay an ecological foundation for the sustainable development of the aquaculture industry.

The book runs through the dialectical ideas of ecological intensification. According to the authors, ecological intensification of aquaculture systems (ELIAS) is the most important rationale of building aquaculture systems, i.e., integrating anthropogenic inputs with aquaculture ecosystem services. The development history of aquaculture production systems is just an evolutionary process of ELIAS, in which processes for intensification (e.g., feeding, aeration) and ecological modification (e.g., polyculture, integrating with ecosystem services) take place alternately with the increasing demand for aquatic food products, advancement of technology, and increasing environmental concerns. Modern ELIAS stresses trade-offs among various considerations and aims to produce aquatic food products efficiently while protecting the environment, conserving natural resources, ensuring food safety, promoting social and economic development, and pursuing the maximization of comprehensive benefits instead of the maximization of a single aspect!

China's aquaculture has indeed the longest history, the largest scale, and the most varieties of aquaculture production systems. They also encountered and studied so many aquaculture problems; therefore, their experiences and achievements can be used as points of reference by many other countries in the world.

Patrick Sorgeloos

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Preface

Several ancient civilizations in the world have a long history of aquaculture. The farmed carp bones were present at the Early Neolithic Jiahu Site (around 6000 BC), Henan Province, China. FAN Li (536–448 BC) wrote the world's earliest fish farming book *Treatise on Fish Breeding*. However, it was not until 1952, when M. Huet began to elucidate the principles of fish farming in terms of biology and engineering and published the textbook *Trwité de Pisciculture* in French, aquaculture was changed from an "art" to a multidisciplinary science.

China is the cradle of ecological aquaculture. Since artificially cultivated rice already existed at the Jiahu Site, carp farming was probably carried out in paddy fields. In the Three Kingdoms Period (220–265 AD), the rice-fish farming was recorded in China. Later, in the book *The Curious in Lingbiao Region* written by LIU Xun of TANG Zhao-zong Dynasty (889–907 AD) it was recorded that "In the spring water was stored in ponds, then grass carp was bought and stocked into the ponds. After one or two years the fish had already grown up and wild weeds were grazed by the fish, meanwhile, paddy fields were also fertile," which might be the first interpretation of the mutually profitable relationship between grass carp and paddy.

However, until the late 1950s, Chinese scientists began to summarize the traditional freshwater fish farming experiences and techniques, and published *Freshwater Fish Aquaculture in China* in 1961. The masterpiece initially elaborated the ecological principles on which Chinese traditional farming techniques were based. Therefore, the 1950s can be regarded as the germination stage of aquaculture ecology in China.

Since then, with the development of the aquaculture industry and the progress of sciences and technologies, the research depth and extent of aquaculture ecology are increasing. After more than 60 years, aquaculture ecology has developed to be a relatively complete knowledge system, and the Chinese edition of *Aquaculture Ecology* was published in 2017, which has been recommended as one of the seven core postgraduate textbooks for fisheries and aquaculture disciplines by the Academic Degrees Committee Office of the State Council of China.

Since 1998, when I began to teach the course *Introduction to Aquaculture Ecology* for graduate students at Ocean University of China, I have been asking myself and the students who take this course every year the question, "What will the pattern of aquaculture industry be in 20 or 50 years?" The purpose of this course is to enable the students to view and understand aquaculture production systems from a broader perspective and over a longer time scale.

Aquaculture production systems or models have gone through or are going through development stages of extensive monoculture, extensive polyculture, semi-intensive polyculture, intensive monoculture, and intensive integrated aquaculture. The history of aquaculture development is an evolutionary process of ecological intensification with the increasing demand for aquatic food products, scientific and technological progress, and increasing environmental concerns. If the extensive fish culture 8000 years ago is counted as the first step of mankind from fishing to farming, then the emergence of polyculture is the milestone of ecological intensification in which mankind makes full use of the productivity or natural feed organisms in ponds. In the 1950s and 1960s, with the invention of pelleted feeds, floating polyethylene net cages and floating aerators, aquaculture production and area coverage increased rapidly, leading to a new stage of intensive monoculture. However, as the negative environmental impacts of intensive monoculture have become noteworthy on a large scale, the development of intensive integrated aquaculture is on the new agenda of aquaculture development.

Nowadays, human beings are confronting with the triple challenges of population growth, environmental pollution, and global climate change, and only the Green Aquaculture or production systems based on non-fossil energy and/or photosynthesis can enable aquaculture to achieve simultaneously the ultimate goals of high yield, zero discharge, and low carbon or carbon neutrality. In this sense, aquaculture ecology is also a science that provides ecological foundation to support the green development of aquaculture.

Since there are huge differences among countries in the world in terms of development stage, geographical location, degree of marketability of aquaculture products, dietary habits, etc., it is unlikely that there is a certain aquaculture production system that can dominate anywhere in the world. However, aquaculture production systems everywhere must contribute to the sustainable development of aquaculture nowadays.

The boundary of an aquaculture ecosystem is the extent of a farm, including aquaculture waters, ancillary land, and the available space above them. Various ecosystem services (provision, regulation, support, and culture) can be integrated into aquaculture ecosystems to improve their outputs, comprehensive benefit, and system sustainability. In fact, the development process of fisheries and aquaculture is just a process in which mankind gradually deepen their understanding and utilization of ecosystem services.

The textbook contains 15 chapters, covering the individual ecology of farmed organisms (Chaps. 5 and 6), management of water and sediment quality (Chaps. 7 and 8), system ecology of aquaculture (Chaps. 1–3, 9–12, and 15), the interaction between aquaculture and the environment (Chaps. 4 and 15), and health maintenance and welfare of farmed animals (Chap. 14). Chapters 10, 12, and 14 of the book were edited mainly by Prof. Xiang-li Tian, Prof. Qin-feng Gao, and Prof. Yun-wei Dong, other chapters were edited by Prof. Shuang-lin Dong. Some of the chapters are translated from Chinese version to English by Prof. Yan-gen Zhou and Associate Prof. Li Li.

Aquaculture ecology is a rapidly developing discipline, with a wealth of new knowledge being generated every day, and there are bound to be some very good findings by colleagues that have not been compiled in this book. In addition, there must be many flaws or even errors in the book, we would like to invite experts and the general readers to correct them, so that the book can be improved in the next edition.

Qingdao, China Shuang-Lin Dong

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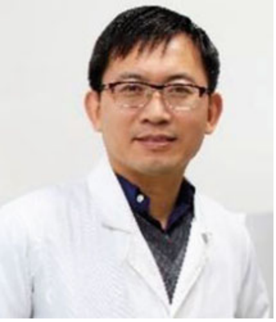
Editors and Contributors

About the Editors

Shuang-Lin Dong is the head of Laboratory of Aquaculture Ecology at Ocean University of China, the director of Marine Economy Society under Chinese Society for Oceanogroghy, and the head of Aquaculture Ecology Society under Chinese Society for Oceanology and Limnology. His research focused on aquaculture ecology, especially biological regulation of water quality, structure optimization of integrated aquaculture systems, ecological intensification, and sustainability of aquaculture systems. Currently, he devotes himself to the ecology and technology of deeper-offshore fish farming. Shuang-lin got his Ph.D. in Aquaculture in 1992 from Ocean University of China in Qingdao. Since 1994, he has been working at Ocean University of China as an associate professor, professor, the Vice President of Ocean University of China (2003–2015). He served as the Vice Chairman of China Society of Fisheries from 2005 to 2012, and the Convenor of Fisheries Discipline of Discipline Assessment Group of the State Council of China from 2014 to 2019.

Xiang-Li Tian is a professor in the Laboratory of Aquaculture Ecology at Ocean University of China. He obtained his Ph.D. in Aquaculture from Ocean University of China in 2001. He has studied aquaculture ecology, especially microbial ecology in mariculture, for over 20 years. Currently, his research has mainly focused on the structure and function of microbial community in aquaculture ecosystems and application of probiotics. Xiang-li has published more than 200 peer-reviewed papers in English and Chinese and six books (in Chinese).



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Yun-Wei Dong is a professor in the Laboratory of Aquaculture Ecology at Ocean University of China, and the deputy director of Aquaculture Ecology Society under Chinese Society for Oceanology and Limnology. He received his Ph.D. in Ecology in 2002 from Beijing Normal University and has worked in the fields of aquaculture ecology and animal ecological physiology for over 20 years and now is interested to study aquaculture zoning in the context of climate change. Yunwei has published more than 100 peer-reviewed papers in English. Yunwei is a member of some scientific associations (e.g., Chinese Society of Marine Ecology, Chinese Society of Animal Ecological Physiology) and services as associate editor of some international journals, like *Diversity and Distributions*, *Journal Marine Experimental Biology and Ecology*, *Marine Life Science & Technology*.

About the Contributors

Li Li is an associate professor in the Laboratory of Aquaculture Ecology at Ocean University of China. She obtained her Ph.D. degree from Auburn University in 2012 and was honored with the “Graduation Marshal” of the university. She has worked in the field of aquaculture ecology especially in the interactions between aquaculture activities and the environment for over 10 years. She has published more than 40 peer-reviewed papers and 2 book chapters.

Yan-Gen Zhou is a professor in the Laboratory of Aquaculture Ecology at Ocean University of China. He obtained Ph.D. degree at Auburn University in 2014. Afterwards, he became a postdoctoral fellow at Auburn University. Currently, his research has focused on aquaculture ecology, especially in eco-physiological of Salmonidae fish. He published more than 40 peer-reviewed papers in English, 11 papers in Chinese, and 2 book chapters until now.

Introduction

1

Shuang-Lin Dong

Aquaculture is the fastest growing food production industry in terms of annual growth rate and has become an important contributor in supplying essential macro- and micro-nutrients for the global population (FAO 2020). In 2018, the global aquaculture production reached 114.5 million tons, including 82.1 million tons of farmed animal products and 32.4 million tons of aquatic plants (live weight), with a total first sale value of USD 263.6 billion.

China is the dominant producer of aquaculture, accounting for 57.9% of farmed seafood of the world. In 2018, the per capita share of aquatic products in China was 46.3 kg, more than two times of the world per capita share (Fisheries Bureau, Ministry of Agriculture of P R China 2019).

Aquaculture shoulders the mission of improving people's livelihood, economy development, reducing poverty, and guaranteeing human food security. However, the development of the world aquaculture, especially the China's aquaculture, has faced grand challenges such as environmental pollution, excessive resource consumption, and is being affected by climate change. These issues will not only affect the efficiency, sustainability of aquaculture, and more importantly the future of human food security. What kinds of aquaculture models are beneficial to the sustainable development of aquaculture industry is worthy of deep consideration and study! Aquaculture ecology is the science of studying these matters.

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1.1 Aquaculture and Aquaculture Ecology

The word “aquaculture” has three meanings: an art, a science, and an industry or business. Aquaculture is the art and industry of farming aquatic organisms including fish, mollusks, crustaceans, and aquatic plants. The scientific meaning of aquaculture refers to the systematic elaboration of aquaculture technology and its rationales, which is an interdisciplinary subject of physiology, ecology, water environment chemistry, engineering, etc. Aquaculture ecology belongs to the category of applied ecology and is the sciences on the interaction between commercial aquatic organisms as well as their farming activities and the environment, and the rationales of building and management of aquaculture systems.

1.1.1 From an Art to a Science of Aquaculture

The earliest fishing arose out of the fundamental human quality of opportunism two million years ago or so in Africa (Fagan 2017). In the sense that we are familiar with it today, fishing came into its own with the natural global warming that ended the last Ice Age glaciation, when many communities now dwelt in the same locations either permanently or for many months of the year (Fagan 2017). Many fish bones were found in the cultural layer of Zhoukoudian Mountain Cave (20,000 years ago), Beijing, indicating the consumption of fish by primitive humans. Fish hooks and fish darts were found in many sites in the Stone Age. When demand for fish mushroomed to the point that the local supply became overfished, one of the options for the people was fish farming.

Several ancient civilizations in the world have a long history of aquaculture. The Chinese, Egyptians, the Sumerians of Mesopotamia, and the Greeks and Romans all had long history of aquaculture (Liu and He 1992; Nash 2011; Nakajima et al. 2019). Easily caught and kept in enclosed ponds, carps were domesticated by the Chinese well at a time from which there are no written records of fishing or aquaculture (Fagan 2017). Nakajima et al. (2019) reported that farmed common carp (*Cyprinus carpio*) was present at the Early Neolithic Jiahu site (around 6000 BC), Henan Province, China, after studying the age mortality and species selection profiles of fish bones. In the eleventh-century BC, there were records of fish farming in Chinese oracle bone inscriptions (Liu and He 1992).

A relief in the tomb of Aktihep, an official of the Middle Kingdom about 2500 BC, shows men removing tilapia from a pond (Nash 2011; Fagan 2017). Marcus Terentius Varro (116–27 BC), a Roman scholar, reported the fish farming activities in freshwater and seawater ponds in his book *Rerum Rusticarum Libri Tres* (*Three Books on Agriculture*) (Fagan 2017). Fish raised in ponds has become an important food for monks and poor people in the Middle Ages (Pillay and Kutty 2005).

During the Spring and Autumn Period and the Warring States Period in 460 BC, FAN Li compiled the world’s earliest fish farming book “*Treatise on Fish Breeding*,” which introduced the pond conditions, artificial breeding, and stocking methods of carp. Later, the farming technology of carps spreadeds to other Asian countries. Common carp has been raised in Japan for more than 1900 years (Ling 1977).

Although aquaculture textbooks were offered in some countries at the beginning of the last century (Roule 1914), their main contents were aquaculture techniques obtained through experiences or trial and error. Until the middle of the last century, due to the intervention of science and technology, aquaculture changed from an "art" or techniques to a multidisciplinary science (Stickney and Treece 2011). In 1952, M. Huet published a fish farming textbook "*Trwité de Pisciculture*" in French. In 1959, several ichthyologists, hydrobiologists, and aquaculture experts in China worked together to summarize China's traditional freshwater fish farming experiences and techniques, and scientific principle-based, and finally published "*Freshwater Fish Aquaculture in China*" (Freshwater Fish Farming Experience Summary Committee of China 1961). The semi-intensive farming techniques of eight words [water (quality), seed, feed, density, polyculture, rotation, (disease) prevention, and management] have been summarized in this book and have been applied for guiding and promoting inland aquaculture in China for several decades. Since then, several other books on fish farming have been published (e.g., Hickling 1962; Bardach et al. 1972).

The aquaculture and enhancement of fishery resources share the same primary goals to increase output of aquatic products in waters. However, the former mainly focuses on the increase in individual or stock weights of farmed organisms, while the latter emphasizes the increase in population size and subsequent increases in production. Silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*) usually cannot reproduce naturally in reservoirs or lakes, while common carp (*Cyprinus carpio*) can reproduce naturally. Therefore, the stocking of silver carp and bighead carp in reservoirs or lakes is an aquaculture activity, while the stocking of common carp in reservoirs or lakes should be called enhancement and aquaculture of the fish. De Silva (2003) called the latter activity as culture-based fisheries.

1.1.2 Aquaculture Ecology

Aquaculture ecology belongs to the category of applied ecology. It studies the interaction between commercial aquatic organisms as well as their farming activities and the environment, and elucidates the rationales of building and regulating aquaculture production systems. Its mission is to lay an ecological foundation for the sustainable development of aquaculture.

As aquaculture organisms are aquatic organisms, some aspects of aquaculture ecology are similar to hydrobiology. However, aquaculture ecology studies broader issues, such as the interaction between aquaculture activities and the environment, the ecological economics of the aquaculture system, and the sustainable development of the aquaculture industry. Aquaculture ecology is closely related to the development of aquaculture industry. The technicalization of its theoretical achievements (i.e., technological innovation under the guidance of new theories) can correspondingly promote the development of the industry; on the other hand, its development is strongly driven by the expansion of the industrial scale and scope, and the increase in farming species.

Aquaculture is the farming activity of commercial aquatic organisms under artificial intervention and is an integration of natural and artificial processes. As a science, aquaculture mainly focuses on the rationales and techniques of reproduction, hatching, stocking and biomass adjustment of farmed organisms, cultivation and utilization of diet or forage organisms in farming waters, feeding strategy, water quality control, disease prevention, and production performance of different production models (Liu 2000; Parker 2002; Liu and Huang 2008). In addition to the ecological principles underlying aquaculture techniques, aquaculture ecology pays more attention to the structure and function of aquaculture ecosystems, the interaction between aquaculture activities and the environment, sustainability of aquaculture production systems, and so on. In sum, aquaculture emphasizes on individual or stock weight growth and actual farming benefits, while aquaculture ecology stresses the issues such as ecological efficiency, the impact of farming activities on the environment, and sustainability of production systems.

1.2 Development of Aquaculture Ecology in China

The development of aquaculture ecology in China can be briefly divided into three phases, i.e., germination, rapid expansion, and maturation phases. After about 60 years' development, aquaculture ecology has formed its distinctive characteristics, and it is not only a sub-discipline of applied ecology but also a sub-discipline of aquaculture.

1.2.1 Germination Phase of Aquaculture Ecology

Humans have carried out fish farming activities for about 8000 years at the Jiahu Site, Henan, China. Since artificially cultivated rice already existed at the Jiahu Site, carp farming was probably carried out in paddy fields. Until the Three Kingdoms Period (220–265 AD), the rice – fish (common carp) farming was recorded in China. Later, in the book "*The Curious in Lingbiao Region*" written by LIU Xun of TANG Zhao-Zong Dynasty (889–907 AD) it was recorded that "In the spring water was stored in ponds, then grass carp was bought and stocked into the ponds. After one or two years the fish had already grown up and wild weeds were grazed by the fish, meanwhile, paddy fields were also fertile," which might be the first record of ecological aquaculture and the interpretation of the mutually profitable relationship between grass carp and paddy. Meanwhile (AD 618–907), the pattern of polyculture of carps was also developed and popular in China.

The German zoologist Haeckel raised the term "Ecology" in 1866. If take this year as the beginning of ecology science, the history of ecology is 156 years. The history of hydrobiology could be traced back to 153 years ago, when the Swedish Forel proposed the term "Limnology" in 1869 (Li and Chen 1996). Although hydrobiologists conducted a lot of research on the ecology of some commercial aquatic organisms before 1950s, a conscious and substantive crossover study of aquaculture and ecology appeared in China in 1950s, indicating aquaculture ecology had begun to germinate.

In 1961, the book "*Freshwater Fish Aquaculture in China*" was published. In this book, the ecological characteristics of some farmed fish, the principles of fish farming in rice fields and pond fertilization, the relationship between water quality and disease occurrence in pond, and the relationship between commercial fish spawning and environmental factors were elucidated. Then, it becomes more and more popular in China to guide the scientific research and production practice of aquaculture with the principles of ecology. The diversity of China's aquaculture production systems is the highest in the world; therefore, research topics of aquaculture ecology in China are also one of the most extensive in the world.

1.2.2 Rapid Expansion Phase of Aquaculture Ecology

In the 1960s and 1970s, some remarkable results were achieved in aquaculture ecology of inland pond farming. People developed the polyculture principles of fishes with divergent ecological niches in intensive and semi-intensive culture ponds, the theories of rotary stocking and harvest to increase ecological carrying capacity, and principles of water quality regulation. At the same time, the theories of paddy fish farming and some other types of integrated aquaculture were improved (Liu and He 1992).

In the early 1960s, the study of physio-ecology of seaweed promoted the southward movement of kelp cultivation areas and the development of nori and wakame cultivation in China. In the 1970s, the studies of fish physio-ecology and water quality management theory promoted the development of indoor intensive fish farming.

In terms of aquaculture in large waters, the Institute of Hydrobiology of the Chinese Academy of Sciences systematically carried out qualitative and quantitative analyses of biological community structure of East Lake, Wuhan, in 1960s. In the late 1970s, aquaculture ecology of large inland waters developed vigorously. The relationship between phytoplankton production and fish productivity was studied, and production promotion trials were conducted in lakes and reservoirs (Li 1980; Wang and Liang 1981; He and Li 1983a, 1983b; Li 1986). Research on the fish physio-ecology provided theoretical support for the development of cage aquaculture in reservoirs and lakes. Parts of the study achievements during this period had been compiled in "*Studies on Ecology of East Lake (1)*" (Liu 1990), "*Chinese Freshwater Fish Aquaculture (Third Edition)*" (Liu and He 1992), and other works.

In 1980s, a comprehensive study on fish productivity and integrated aquaculture was carried out in China, and all these works effectively promoted the vigorous development of fish farming in lakes and reservoirs. During this period, fish productions of lakes and reservoirs in China were promoted dramatically. Meanwhile, great progress was made in the studies of aquaculture ecology of shallow lakes, especially on the relationship between lake eutrophication and aquaculture. These research achievements were partly compiled in "*Studies on Ecology of East Lake (2)*" and other works (Li et al. 1993a; Liu 1995).

Beginning in 1980s, aquaculture ecologists began to use medium-sized enclosures for aquaculture ecology (Xie and Liu 1992; Li et al. 1993b), such as the carrying capacity of reservoirs for fed fish farming in net cages and the ecological effects of filter-feeding fishes in lakes and reservoirs. The application of enclosure experiment promotes the field research of aquaculture ecology stepping into the research stage of manipulative experiments. Subsequently, Professor Li De-Shang's team in Qingdao Ocean University (now Ocean University of China) used medium-sized land-based enclosures in pond to investigate the structure optimization of Chinese shrimp (*Fenneropenaeus chinensis*) and the structure optimization of fishes in seawater and saline-alkali ponds (Li et al. 1998; Zhao et al. 2000a).

In 1990s, the negative effects of overstocking and over-feeding have appeared in some lakes and reservoirs in China. The over-feeding issues and pollutant discharge from shrimp farming ponds were also emerged. Therefore, aquaculture ecologists began to study the relationship between aquaculture development and environmental protection, principles of pollution-free aquaculture models, carrying capacity of fish farming in reservoirs, high-quality and high-efficiency farming models in shallow lakes, etc. Parts of the study results were compiled in "*Resources, Environment and Fishery Ecological Management of Macrophytic Lakes*," "*Fishery Resources and Environment Conservation in Lakes of the Changjiang River Basin*," and other works (Li et al. 1994; Liang and Liu 1995; Li et al. 1999; Cui and Li 2005).

Although the research scopes on aquaculture ecology in abroad are relatively narrow due to less variety of aquaculture production systems compared with that in China, some fundamental studies have been done in-depth. Representative works include "*Detritus and Microbial Ecology in Aquaculture*" (Moriarty and Pullin 1987), "*Pond Aquaculture Water Quality Management*" (Boyd and Tucker 1998), and "*Aquaculture on the Environment*" (Pillay 1992). Since the late 1980s, European countries around the North Sea established the organization within the International Council for the Exploration of the Sea (ICES) to study the interaction between mariculture and the coastal environment. Through years of large-scale and in-depth research, main types of pollutants discharged by the mariculture, the paths, and degree of pollution to the North Sea have been basically identified. Meanwhile, control measures of mariculture pollution have been proposed, and the aquaculture technology has been improved accordingly (Dong et al. 2000). Odum and Arding (1991) have also begun to study aquaculture systems as an economic ecosystem.

At the end of the twentieth century, people began to pay great attention to the sustainable development of aquaculture. In China, people began to introspect the farming models of lakes and reservoirs (Li and Chen 1996). Seaweed is proposed as a biofilter to treat the pollution of mariculture ponds (Neori et al. 1996). Well-known scholars led by Professor Naylor of Stanford University published articles in Science and Nature magazines (Naylor et al. 1998, 2000) and questioned the development patterns of mariculture. Since then, people began to pay high attention on the issue of sustainable development of aquaculture in the world.

1.2.3 Mature Phase of Aquaculture Ecology

Entering the twenty-first century, people begin to advocate closed integrated shrimp mariculture in pond and sustainable aquaculture models (Li and Dong 2002; Christou et al. 2012; Hai et al. 2018). The concepts of zero pollutant discharge, pollution-free, ecological aquaculture, and sustainable development have become popular in published papers in the field of aquaculture ecology.

In response to climate change, many scholars around the world have begun to study its impacts on fisheries and aquaculture. Chinese scholars have also proposed the concept of “carbon sinking fishery” (Tang et al. 2011). The main products in China’s mariculture are mollusks, and their shells contain a large amount of carbon. From 1999 to 2008, farmed mollusks fixed 670,000 tons of carbon in China, equivalent to 2.45 million tons of CO_2, which could be converted into a “carbon sink forest” of about 279,000 ha.

In recent years, some scholars have begun to pay attention to water footprint, land occupation, carbon footprint, ecological footprint of aquaculture production systems, and the welfare of farmed fishes (Boyd et al. 2007; Cao et al. 2013; Boyd and McNevin 2015; Dong 2019a; Tonil et al. 2018). In order to reduce the negative impact of aquaculture on the environment, the concept of ecological intensification of aquaculture systems, i.e., integrating anthropogenic inputs with aquaculture ecosystem services, is proposed, and solar recirculating aquaculture systems (SRAS) and deeper-offshore mariculture have been put into practice (Dong 2015a, 2019b; Dong et al. 2022).

Since the publication of “*Freshwater Fish Aquaculture in China*” in 1961 as the birth of aquaculture ecology in China, it has been developed for 60 years since then. As a sub-discipline of applied ecology or sub-discipline of aquaculture, aquaculture ecology has gradually formed a distinctive theory system (Dong 2016).

1.3 Sustainable Development of Aquaculture

Aquaculture has a history of 8000 years, but now significant environmental pollution due to aquaculture activity has emerged in recent decades. The reason, in addition to its rapid expansion, is related to some of aforetime improper development ideas and models. This section is going to introduce the status, trends, challenges, and sustainable development of aquaculture industry with references to China.

1.3.1 Status and Trends of Aquaculture Development

1.3.1.1 Status of Aquaculture Development

In 2018, the world fisheries production reached about 179 million tons (excluding aquatic plants), of which 87.2% were used for human consumption, equivalent to an estimated annual supply of 20.5 kg per capita (FAO 2020). Global food fish consumption increased at an average annual rate of 3.1% from 1961 to 2017. The rate is almost twofolds of annual world population growth (1.6%) for the same period and higher than that (2.1%) of all other animal protein foods (meat, dairy, milk, etc.). Fisheries and aquaculture have made important contributions to ensuring human food security and relieving hunger or malnutrition.

In 2018, the total world aquaculture production attained 114.5 million tons, of which 82.1 million tons were farmed animal products and 32.4 million tons were aquatic plants (live weight). The contribution rate of aquaculture (excluding aquatic plants) to the total global fisheries and aquaculture production increased from 25.7% in 2000 to 46% in 2018 and 52% in terms of edible parts. The aquaculture production of 39 countries including China has surpassed production of capture fisheries.

A total of 62.5% of the world's aquaculture animal production was produced from inland aquaculture in 2018. Among the aquaculture products, fish, mollusks, and crustaceans accounted for 66.1%, 21.3%, and 11.4%, respectively. The proportions of the top five species to total farmed fish production were 10.5% for grass carp, 8.8% for silver carp, 8.3% for Nile tilapia, 7.7% for common carp, and 5.8% for bighead carp. The production of white-leg shrimp (*Litopenaeus vannamei*) and red swamp crayfish (*Procambarus clarkii*) accounted for 52.9% and 18.2% of farmed crustacean production, respectively. Oyster (*Crassostrea* spp.), Philippine clam (*Ruditapes philippinarum*), and scallop (*Pectinidae* spp.) accounted for 29.5%, 23.6%, and 11.0% of farmed mollusk production, respectively.

World widely, the top five countries in terms of aquaculture animal production in 2018 were China (67.9.5% of total aquaculture production), India (8.6%), Indonesia (6.6%), Vietnam (5.0%), and Bangladesh (2.9%), and the five are all Asian countries, while the major aquaculture countries in Europe, America, and Africa were Norway (1.6%), Chile (1.5%), and Egypt (1.9%).

China is the dominant country of the world in aquaculture production. The total aquaculture production of China mainland in 2018 was 49.91 million tons, of which finfish production was 26.94 million tons and mollusk production was 14.65 million tons (Table 1.1).

The structure of China's aquaculture is different from that of the developed countries. China's mariculture products are mainly filter-feeding mollusks and seaweeds, which do not need to be fed. Marine finfish and crustaceans that need to be fed only account for 15.8% of the total mariculture production (Table 1.1). The freshwater farmed finfish such as silver carp, bighead carp, and grass carp, which are popularly cultured in China, are filter-feeding or herbivorous fishes. They can effectively use natural diet organism resources, such as phytoplankton, zooplankton, and aquatic plants in waters. The trophic levels of farmed species currently in China are generally low, and the ecological efficiencies of the species are high. Therefore,

Table 1.1 Aquaculture production and composition of the China in 2018

Groups	Mariculture Productions/10^4t	 %	Inland aquaculture Productions/10^4t	 %
Finfishes	150	7.4	2544	85.9
Crustaceans	170	8.4	344	11.6
Mollusks	1444	71.1	20	0.7
Aquatic plants	234	11.5	0.7	0.02
Others	33	1.6	51	1.7
Total	2031	100	2960	100

Note: the data excluding Hong Kong, Macao, and Taiwan. Similarly, hereinafter

Table 1.2 Aquaculture productions of different systems in China in 2018

Mariculture			Inland aquaculture		
Types	Productions (10^4t)	%	Types	Productions (10^4t)	%
Pond	246.7	12.1	Pond	2211.0	74.7
Raft and lantern cage	740.0	36.4	Lake and reservoir	392.7	13.3
Net cage	74.9	3.7	Net cage and pen	67.5	2.3
Indoor intensive	25.5	1.3	Indoor intensive	21.3	0.7
Bottom enhanced	531.2	26.1	Paddy field	233.3	7.9
Others	412.9	20.4	Others	34.0	1.1

China's aquaculture has been widely praised by the international community and has made essential contributions to human food security.

Table 1.2 lists the sources of China's aquaculture production in 2018. Mariculture products mainly come from raft, net lantern cage, and bottom enhanced culture, and farmed species are mainly mollusks, while inland aquaculture products mainly come from pond farming, and farmed species are mainly finfish. Intensive aquaculture (net cage, pen, and indoor intensive tank) accounts for 5.0% of mariculture and only 3.0% of inland aquaculture (Fisheries Bureau, Ministry of Agriculture of P R China 2019).

Due to the rapid expansion of aquaculture, the industry has encountered many challenges. Understanding the development trends and challenges of the industry is of significant importance to solve these problems and to guide aquaculture to the track of sustainable development.

1.3.1.2 Trends of Aquaculture Development

Aquaculture production has progressively surpassed that of capture fisheries in the world. The "farming more than catch" was reached for seaweeds in 1970, for freshwater finfishes in 1986, for mollusks in 1994, for diadromous fishes in 1997, and for crustaceans in 2014. In 2016, in terms of consumption (excluding fishmeal, fish oil, etc.), global aquaculture production exceeded global capture production (FAO 2018). As early as in 1988, the aquaculture production has surpassed the

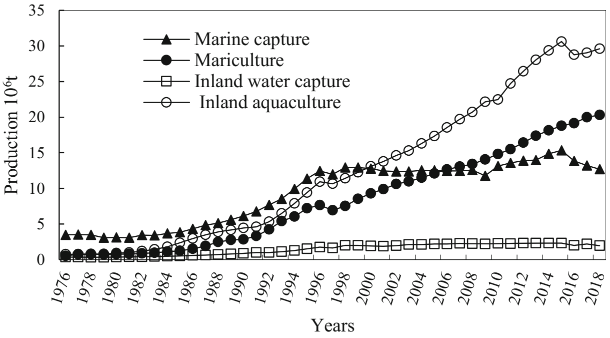


Fig. 1.1 Fisheries production in China. The data excluding Hong Kong, Macao, and Taiwan. Similarly, hereinafter

capture production in China. In 2006, the mariculture production has also exceeded the production of marine capture fisheries (Fig. 1.1). Due to the limited inland fishery resources and the decline of coastal fishery resources, the increment of fisheries production in near future will mainly come from the development of aquaculture in China.

World aquaculture production of farmed animals grew on an average of 5.3% per year in the period 2001–2018, whereas the growth was only 3.2% in 2018 and 1.6% in 2018 in China (FAO 2020). The supply of aquatic food products in China has changed from an overall shortage to a structural surplus, accompanied by regional and seasonal imbalances in supply and demand (Sun 2000). Therefore, the growth rate of aquaculture production in China has slowed down significantly in the past decade. The policy of "reducing volume and increasing efficiency" implemented in China after 2016 has exacerbated this trend. In addition, the number of farmed species, the proportion of fed species production, and the level of intensification continue to increase in China.

1.3.1.3 The Number of Farmed Species Items Continues to Increase

According to FAO, in the past 10 years, the total number of commercially farmed aquatic species items increased by 26.7%, from 472 in 2006 to 598 in 2016 (FAO 2018). At present, there are more than 200 farmed aquaculture species in China. Driven by the product value, Chinese are keen to develop "famous, special, excellent, and new" species items to culture (Fig. 1.2). Although a newly developed species item has a price advantage in the market, its price usually falls eventually when its breeding technology matures and its aquaculture industry has achieved a certain farming scale. Because the cost of its farming will increase gradually with the increase in fish meal, energy prices, and labor costs, the profit margin will become narrower. Then, farmers try to find other new farming species items.

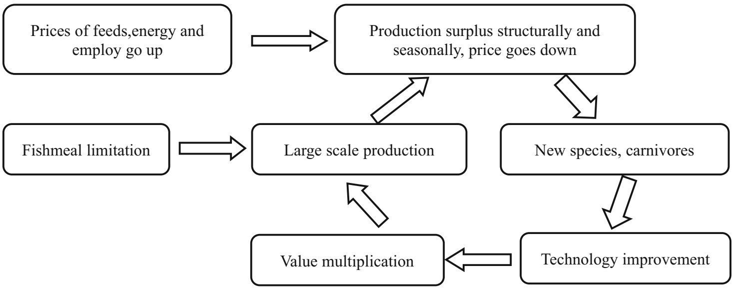


Fig. 1.2 An example of the aquaculture development patterns driven by the product price in China

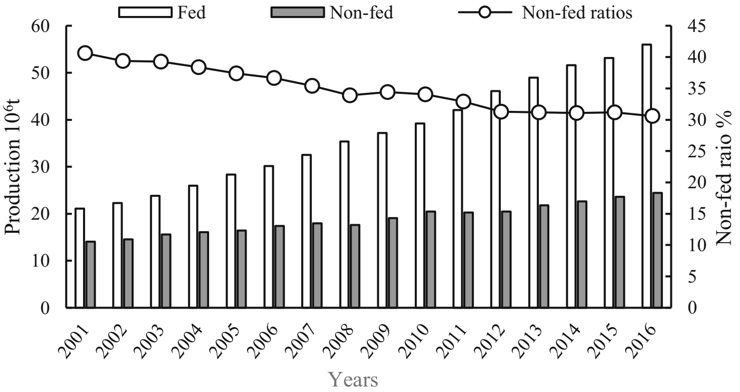


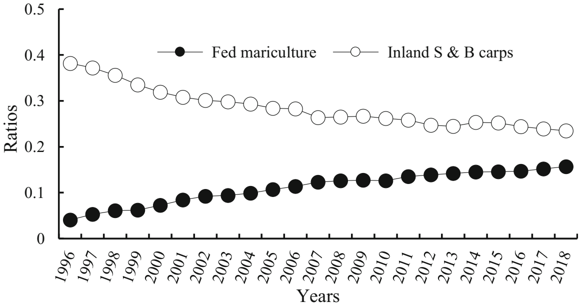
Fig. 1.3 Fed and non-fed food fish aquaculture production in the world (from FAO 2018)

1.3.1.4 The Proportion of Fed Species Production Keeps Increasing

The production share of fed aquatic animal species is increasing and has exceeded the proportion of non-fed species in world aquaculture. The share of unfed species in total aquatic animal production decreased gradually to 30.5%, shrinking by 10% points from 2000 to 2016 (Fig. 1.3). In absolute yields, the unfed species farming output continues to expand, but the expansion is slower than fed species. It is worth mentioning that traditional grass carp culture in China was fed with fresh grasses, but now it is basically fed with pellet feeds. In 2018, the production of farmed grass carp in China was 5.50 million tons, accounting for 21.6% of inland farmed fish production in China and 10.5% of farmed fish production in the world.

In 1996, mariculture production was 7.66 million tons in China, 4.1% of which was fed fish and crustaceans. By 2018, the mariculture production reached 20.31 million tons; however, 15.7% of which was fed fish and crustaceans (Fig. 1.4). In 1996, the production of inland aquaculture in China was 10.94 million tons, 38.2% of which was non-fed silver carp and bighead carp. By 2018, it reached 29.6 million tons; however, the proportion of the non-fed carps dropped to 23.5%. In both mariculture and inland aquaculture, the share of fed species continues to rise.

Fig. 1.4 Production ratio of fed fish and crustacean in mariculture to total mariculture and the production ratio of silver carp (S) and bighead carp (B) to total inland aquaculture in China



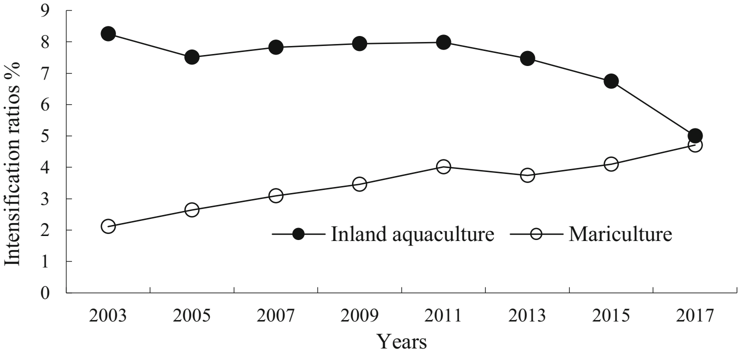


Fig. 1.5 Intensification ratios of aquaculture production from 2013 to 2017 in China

Overall, in 2009, about 41% of China's aquaculture production were derived from fed species aquaculture (Dong 2009b), and it rose to 47% by 2016 (Dong 2019a).

1.3.1.5 The Level of Intensification Continues to Increase

The level of intensification of aquaculture can be divided into intensive, semi-intensive, and extensive aquaculture based on nutrient input, stocking density, and productivity (Boyd and McNevin 2015; Hai et al. 2018). From an ecological perspective, the intensification of aquaculture can also be classified according to the composition of energy source of production system and the ecological factors limiting productivity (see Sect. 2.1 for details). The proportion of fed species production can be used as an indicator of intensification level of a country or region. In addition, the adoption rate of intensive aquaculture systems (cage, pen, raceway, indoor facilities) is also an indicator of intensification level. Figure 1.5 shows the changes in the intensification ratios (the ratio of intensive aquaculture system production to total aquaculture production) in China in the past 15 years. The intensification level of mariculture has been increasing, from 2.1% in 2003 to 4.7% in 2017. However, due to environmental protection reasons, many aquaculture pens and net cages in reservoirs and lakes have been restricted or banned, and the intensification ratios of freshwater aquaculture has been decreasing significantly in recent years.

In addition, the wide application of pellet feed and aeration greatly increases the stocking density and yield per unit waters accordingly. Annual production of channel catfish (*Ictalurus punctatus*) in ponds in the southern United States was less than 2000 kg/hm^2 in the early 1970s and increased to 3713 kg/hm^2 in 2000 and to 5544 kg/hm^2 in 2010 (Boyd and McNevin 2015). In 2008, the productivities of inland and seawater ponds in China were 6800 kg/hm^2 and 4030 kg/hm^2, respectively, and by 2018, the corresponding productivities reached 8290 kg/hm^2 and 6170 kg/hm^2, respectively.

1.3.2 Major Challenges to Aquaculture Development

Aquaculture activities have a certain impact on the environment, and on the other hand, environmental changes have also an impact on aquaculture system and farmed organisms (see Chap. 4 for details). Although aquaculture has a history of 8000 years, the aquaculture scale has been expanding rapidly only since 1970s due to the application of artificial pellet feed, aerators, and modern net cages. Nowadays, the development of aquaculture is subjecting to various constraints and challenges.

The factors restricting the development of world aquaculture include three aspects, i.e., environment, resources, and society. Resources and environmental factors are pollution (organic matter, N, P, antibiotics, pesticides, heavy metals, etc.), natural resources (fishmeal, freshwater, habitat, etc.), diseases, biodiversity, etc. (Granada et al. 2016; Boyd and McNevin 2015; Naylor et al. 1998, 2000), while social factors include conflicting with other sectors, regulatory gaps, and fish welfare (Naylor and Burke 2005; Jennings et al. 2016). The National Oceanic and Atmospheric Administration of the United States (NOAA) hopes to increase the output value of the US aquaculture industry from less than US$ 100 million to US$ 5 billion by 2025 (US Dep. Commer 2001). Offshore mariculture is the strategic direction of its development, but the development of offshore mariculture in the exclusive economic zone (EEZ) under the jurisdiction of the federal government still faces strict restrictions, such as lack of regulations and social welfare (Naylor and Burke 2005).

A healthy aquaculture development pattern should be able to provide people with sufficient, safe, sustainable, shockproof, and sound aquatic products (Jennings et al. 2016). Due to difference in development stages, farming models, geographical environment, and resource endowments of aquaculture in various countries, the current constraints and challenges faced by different countries in aquaculture development are also different. For example, the most urgent challenges facing Norwegian aquaculture are the parasitic sea lice problem of Atlantic salmon and the limited carrying capacity of fjords, while the most urgent issues in the face of China's aquaculture are pollution, food safety, freshwater shortage, etc. (Dong et al. 2022).

Although the development of aquaculture has encountered many constraints and challenges, some of them are not inherent in aquaculture. For example, some epidemic diseases in aquaculture are largely management issues and economic affordability for prevention and treatment. If the strategies of thorough quarantine and disinfection were carried out at any cost while the white spot disease of shrimp first occurred in Asia, perhaps the shrimp farming industry would not be trapped by the disease as it is now! However, some problems are inherent in the aquaculture industry itself. From a global perspective and a longer time scale, the major challenges to aquaculture are the high and increasing pressure of environment and constraints of resources.

1.3.2.1 Limited Available Land and Freshwater Resources vs. Growing Demand for Quality Aquatic Products

It is predicted that human demand for aquaculture products will reach 93 million tons by 2050. Globally, although the land used for aquaculture (land occupied by facilities and planting feedstuff) only accounts for 0.17% of the earth's land surface area and 3.6% of the land used for animal husbandry (Boyd and McNevin 2015), the impacts of aquaculture on wetlands, mangroves in particular, are nonnegligible (Naylor et al. 1998).

Inland closed and semi-closed aquaculture systems (ponds, in-pond raceways, tanks, recirculating aquaculture systems) not only occupy land but also consume great volume of high-quality water to culture organisms. In addition, the planting of some feedstuff also consumes a lot of freshwater, which makes aquaculture products have an extra amount of water footprint (see Chap. 14 for details).

The consumptive use of water in aquaculture is 111.4 km^3/year, 6.6% of total water use for agricultural production. However, aquaculture uses more water per unit of production than does most kinds of terrestrial agriculture (Boyd and McNevin 2015). For countries in water-scarce areas, the fresh water consumption for inland aquaculture expansion is a challenge that cannot be underestimated.

China is one of the most water-scarce countries in the world, and the water resources per capita are only 1/4 of the world average. China's agriculture production needs to increase on the basis of consecutive years of bumper harvests in order to meet the food demands of increasing population. However, considering the national water security strategy, China's agricultural water consumption can only maintain zero growth in near future, which is the priority target of the Ministry of Water Resources of China (Wu et al. 2006). China has determined to stick to the red line of 120 million hectares of arable land. Therefore, the development of inland aquaculture in China will be increasingly restricted by available land and freshwater resources.

1.3.2.2 Increasing Energy Consumption vs. Global Emission Reduction Tasks

The aquaculture activity consumes energy and eventually emits greenhouse gases directly or indirectly. The world's fisheries and aquaculture consume 2 EJ and 0.4 EJ of energy each year (EJ $= 10^{18}$ J), which are 0.68% and 0.14% of the world's end-use energy, respectively (FAO 2011). According to the life cycle assessment (LCA), the total energy consumption of aquaculture industry is 1.38 EJ, which is only 0.47% of the world's end-use energy. The world's aquaculture emits 219.5 Mt. of carbon dioxide equivalent ($\mathrm{Mt} = 10^6$ t) of greenhouse gas each year, and the data estimated by LCA are 245 Mt. of carbon dioxide equivalent, which accounts for 0.55% of the total greenhouse gas emissions of the world (Boyd and McNevin 2015). The proportion of global aquaculture energy consumption is not great, but its increasing trend cannot be ignored.

According to a survey in China, the total annual energy consumption in fisheries and aquaculture in 2008 was 17.54 million tons of standard coal (1 kg standard coal = 29.31 KJ), of which aquaculture accounted for 21% (Xu et al. 2011). The energy consumption of pond aquaculture accounted for 61.3% of the total energy consumption of aquaculture, followed by indoor intensive farming (21.3%) and net cage and pen aquaculture (14.3%).

Intensive aquaculture is characterized by high carbon emission. The energy consumption per unit weight product of ponds, net cages, and indoor intensive farming in China are 1.33, 11.3, and 31.2 MJ/kg, respectively (Xu et al. 2011). More energy consumption usually results in more CO_2 emission. So, with the intensification and scale expansion of aquaculture production systems, the industry will become more energy-dependent and produce more CO_2.

Global warming has become the most severe challenge to the sustainable development of society and economy in the twenty-first century of the world. Chinese government has committed that China will reach a carbon peak by 2030 and become carbon neutral before 2060. CO_2 emission per GDP by 2030 should be reduced by 65–70% based on the 2005 level. In this context, there is no way to increase aquaculture production by simple intensification.

1.3.2.3 Crowded Inland Waters and Coastal Aquaculture Areas vs. Almost Vacant Offshore Areas

Only parts of the N and P in aquafeed are ingested and assimilated by farmed animals, and considerable amount of nutrients is released into the water environment through residues, feces, and dissolved metabolites and consequently results in the increment of nutrient loading of aquaculture waters or eutrophication of adjacent waters. Different aquaculture systems and different stocking densities possess different utilization rates of N and P in aquafeed. When the amount of organic matter, N, and P discharged from aquaculture activity exceeds the self-purification capacity of the waters, the water quality will deteriorate, and the production system will not be sustainable.

The rapid development of intensive aquaculture systems has caused a rapid increase in aquafeed consumption. In 2012, global aquaculture consumed 39.6 million tons of commercial pellet feed (58% of which were consumed by China's aquaculture). It is estimated that the production of commercial aquafeed will reach 87.1 million tons by 2025 (Tacon and Metian 2015). In general, only 10–20% of the dry weight of the feed material are converted into farmed animal biomass. The average environmental loads of N and P of fish and shrimp farming are 25.7 kg/t production and 5.6 kg/t production, respectively, while those for net cage culture are 64.4 kg/t and 13.9 kg/t, respectively (Boyd and McNevin 2015). With the increase in fed species production and aquafeed input, the pollutant discharge from aquaculture will also increase.

The scale of aquaculture in China is the largest in the world, reaching 7.19 million hm^2 (Fisheries Bureau, Ministry of Agriculture of China 2019), of which 3.93 million hm^2 are large water area (near shore and offshore 1.14, tidal zone 0.596, lakes 0.746, reservoirs 1.44) and 3.07 million hm^2 are ponds (seawater 0.40). In the aspect of environmental impacts, China's aquaculture, especially fed species farming industry, is too large to be ignored now.

The outflow of mariculture wastewater along the Yellow Sea and Bohai Sea in China reached 119.8×10^8 m^3 in 2002, including 6010 tons of nitrogen, 924 tons of phosphorus, and 29,016 tons of COD (Cui et al. 2005). The N and P discharged from the aquaculture activity accounted for 2.8% and 5.3% of the land-source pollutant discharge in the region, respectively. According to an estimation (Cheng 2009), the annual nitrogen discharged from mariculture of net cage and pond in China was 37,000 tons and 450,000 tons, respectively, while the total ammonia nitrogen discharged from Chinese urban domestic sewage was 900,000 tons at the same time. These aquaculture pollutants can not only cause diseases and growth retardation of farmed organisms, but also cause more serious marine environmental problems.

Aquaculture pollution has drawn widespread concern of the public. Beginning from the spring of 2016, China government has begun to ban and restrict the aquaculture activities of net cages and pen in lakes and reservoirs and has prohibited the use of coal-fired boilers for heating water in aquaculture. These policies have significantly affected the development patterns of China's aquaculture (Figs. 1.1 and 1.5).

The total amount of nitrogen and phosphorus discharged into natural waters by human activities in the world each year is 50 Mt. and 10.5 Mt., of which aquaculture accounts for 2% and 2.9%, respectively (Boyd and McNevin 2015). In view of the excessive environmental load of nearshore mariculture, some countries or regions have begun to restrict the development of nearshore mariculture. For example, Norway has severe restriction about the scale of Atlantic salmon farming in fjords and encourages the development of offshore farming outside the fjords. The United States has also begun to pay attention to offshore mariculture, but the development of offshore mariculture in the areas of EEZ is still affected by the lack of related regulations (Naylor and Burke 2005).

At present, nearshore mariculture within −10 m isobath in China has used about 40% of the total available shallow sea area, while the mariculture utilization rate within the area between −10 and −30 m isobath is only 1%, and offshore mariculture in the sea area with a depth of >30 m is almost zero. China government has issued licenses to encourage companies and fish farmers developing deeper-offshore mariculture in the EEZ of China.

Humanity is facing triple crucial challenges from population growth, environmental pollution, and global climate change. Therefore, aquaculture industry must not only increase production to meet the demand of increasing population for food but also reduce nutrient discharge and CO_2 emissions to achieve the goal of sustainable development. Land-based recirculating aquaculture systems (RAS) can achieve the goals of high production and low even zero discharge of eutrophic nutrients. However, what kind of aquaculture systems or models can simultaneously achieve the three goals of high productivity, low discharge of nutrients, and low CO_2 emission? These are exactly the matters that aquaculture ecology should focus on in the Anthropocene.

1.3.3 Dialectical Thinking in Integrated Aquaculture in China

In the eighteenth century, there were two major but opposite attitudes toward nature in the Western world. One was an "Arcadian" stance toward nature epitomized by Gilbert White (1720–1793), the parson-naturalist of Selborne, UK. This Arcadian view advocates a simple, humble life for humans with the aim of restoring humans to a peaceful coexistence with other organisms. Another, "imperial" tradition, is best represented in the work of Carolus Linnaeus (1707–1778). His ambition is to establish, through the exercise of reason and hard work, human's dominion over nature (Worster 1994). These two extreme thoughts can also be found in modern ecology. In terms of the development of aquaculture, neither the Arcadian view nor the imperial view is practical.

World view of ancient Chinese was affected by Lao Tzu (about 600–500 BC), a great ancient Chinese philosopher. His theory includes "Reversal is the movement of Tao," namely when the development of anything brings it to one extreme, a reversal to the other extreme takes place. This is one of the main theories of Lao Tzu's philosophy and also that of the Book of Changes as interpreted by the Confucianists. This theory has also provided the principal argument for the doctrine of the "golden mean," favored by Confucianist and Taoist alike. "Never too much" has been the maxim of both (Feng 2008).

Influenced by this mode of thinking, it is not surprising that ancient Chinese invented the integrated aquaculture of grass carp and rice shoots 1100 years ago. In the book "*The Curious in Lingbiao Region*" written by LIU Xun in TANG (Zhao-Zong) Dynasty (889–907 A.D.) it was recorded that "In the spring water was stored in ponds, then grass carp was bought and stocked into shallow ponds. The fish grown up after one or two years and wild weeds were grazed by the fish. Meanwhile, paddy fields were also fertile." It was the first interpretation of the mutually profitable relationship between grass carp and rice shoots (Liu and He 1992). This case might be the earliest record of the integrated aquaculture of grass carp and rice in China and is an application of traditional Chinese philosophy in the integrated aquaculture.

In this integrated aquaculture model, the opposite yet complementary relationships between grass carp and rice shoots are clearly exhibited. Small size grass carp cannot graze tall rice shoots. Therefore, small-sized grass carp is stocked when rice shoots grow up to a certain size. At that time, the grass carp cannot graze the rice shoots, and the relationship between grass carp and rice shoots is mutually

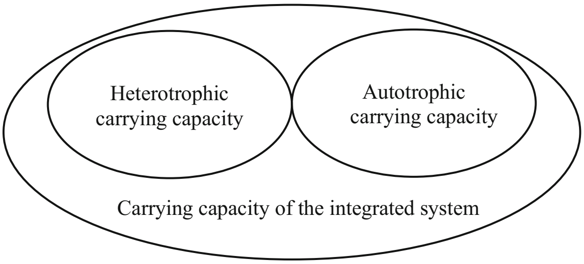


Fig. 1.6 Ecological effects of integration of two complementary aquaculture organisms or systems (from Dong 2015a)

Fig. 1.7 Unity and balance of opposites in ecological intensification of aquaculture systems (modified from Dong 2015a)

beneficial (see Chap. 9 for details). Rice and grass carp are a pair of contradictions in the case. Under certain conditions, their opposite relationship can be reversed.

The popular integration model of fed fish with seaweed is also a unity of opposites. Fed fishes are heterotrophic organisms, while seaweeds are autotrophic organisms. They are opposite and complementary in ecological characteristics (Dong et al. 1998). For example, carrying capacity of seaweed monoculture in a water body will be limited by the lack of nutrients (ammonia, CO_2, etc.), while carrying capacity of fed fish monoculture in a water body will be limited by the lack of dissolved oxygen or excessive ammonia; but if they are integrated together (polyculture), the total carrying capacity of the waters can be enlarged, i.e., $1 + 1 > 2$ (Fig. 1.6).

The core of aquaculture ecology is the construction of a unity of opposites. In aquaculture “fed species versus extractive species,” “heterotroph versus autotroph,” “decomposer versus producer,” “oxidation versus deoxidation,” “source versus sink,” and so on are all the unity of opposites, the balance or golden mean can be reached through integration of these opposites in an appropriate proportion (Fig. 1.7).

Aquaculture is now facing a matter of dialectical unity. The extensive aquaculture system can achieve the goal of low carbon (emission), but it cannot meet the demand for high yield; the intensive RAS can meet the demand for high yield, but it is likely to be a high carbon production system. In a long run, the development of the aquaculture industry should consider both the demands for food and environmental protection. It should be both "intensive" and "ecological," that is, ecological intensification development.

1.3.4 Ecological Intensification of Aquaculture Production Systems

The main goal of aquaculture industry is to sustainably ensure food security for humans, i.e., providing sufficient, safe, sustainable, shockproof, and sound aquatic food (Jennings et al. 2016). Today, there are 7 billion people in the world, and they consume an average of 7 billion units of resources. By 2050, there will be at least 9 billion people and they are expected to have 2.9 times as much income per capita and consume about twice as much per capita. Based on the projections of the World Bank, by 2050, we will have 18 billion units of consumption if nothing is done differently later on. By 2050, human demand for aquatic food will be 156 million tons, 60% of which will probably come from aquaculture (Boyd and McNevin 2015). As mentioned above, the development of aquaculture has been facing many challenges; therefore, it is an arduous task to address these challenges for ensuring human food security and making aquaculture industry to enter a sustainable track. There are reasons to believe that with the progress in science and technology, fishmeal replacement or reduction will gradually be solved (Powell 2003; Teves and Ragaza 2016; Gamboa-Delgado and Márquez-Reyes 2018), while some other challenges should be dealt with under the guidance of ecological thinking.

1.3.4.1 The Gains and Losses of Simplistic Intensification

The increase in aquaculture yield can be achieved by promoting the intensification level of aquaculture system. However, the intensification is a double-edged sword. As shown in Fig. 1.8, compared with the extensive farming system, with the increase in labor, energy, and feed, the yield of intensive farming system is greatly increased, land used is greatly reduced, and direct economic benefits may also increase. Nevertheless, the intensive system consumes more feed resources (including fish meal) and weakens the role of solar energy and natural feed resources. Moreover, high-density monoculture may also cause more problems of disease, drug residue, and food safety. When the discharged water from the intensive system is poorly treated or not treated, it will cause serious degradation of water quality and eutrophication of adjacent waters.

Agricultural practice of the world in last decades has proved that simplistic intensification of agriculture systems has paid high prices while increasing crop production and production efficiency, such as land degradation, loss of soil organic matter and nutrients, depletion of water resources, and water pollution. If the environmental costs involved are properly accounted for, the real costs of producing food would be much higher. Therefore, the concept of sustainable intensification of agriculture is proposed by some scholars (Tilman et al. 2011; Cassman and Grassini 2020), seeking to increase crop yields and associated economic returns per unit time

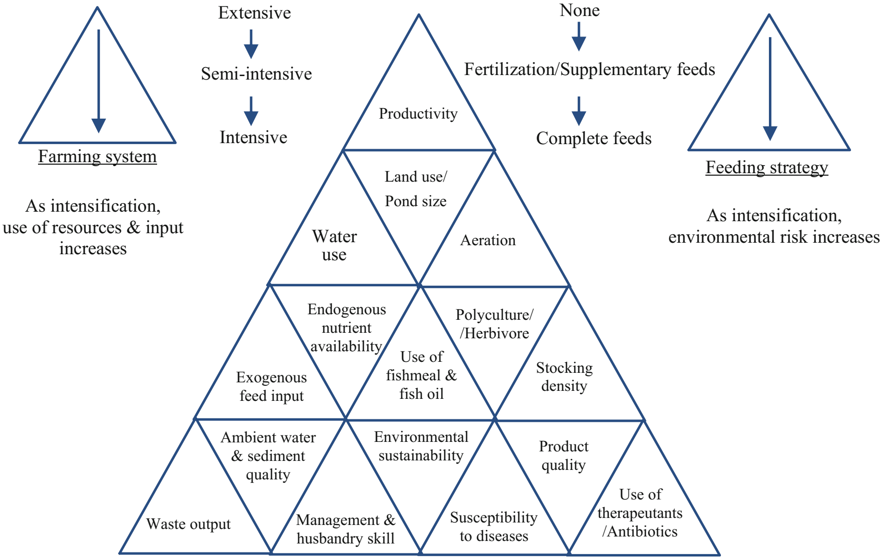


Fig. 1.8 Main differences between conventional extensive, semi-intensive and intensive farming systems in terms of resource use and potential environmental risks (from Tacon and Forster 2003)

and land without negative impacts on soil and water resources or the integrity of associated non-agricultural ecosystems. The development of aquaculture industry should also follow the path of sustainable intensification, rather than the path of simplistic intensification.

RAS is one of the most intensive aquaculture production system and possesses several advantages over conventional aquaculture systems, such as reducing freshwater and land use, enhancing feed efficiency, and improving biosecurity (see Chap. 10 for detail). However, most RAS nowadays are highly artificial, not taking advantage of many possible ecosystem services, such as photosynthesis. There are three major constraints to application of RAS. The first is its economic feasibility in many developing countries. RAS was invented and implemented in developed countries (Takeuchi 2017), where electricity price is relatively low and labor cost is very high. But in many developing countries the situation is opposite; that is, electricity price is higher and the labor cost is lower, making the products from RAS uncompetitive in markets. The second is the inorganic nitrogen accumulation in RAS. There is only nitrification process in many RAS (Ebeling and Timmons 2007; Yamamoto 2017). Nitrification can only turn toxic ammonia and nitrite into low toxic nitrate, but the total inorganic nitrogen is still in RAS! Accumulation of inorganic nitrogen in RAS is harmful to farmed animals. Denitrification can turn ammonia into gas nitrogen, but is costly (large space and more power). The third is energy-consuming or high CO_2 emission. Therefore, RAS is expensive to run, and their products have a much higher carbon footprint; therefore, it is a less sustainable system so far (see Chap. 14 for detail).

To overcome the higher operation costs for removing dissolved waste, RAS can be integrated with ecosystem services, like nutrient recovery through photosynthesis of aquatic plants, in situ or ex situ. Aquatic plants integrated in RAS can release dissolved oxygen, absorb inorganic nitrogen, and may serve as a commercial product (e.g., edible seaweeds, vegetables, or fruits).

1.3.4.2 Ecosystem Aquaculture Approach

To promote sustainable development of aquaculture industry, the article 9 of FAO Code of Conduct for Responsible Fisheries stipulates for the responsible aquaculture at the production level states should:

Promote efforts that improve selection and use of appropriate feeds, feed additives, and fertilizers, including manures.

Promote effective farm and fish health management practices favoring hygienic measures and vaccines. Safe, effective, and minimal use of therapeutants, hormones and drugs, antibiotics, and other disease control chemicals should be ensured.

Regulate the use of chemical inputs in aquaculture that are hazardous to human health and the environment.

Require that the disposal of wastes such as offal, sludge, dead or diseased fish, excess veterinary drugs, and other hazardous chemical inputs does not constitute a hazard to human health and the environment.

In 2007, “Building an Ecosystem Approach to Aquaculture” was discussed in Spain, and “*Aquaculture Development 4. Ecosystem Approach to Aquaculture*” was published (FAO 2010), which is recommended as requirements of the “Code of Conduct for Responsible Fisheries” (FAO 2013).

The ecosystem approach to aquaculture (EAA) is a strategy to promote sustainable development of aquaculture industry, and the three main principles of it are as follows: (1) Aquaculture development and management should take account of the full range of ecosystem functions and services and should not threaten the sustained delivery of these to society; (2) aquaculture should improve human well-being and equity for all relevant stakeholders; and (3) aquaculture should be developed in the context of other sectors, policies, and goals. Obviously, implementation of EAA requires changing some of the improper behaviors of human beings and deepening the understanding of the functions of aquaculture ecosystems.

1.3.4.3 Ecological Intensification of Aquaculture Systems

Globally, the intensification of aquaculture production systems is accelerating as land and water resources increasingly restrict the development of aquaculture. Simplistic intensification of a production system may obtain a high production in a short term; however, it may remain potential risks in a long run (Nyström et al. 2019). Ecological intensification of aquaculture systems (ELIAS), i.e., integrating anthropogenic inputs with aquaculture ecosystem services, is a concept or approach to improve the production and comprehensive benefits of aquaculture production systems (Dong 2015a; Dong et al. 2022). It stresses the trade-offs among various considerations and pursuits the maximization of comprehensive benefits.

ELIAS is the implementation of dialectical thinking in modern aquaculture production. It is not only a strategy, but more importantly it is a means or method to balance the environment and human production activities. Intensification implies high density and high yield, while ecology implies wastes converting to resource, balance of autotrophic and heterotrophic processes, and so on (Fig. 1.7). The current extensive aquaculture system should be intensified based on ecosystem services, while some intensive aquaculture systems should be ecologically transformed (see Chaps. 9, 10, and 15).

1.3.5 Toward to the New Era of Green Aquaculture

The development history of aquaculture production systems is just an evolutionary process of ELIAS, in which the intensification (e.g., feeding and aeration) and ecological improvement (e.g., polyculture, integrating with ecosystem services) take place alternately with the increasing demand for seafood, advancement of technology, and increasing environmental concerns. There are four stages generally in the development of aquaculture production systems, i.e., natural productivity-based intensification, anthropogenic feed-based intensification, ecosystem service-based intensification, and green energy-based aquaculture (Table 1.3).

Extensive monoculture of common carp was firstly recorded in the document by FAN Li 2500 years ago (460 BC) in China (Nash 2011). Then, paddy–fish farming, one model of the integrated extensive aquaculture, occurred during 220–265 AD in China (Lu and Li 2006). With the increment in population and demand for aquatic products in Tang Dynasty of China (618–907 AD), the semi-intensive polyculture (multi-species carps) was developed, resulting in a significant increase in pond productivity (Nash 2011). According to the Agricultural Administration Encyclopedia written by XU Guang-Qi (1639), grass carp in polyculture ponds were fed with grass, and the polyculture ponds were fertilized with sheep feces. Until 1950s, the strategies of aquaculture development in general are either full use of natural productivities by polyculture, or improving pond productivities by fertilization or supplementary feeds. However, the application of manure is bound to consume a lot of dissolved oxygen in fish pond water, and excessive application will cause hypoxia and affect the improvement of aquaculture output.

Since 1950s, aquaculture entered its intensive monoculture or called industrial monoculture stage (Costa-Pierce 2010). Development of pellet feeds (e.g., Oregon moist pellet in United States) in the late 1950s and floating net cages in 1960s, especially the polyethylene (PE) and then polyvinylchloride (PVC) cages in Norway, accelerated aquaculture development in large inland waters and nearshore areas (Nash 2011). Meanwhile, the application of pelleted feeds and aerators is good solutions to the problem of hypoxia caused by the application of manure and table scraps and rapidly promoted the yields of tank and pond farming (Boyd and Tucker 1998; Nash 2011). The internationalization of seafood market and massive investment accelerated the development of intensive monoculture. In this stage, aquaculture development is largely supported by supplementary energy and feed input.

Table 1.3 Evolution of ecological intensification and characteristics of aquaculture production systems

Production systems	Extensive monoculture	Integrated extensive aquaculture	Semi-intensive polyculture	Intensive monoculture	Intensive integrated aquaculture	Green aquaculture
Time	500 BC	220–265 AD 618–904 AD	1639	1950s–1990s	2000s-	Near future
Examples or models	Carp monoculture in ponds	Rice–fish farming, polyculture of carps in ponds	Fed grass carp with grass in carp polyculture pond	Intensive pond farming with aerator, cage in large waters, or nearshore mariculture	RAS, aquaponics, bioflocs, offshore IMTA	Non-fossil energy-based RAS, carry capacity-based offshore mariculture, photosynthesis-based non-fed aquaculture
Nutrients	Natural organisms → supplementary feeds → pelleted feeds				Integrating aquaculture inputs with ecosystem services	Integrating aquaculture with green energy
Environments	Ponds → tanks, large inland waters → nearshore					
Technology	Water exchange → aeration → water circulation, net cage → nearshore facilities					
Key constrains	Productivity of natural feed organisms → oxygen → multi-factors (oxygen, ammonia, temperature, etc.)					
Development strategies	Natural productivity-based intensification → anthropogenic feeds-based intensification → ecosystem services-based intensification → non-fossil energy-based aquaculture					

Simplistic intensification of food production systems has resulted in major negative effects despite increases in yield and scale. Consequently, intensive integrated aquaculture, or called ecological aquaculture (Costa-Pierce 2010; Dong et al. 2022), is proposed to balance the concerns of economy, environment, and society. Aquaculture has stepped into a new stage; therefore, the strategies of aquaculture development have been changing from pellet feed-based intensification to ecosystem service-based intensification.

In face of population growth, environmental pollution, and global climate change, we urgently need to increase production, reduce organic matter discharge, and reduce CO_2 emission for aquaculture production simultaneously. Only the non-fossil energy-based aquaculture systems and photosynthesis-based aquaculture systems can feasibly achieve the ultimate goals of zero waste discharge, less carbon footprint, and high productivity simultaneously.

1.4 Characteristics of Aquaculture Ecology

The research areas and focuses of aquaculture ecology are constantly changing with science development and technology progress in aquaculture. In the 1960s and 1970s, aquaculture ecology scholars mainly paid attention to the ecological niche and physio-ecology of farmed fish, pond water quality management, and their research achievements promoted pond productivity significantly. In the 1980s, with the rapid development of fish stocking in lakes and reservoirs, the scholars began to study the structure and function of aquaculture ecosystem and fish productivity of large aquaculture waters. In the 1990s, with increasing intensification level and the expansion of aquaculture scale, the pollution of aquaculture waters became increasingly serious; therefore, scholars began to study the interaction of aquaculture activities and the environment, carrying capacity of aquaculture waters. Entering the twenty-first century, the concepts of sustainable development and circular economy become popular, and aquaculture systems are studied as an economic ecosystem. In recent years, the ecological footprint, water footprint, and welfare of aquaculture animals have also begun to attract people's attention. In addition, aquaculture ecology is an interdisciplinary science, and the development of relative disciplines in theory and technology will also promote the development of aquaculture ecology.

1.4.1 Major Research Areas of Aquaculture Ecology

At present, the major research areas of aquaculture ecology include the individual ecology of farmed organisms, the rationales of water and sediment quality management, the ecology of aquaculture systems, the interaction between aquaculture activities and the environment, and the ecological rationales of disease prevention.

1.4.1.1 Individual Ecology of Farmed Organisms in Aquaculture

This research area focuses on the optimal environmental conditions for growth at each development stage of farmed animals and plants in aquaculture, and the adaptability of farmed organisms to environmental changes. Its goal is to provide a theoretical basis for improving aquaculture technology (see Chaps. 5, 6, 7, and 11).

1.4.1.2 Water and Sediment Quality Management of Aquaculture Systems

This research area mainly studies dynamics of water quality and sediment quality, the conservation, and restoration rationales of water quality and sediment quality. Its goal is to provide theoretical basis for building the optimal conditions for the growth, survival, and feed utilization of farmed organisms (See Chaps. 2, 7, and 8).

1.4.1.3 Ecology of Aquaculture Systems

This research area mainly studies the structure and function of aquaculture ecosystems, the structure optimization of integrated aquaculture systems, the mutual benefit mechanisms between farmed species in an integrated aquaculture system, the ecological parameters, and sustainability of aquaculture system. Its goal is to provide a theoretical basis for building relatively stable and efficient aquaculture ecosystems (see Chaps. 2, 3, 9, 10, 11, 12, and 15).

1.4.1.4 Interaction between Aquaculture Activities and the Environment

This research area mainly studies the impact of aquaculture activities on the environment, the impact of environmental factor variation and other human activities on aquaculture, and the rationales of integrated management of aquaculture systems. Its goal is to provide a theoretical basis for integrated management of aquaculture systems, rational utilization of resources, and maintenance of ecological security (see Chaps. 4, 14, and 15).

1.4.1.5 Ecological Rationales of Disease Prevention

This research area mainly studies the relationships of disease incident to pathogenicity of pathogens, health level of farmed organisms, and environmental quality. Its goal is to realize the ecological prevention of epidemic disease by blocking the transmission routes of pathogens, improving environmental conditions, improving the disease resistance of farmed organisms, and reducing the pathogenicity of pathogens (see Chap. 13).

In addition, ecological economics of aquaculture systems, ecological nutrition of farmed animals, and other areas of cross-disciplinary are also the research areas that people begin to pay attention to.

1.4.2 Characteristics of Aquaculture Ecology

The characteristics of aquaculture ecology include diversity of target objects, versatility of aquaculture systems, applicability for industrial development, and interdisciplinary approach.

1.4.2.1 The Diversity of Target Objects

Aquaculture includes all farming activities carried out in waters; therefore, the diversity of aquatic ecosystems and farmed species determine the diversity of research objects of aquaculture ecology. Aquaculture waters are various, such as tank, pond, reservoir, lake, intertidal and coastal zone, and offshore. Farmed organisms live in a dynamic physical (temperature, light, current, etc.) and chemical (dissolved oxygen, pH, ammonia, etc.) environment. In addition, aquaculture system is a semi-artificial and semi-natural ecological system, in which the natural functions of production, consumption, and decomposition are still at work, and even play a leading role. However, the biomasses of farmed organisms in some aquaculture waters are so great that artificial intervention becomes necessary to maintain the stability of the structure and function of aquaculture ecosystem, such as feeding to offset the inadequacy of primary production and aeration to meet the huge oxygen demand of farmed animals in intensive aquaculture systems. The energy sources of most aquaculture systems come from both solar radiation and feed input, so most aquaculture systems are the dual drive systems of solar and feed energy.

Farmed species in aquaculture are the most diverse in trophic levels among food production systems (Table 1.4). Kelp (*Laminaria japonica*) absorbs inorganic nutrients in water, grass carp grazes aquatic plants, silver carp filters phytoplankton, common carp feeds zoobenthos, mandarin fish (*Siniperca chuatsi*) preys live bait fish, and sea cucumber (*Apostichopus japonicus*) ingests organic matters in sediment. Due to the diversity of target objects, various ecosystem services can be integrated into aquaculture ecosystems to improve their outputs, comprehensive benefit, and system sustainability.

1.4.2.2 Versatility of Aquaculture Systems

The aquaculture system has three basic functions, namely food production, economic value multiplication, and environment maintenance (Fig. 1.9). The coordination and balance of the three functions are the guarantee for the sustainable

Table 1.4 Feeding habit diversity of aquaculture species

Species	Functions	Similar industries
Aquatic plants	Absorb inorganic nutrients	Crops
Grass carp/herbivores	Turn grass into meat	Cattle, sheep
Common carp/omnivores	Turn zoobenthos into meet	Pig, poultry
Mandarin fish/carnivores	Turn low-value meat into high-value meat	/
Silver carp/filter feeders	Turn plankton into meat	/
Sea cucumber/deposit feeders	Turn sediment organic matter into meat	/

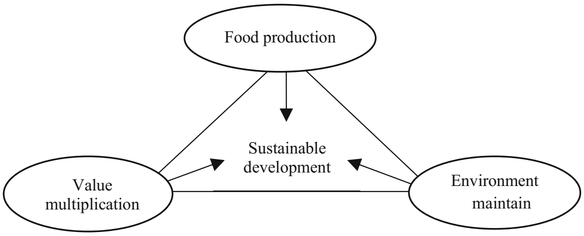


Fig. 1.9 Functions of aquaculture system and the relationships among them (from Dong 2009b)

development of the system (Dong 2009b). Culturing carp several 1000 years ago might be a simple production activity for food. Later on, with the expansion of pond farming, the production of farmed fish exceeded the demand of farmers themself, and the bartering and trading of the farmed fish would become a natural behavior. Since then, the aquaculture is no longer just a simple food production activity, and it is also an economic activity.

Over the past 8000 years, aquaculture was mostly extensive and semi-intensive aquaculture activities, which did not have a significant impact on the environment. However, since the 1970s, due to the invention of pelleted feeds, modern floating net cages, and aerators some intensive aquaculture models have been developed, and aquaculture production has increased unprecedentedly. The cases of overstocking of aquatic animals in many farming waters sometimes occur. The environmental issues of aquaculture activity have gradually drawn the attention of the public. People gradually realize that the aquaculture system should have the function of maintaining the environmental safety for farmed organisms and human society.

Aquaculture system is a part of the larger ecosystem and has a complex interaction with its surrounding environment. The sustainable development of the aquaculture must balance the three basic functions of the aquaculture system and maximize the comprehensive benefits of food production, economic value multiplication, and environment maintaining.

Aquaculture system is a typical ecological economic system. It would be biased to study the system simply with ecological or economic methodology. Extensive aquaculture systems usually have higher ecological efficiencies, while intensive monoculture systems may obtain higher apparent economic benefits, but have potential environmental costs. Ecological intensification should be a strategy or an approach that gives better consideration to ecological efficiencies and economic benefits. In addition, the methodology of combining economics and ecology should also be adopted in the study of aquaculture system (see Chap. 15 for details).

1.4.2.3 Applicability for Industrial Development

Aquaculture ecology has a visible mark of industrial ecology; that is, it has strong application characteristics. The applicability of aquaculture ecology is mainly manifested as follows.

First, the research hotspots of aquaculture ecology change with the development of the industry and technology. In the 1960s–1980s, aquaculture ecologists mainly studied the ecological principles of the yield improvement of aquaculture waters.

Since the 1990s, they began to pay attention to the issues such as the interaction between aquaculture activities and the environment, and the sustainability of aquaculture systems. Aquaculture is the fastest growing sector among food production sectors in terms of annual growth rate in the world. In its rapidly developing process, it will encounter new problems constantly, many of which need to be solved based on the progress of ecological studies.

Second, people's demand for new species items and the expansion of new space or area requires corresponding research in aquaculture ecology. Let us take the salmon and trout farming in the Yellow Sea as an example. Due to the disadvantages of nearshore mariculture, many governments around the world encourage companies or farmers to move mariculture offshore. In 2012, we began to study the possibility of farming salmon and trout in the open seas of China. Although the sea surface temperature (SST) in China's seas is too high in summer for farmed salmon and trout to survival, there is a shallow Yellow Sea Cold Water Mass (YSCWM) under the thermocline around the center of the Yellow Sea in summer. Before culturing salmon and trout in the YSCWM, we have to clarify the following questions: Can salmon and trout be farmed in YSCWM? And how? What kind of species or varieties are suitable for farming? How to achieve profitability? And so on.

From the perspective of aquaculture ecology, we should study the comparative physiological ecology of alternative farmed species or varieties, carrying capacity of farming area, farming models, ecological basis of intelligent management, impacts of global climate change and eutrophication, and so on. The technicalization of these research results (transformation of basic research into technology) can lead or promote the progress of the industry.

Third, its research topics come from the needs for optimization of aquaculture models. Most current aquaculture technics are invented and optimized by professionals, but also many technics are invented by experienced fish farmers or technicians in China. Some of this latter type of technique still need to be further optimized. Let me explain it with following example.

At present, the hatching and larval breeding of sea cucumber (*Apostichopus japonicus*) in China are usually carried out under dark conditions. However, the natural hatching of the sea cucumbers can be seen in non-dark environment. In order to find out the best light conditions for the larval breeding of the sea cucumber, we studied the effects of light intensities on the survival, growth, and metamorphosis of the sea cucumber larvae. The experimental results showed that the larvae of the sea cucumbers grew fastest under the light intensity of 500 Lx in the first 3 days after fertilization and on the fifth day of start feeding; and the larvae on the ninth day of start feeding and the juvenile of the sea cucumber grew fastest under 2000 Lx (Dong 2009a; Li et al. 2019). These results indicate that light is important for improving hatching and breeding of the sea cucumber.

I have ever asked some technicians why they chose to hatch and breed the sea cucumber in dim lighting conditions. Most of them did not know the reason why and just follow others! An elder technician who knew it said that sea cucumber larvae would drag their feces (indigestion) under light conditions, and the mortality rate was higher. Sea cucumber larvae do sometimes have indigestion problems when exposed to light, because they ingest pure microalgae growing on the corrugated board used for seedling breeding (Shi et al. 2015). The point I'm trying to raise here is that shading is not the best way to solve this problem! Sprinkling a little sea mud on the corrugated board covered with microalgae can solve the indigestion problem! For solving this kind of problems, it will be better to find out the answers in the natural habitat of the aquaculture species. Due to sedimentation and resuspension of sediment in nature, sea cucumber larvae seldom feed on pure live microalgae in large amounts. Therefore, we should simply adjust the diet composition instead of adjusting the light for inhibiting the growth of microalgae.

An important research direction of aquaculture ecology is the individual ecology of farmed aquatic organisms, and the purpose is to find out the optimal environmental conditions for the growth of the organisms. Generally, in order to find out the optimal conditions, one must first understand the environmental conditions in which they live naturally. The organisms have undergone a long period of adaptive evolution to their habitat. The central region of their natural distribution is usually their optimal growth and survival area, and the conditions of that area are usually their optimal growth and survival conditions. In many cases, the failure of farming results from the difference between their farming conditions and their natural living conditions. Therefore, it is an important study topic of the individual ecology to find these differences and improve them in practice (see Chaps. 5 and 6 for details).

We should learn from the nature and stock farmed organisms with diverse ecological niches so as to make full use of various resources of farming waters (natural forage or diet organisms, space, time). In order to realize the balance between autotrophy and heterotrophy processes, the farmed organisms or sub-systems with ecologically complementary functions are stocked or allocated in a certain proportion (see Chap. 9 for details).

Technicians usually try to keep water environment stable at some optimal conditions that were best for a farmed animal in RAS. In fact, the various environmental factors in natural waters mostly have certain periodic variations, such as daily fluctuation. Numerous studies have shown that for many water quality parameters there is not a so-called optimum "value" for the growth of aquatic organisms, but rather an optimal amplitude of variation. Farmed organisms grow better in the optimal "amplitude or range" of variation than in the stable optimal "value" (see Chap. 6 for details). Therefore, we should learn from the nature and can build some production systems that are more efficient than the natural ones in some controllable farming waters.

1.4.2.4 Interdisciplinary Approach

Both aquaculture and ecology are highly interdisciplinary subjects, and aquaculture ecology is a combination of aquaculture and ecology. Therefore, aquaculture ecology has strong interdisciplinary characteristics. In recent years, the introduction of concepts and methodologies of system theory, cybernetics, and information theory has also led to great development of ecological studies. The rapid development of ecological disciplines continuously provides new theories and new methodologies for the development of aquaculture ecology. The highly interdisciplinary nature of aquaculture ecology also determines the characteristics of its rapid development.

This book is a textbook for graduate students in fisheries and aquaculture. China's aquaculture has the longest history, the largest scale, the most varieties of aquaculture production systems, and the most problems encountered and studied. Most contents of the book are the achievements of Chinese scholars' systematic studies for the sustainable development of aquaculture industry. The cases of China's aquaculture can serve as a precedent for other countries, especially developing countries.

Brief Summary

1. Aquaculture ecology belongs to the category of applied ecology. It studies the interaction between commercial aquatic organisms as well as their farming activities and the environment and elucidates the rationales of building and regulating aquaculture production systems. Its mission is to lay an ecological foundation for the sustainable development of aquaculture. Aquaculture science emphasizes mainly on individual or stock weight growth and actual farming benefits, while aquaculture ecology stresses mainly the issues such as ecological efficiency, the impact of farming activities on the environment, and sustainability of production systems.
2. A healthy aquaculture development pattern should be able to provide people with sufficient, safe, sustainable, shockproof, and sound aquatic products. Although the development of aquaculture encounters many constraints and challenges, some of them are not inherent in aquaculture, such as prevalent diseases. However, some problems are inherent in the aquaculture industry itself. From a global perspective and a longer time scale, the main factors that challenge the development of aquaculture are the high and increasing pressure of environment and constraints of resources. Due to difference in development stages, farming models, geographical environment, and resource endowments of aquaculture in various countries, the current constraints and challenges faced by different countries in aquaculture development are also different.
3. Aquaculture industry is now facing a matter of dialectical unity. The extensive aquaculture system can achieve the goal of low carbon, but it cannot meet the demand for high yield. The intensive RAS can meet the demand for high yield, but it is likely to be a high carbon production system. In a long run, the development of the aquaculture industry should consider both demands for food security and environmental protection.
4. The ecosystem approach to aquaculture (EAA) is a strategy to promote sustainable development of aquaculture industry, and the three main principles of it are as follows: (1) Aquaculture development and management should take account of the full range of ecosystem functions and services and should not threaten the sustained delivery of these to society; (2) aquaculture should improve human well-being and equity for all relevant stakeholders; and (3) aquaculture should be developed in the context of other sectors, policies, and goals.

5. Ecological intensification of aquaculture systems (ELIAS), i.e., integrating anthropogenic inputs with aquaculture ecosystem services, is a concept or approach to improve the production and comprehensive benefits of aquaculture production systems. It stresses the trade-offs among various considerations and pursuits the maximization of comprehensive benefits.
6. The development history of aquaculture production systems is just an evolutionary process of ELIAS, in which the intensification (e.g., feeding and aeration) and ecological improvement (e.g., polyculture, integrating with ecosystem services) take place alternately with the increasing demand for seafood, advancement of technology, and increasing environmental concerns. There are four stages generally in the development of aquaculture production systems, i.e., natural productivity-based intensification, anthropogenic feed-based intensification, ecosystem service-based intensification, and green energy-based aquaculture.
7. At present, the major research areas of aquaculture ecology include the individual ecology of farmed organisms, the rationales of water and sediment quality management, the ecology of aquaculture systems, the interaction between aquaculture activities and the environment, and the ecological rationales of disease prevention. We should learn from the nature in order to build the production systems with balanced production, consumption, and decomposition, and to build the production systems that are more efficient than the natural ones in some controllable farming waters.
8. The characteristics of aquaculture ecology include the diversity of research objects, the versatility of aquaculture system, applicability for industrial development, and interdisciplinary approach.

Aquaculture Ecosystem

2

Shuang-Lin Dong, Qin-Feng Gao, and Li Li

Aquaculture ecosystem is a special type of industrial ecosystem, which is similar to aquatic ecosystem in natural attributes and similar to terrestrial agroecosystem in human intervention. However, the aquaculture ecosystem is different from natural aquatic ecosystem and terrestrial agroecosystem in many aspects.

2.1 Classification of Aquaculture Systems

China is not only the earliest country in the world to carry out aquaculture activities, but also the country with the most diverse aquaculture systems or models. In order to facilitate production and management, people have given different names to these aquaculture systems or models, such as algae cultivation, fish farming, mariculture, and freshwater aquaculture. This section will classify these aquaculture systems from an ecological point of view in order to better understand the ecological nature of various aquaculture systems.

2.1.1 Characteristics of Aquaculture System

2.1.1.1 Differences from Natural Aquatic Ecosystems

Aquaculture ecosystem is similar to aquatic ecosystem in natural attributes, but it is different from aquatic ecosystem in the following four aspects:

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1. The energy and material input of aquaculture system are not entirely dependent on solar radiation, precipitation, runoff, etc., but are partly intervened by human beings. Human activities in the system include seedlings stocking, feeding, artificial aeration, and labor input.
2. In order to maximize the production of target organisms (farmed animals), the biodiversity of the system has been artificially reduced.
3. Biological communities in the system are not naturally formed (large-scale extensive aquaculture systems are similar to natural systems), and the dominant organisms are usually artificially stocked. Therefore, aquaculture ecosystems are unstable comparing with natural aquatic ecosystems unless there is human intervention.
4. Some aquaculture systems may exert negative impacts on the adjacent environment when their wastewater is discharged.

2.1.1.2 Differences from Terrestrial Agroecosystems

Aquaculture ecosystem is similar to agroecosystem in terms of human intervention, but it is different from it in the following five aspects:

1. Aquaculture organisms have diverse trophic levels. Aquaculture activities include not only the cultivation of aquatic plants (e.g., macroalgae), but also farming of the herbivores who convert plant protein into animal protein (e.g., grass carp like cattle or sheep), the omnivores who convert invertebrate and plant protein into farmed animal protein (e.g., common carp like poultry or pig), the carnivores who convert low-value animal protein into high-value animal protein (e.g., Mandarin fish *Siniperca chuatsi*), the filter feeders who convert plankton protein into animal protein (e.g., silver carp and oyster), and the deposit feeders who convert sediment organic matter into animal protein (e.g., sea cucumber).
2. Aquaculture animals are poikilothermic and can save energy for regulating body temperature, so the protein retention of feed is higher than other farmed animals. For example, salmon can retain 31% of feed protein, compared with 15% for cattle, 18% for pigs, and 21% for chickens. Aquaculture animals have many types of temperature adaptabilities. There are stenothermal species, eurythermal species, cold-water species, and tropical species. The body temperature of aquaculture animals varies with water temperature, and a small change in water temperature will directly affect the growth even survival of stenothermal species.
3. Most aquaculture animals could regulate their osmotic pressure. Animals that regulate the osmotic concentration of body fluids to a higher osmotic concentration than that of ambient water are called hyperosmotic regulators, and the opposite is called a hypoosmotic regulator. Freshwater animals belong to the former, while marine teleost belongs to the latter. Salmonids are mostly euryhaline, which hatch and develop in freshwater and grow up in the seawater. They are hyperosmotic regulator in freshwater and hypoosmotic regulator in seawater.
4. Aquaculture animals have a variety of life habits, most of which are pelagic, while the others are benthic species. The advantage for the pelagic animals (such as fish) is that they can use the three-dimensional space of the waters, but one

obvious disadvantage is that they can be directly affected by water quality. The dissolved oxygen content in water is much less than in air. Fish breathe with gills, and slightly changes in dissolved oxygen in water will directly affect the growth and even survival of the fish. The pollution and hypoxia in the sediment are sometimes fatal to the benthic species, such as echinoderms and bivalves. Less amount of oxygen can be dissolved in water at high temperature. However, the aquatic animals have higher oxygen consumption rate at higher water temperature. This is a contradiction of great concern.

5. Aquatic animals are more fecund than livestock and poultry and are more like r-selection strategy opportunity species. Aquatic animals are small and abundant at birth. They feed on the small size organisms such as unicellular algae and rotifers. Few of them can feed on artemia of hundreds of micrometers. Comparatively higher fecundity permits the use of less space for maintenance of the needed broodstock.
6. Aquaculture animals can use land more efficiently than other farmed animals because they can use space in three dimensions. One hectare of land can support the production of less than a ton of beef, whereas the same water area can support more than 100 ton of fish by year.

The aquatic environment in which aquaculture animals live is very important. In production practices, we managed the water quality to provide the aquaculture animals optimal temperature for growth, enough oxygen to breathe, and plenty of food to eat and remove excess wastes from aquatic environment.

2.1.2 Traditional Classification of Aquaculture Systems

There are various types of aquaculture systems or models. Scholars and aquaculture managers around the world classified aquaculture systems based on their characteristics. The following are some examples as follows:

Based on the salinity of water, the systems are classified as mariculture, freshwater aquaculture, and brackish water aquaculture;

Based on the temperature tolerance of farmed species, the systems are classified as tropical fish farming, cold-water fish farming, and warm-water fish farming;

Based on the name of the waters used, the systems are classified as pond culture, rice field fish farming, reservoir (lake) stocking, offshore mariculture, etc.;

Based on the group of aquatic organisms, the systems are classified as algae cultivation, fish farming, shellfish culture, shrimp farming, etc.;

Based on the development stage or size of the aquatic animals, the systems are classified as fingerling breeding, fish grow-out, broodstock cultivation, etc.;

Based on the name of the facility, the systems are classified as cage (pen) culture, raft culture, raceway, etc.;

Based on the degree of intensification, the systems are classified as extensive aquaculture, semi-intensive aquaculture, intensive cultivation, recirculating aquaculture system, etc.;

Based on the number of cultured species, the systems are classified as monoculture and polyculture;

Based on the degree of openness of water bodies, the systems are classified as open system, semi-closed system, closed system, and hybrid system (Tidwell 2012);

There are also many special aquaculture systems such as aquaponics, aquasilviculture, and biofloc systems.

The above classification methodologies are used for the management convenience of aquaculture production, and most of them do not involve their essential ecological characteristics.

2.1.3 Classification Based on the Energy Sources

Ecosystems can be classified according to their structure or function characteristics. For example, marine ecosystems can be divided into open ocean, continental shelf waters, upwelling regions, deep sea, and estuaries; freshwater ecosystem can be divided into lentic waters (lakes, ponds), lotic waters (rivers, streams), wetlands, etc.; terrestrial ecosystems can be divided into tundra, grassland, forest, desert, etc.; domesticated ecosystems can be divided into agroecosystem, plantation forest ecosystem, rural techno-ecosystem (small towns, industries), urban-industrial techno-ecosystem (metropolitan districts), etc.

There are many other methods of ecosystem classification, but the classification based on energy structure could better represent the essence of ecosystem. In aquaculture systems, most even all of the aquatic organisms are artificially stocked. Therefore, the system is more or less similar to system with artificial replenishment energy. Electricity or fossil energy is needed to cultivate the artificially stocked organisms. Moreover, the stocked organisms themselves contain energy. Therefore, the stocking of seedlings is the input of artificial replenishment energy into the aquaculture systems.

The aquaculture ecosystems are much diverse and have variety of energy structures, but their basic energy structure consists of four parts (Fig. 2.1): the received solar energy (S) by the aquaculture system (AS), the energy necessary to

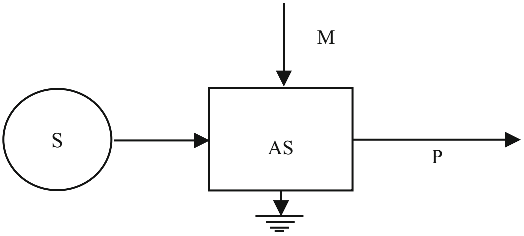


Fig. 2.1 Energy structure of aquaculture under artificial replenishment (from Odum and Barrett 2005). *AS* aquaculture system, *M* maintaining energy, *P* products, *S* solar energy

Table 2.1 Emergy accounting table for indoor and extensive culture systems for sea cucumber (SC) and intensive culture system for eel (sej/(hm^2·yr)) (from Wang et al. 2015a; Li et al. 2011b)

Note item	Indoor SC	Extensive SC	Intensive eel
Local renewable resource input			
1. Solar radiation	\	3.42×10^{13}	3.15×10^{13}
2. Wind	\	5.73×10^{8}	6.61×10^{14}
3. Rain	\	3.70×10^{10}	1.45×10^{15}
4. Tide	\	3.87×10^{11}	\
5. Sediment accumulation	\	4.15×10^{5}	\
Purchased resource input			
6. Fingerling	1.0×10^{9}	3.77×10^{7}	2.08×10^{15}
7. Electricity	5.00×10^{5}	\	1.10×10^{16}
8. Coal or oil	9.59×10^{12}	\	6.35×10^{14}
9. Direct labor	1.00×10^{6}	7.50×10^{3}	2.22×10^{15}
10. Rent	1.00×10^{6}	3.00×10^{4}	1.03×10^{16}
11. Maintenance	5.67×10^{5}	2.50×10^{3}	
12. Pesticide	5.00×10^{5}	\	1.49×10^{16}
13. Feed	9.17×10^{5}	\	1.63×10^{17}
14. Capture	\	5.95×10^{3}	
15. Others			1.06×10^{15}
Economic return	8.00×10^{6}	1.81×10^{5}	4.18×10^{17}

maintain or sustain the system production (M), the energy output in products (P), and the dissipated energy.

Aquaculture systems can be divided into the following four types based on the energy structure relationship of the system (Dong 2015b):

1. Natural aquaculture systems. An example of this type of aquaculture system is fish stocking or releasing in large waters. The energy structure of the system is $M \approx 0$. Taking the stocking of silver carp and bighead carp in reservoirs as an example, the stocked fish mainly feed on the natural plankton in water. The energy contained in the stocked fingerlings can be neglected. The energy contained in the products of the system is basically derived from solar energy.
2. Subnatural aquaculture systems. Examples of this type of aquaculture system are extensive pond aquaculture (fertilization), scallop culture, and algae cultivation. The energy structure of this type of aquaculture system is $M > 0$ and $M < S$. Pond culture of sea cucumber without feeding also belongs to this type. Although the shelters for the sea cucumber are placed in the system, the artificial replenishment energy is far less than the solar energy received by the system. Table 2.1 is the emergy accounting table of indoor and extensive culture systems for sea cucumber. As indicated by the table, the solar radiation accepted by the system is much higher than the artificial replenishment energy input (Wang et al. 2015a).
3. Artificially replenished aquaculture systems. Examples of this type of aquaculture system are semi-intensive or intensive pond aquaculture (feeding and aeration).

The energy structure of this type of aquaculture system is S > 0 and $M > S$. Pelleted feed is provided in this type of aquaculture system. When the density of farmed animals is high, aeration is required. The input of replenished energy to the system is greater than the input of natural solar energy. Table 2.1 is the emergy accounting table for three aquaculture systems (see Chap. 14 for details). As indicated by the table, the intensive eel culture system consumes more electricity emergy than the radiation solar emergy (Li et al. 2011b).

4. Fully artificially replenished aquaculture system. An example of this type of aquaculture systems is recirculating aquaculture system (RAS). The energy structure of this type of aquaculture system is $S \approx 0$. Almost all the energy received by RAS is from artificial replenished energy. The roles of natural forage and the aerobic effect of aquatic plant photosynthesis are almost negligible. Table 2.1 shows the emergy accounting table of indoor intensive culture systems for sea cucumber. As indicated by the table, the solar radiation is almost zero and almost all the emergy input into the system is artificial replenished emergy (Wang et al. 2015a).

2.1.4 Classification Based on Systemic Metabolic Characteristics

Aquaculture systems can be divided into "autotrophic" and "heterotrophic" systems based on the drivers or metabolic characteristics of the systems (Table 2.2, Dong et al. 1998). An example of the autotrophic system is the kelp cultivation system. Solar radiation is the main energy source of this type of aquaculture system, and the system absorbs inorganic nutrients from the water environment. People only need to invest seedlings, and the system can use solar energy and the nutrients in water to produce seafood. The productivity of such systems will ultimately be limited by the availability of solar energy and/or the nutrients. The heterotrophic system such as the cage culture system stocked with fed fish mainly relies on artificial feeding to provide energy. Pellet feed is the main source of energy for the heterotrophic system.

The autotrophic system will export a large amount of N, P, and other nutrients from the culture system every year with the harvest of aquatic products and thus reduces the nutrient load of the waters. The productivity of heterotrophic systems (fish productivity) is mainly limited by water quality conditions and feed inputs. Water quality management and feed input are the key factors to increase the yield of

Table 2.2 Metabolic characteristics of autotrophic and heterotrophic cultural systems

Types	Autotrophic systems	Heterotrophic systems
Examples	Kelp culture	Fed fish in cage
Energy	Solar radiation	Pellet feeds
O_2	Produce	Consume
CO_2	Uptake	Exhale
Inorganic nutrients	Absorb	Excrete
Eutrophication	Delay	Accelerate

such systems. Since the utilization rate of the input feed is far less than 100%, the system will accumulate a large amount of N, P, and organic matter, which could become a burden on the system or the adjacent waters. These two types of systems have many ecological complementarities, and their combination can increase the carrying capacity of the integrated system (Fig. 1.7).

2.1.5 Classification Based on Material Budget in the System

According to Chopin et al. (2001), the aquaculture species can be classified into fed species such as shrimp, Atlantic salmon, and extractive species such as oyster and kelp. The aquaculture systems cultured fed or extractive species can be named as fed aquaculture systems or extractive aquaculture systems, respectively. In general, the polyculture of these two types of species can reduce pollution and improve resource utilization efficiency.

Chopin's classification method is very popular in the world, but this classification method ignored the animal metabolic properties of filter-feeding shellfish. Considering the nutrient budget, the filter-feeding shellfish belongs to the extractive species; however, due to biodeposition (deposition of feces and pseudofeces), there will be accumulation of energy and nutrients at the bottom of the culture system, which will cause pollution. Moreover, filter-feeding shellfish can consume dissolved oxygen in water and release carbon dioxide and ammonia during cultivation. If shellfish and fish are cultured together, the problem of dissolved oxygen deficiency and ammonia accumulation will be aggravated. These problems will not occur when shellfish and macroalgae are cocultured. The shellfish and macroalgae were successfully cocultued in Sanggou Bay, Shandong Province (Fang et al. 1996).

Although shellfish are extractive species and Atlantic salmon are fed species, polyculture of the two species will still cause some problem. If macroalgae are added into the system to form an integrated multi-trophic aquaculture system (IMTA), the problem will be solved. The shellfish will filter the residual feed and feces of the fish. The ammonia and carbon dioxide produced by shellfish and fish will be absorbed by macroalgae, and the macroalgae can provide more oxygen for shellfish and fish (Chopin 2012).

2.1.6 Classification Based on Ecological Limiting Factors

The aquaculture system is basically a semi-artificial ecosystem established for producing aquatic products. One of the most important ecological characteristics people concerned is the ecological factors limiting the productivity of the system. According to Boyd and Tucker (1998), aquaculture system can be divided into three categories based on the food sources of the system: food provided by the plants growing in the pond (autotrophic food web), food indirectly derived from the organic inputs (heterotrophic food web), and the food directly derived from the organic input (including feed). In addition to the food sources, some other factors are

Table 2.3 Aquaculture types and their ecological features (from Dong 2015b)

Ecological types		Features
1. Inorganic nutrient-dependent systems		Including seaweed plantation; nutrient and solar radiation often restrict the yield
2. Food-dependent systems	2-1 Stocking without feeding and fertilization	Generally, for filter feeder, saprophagous, and omnivorous species aquaculture; limiting factor is natural food production; fish productivity is about 0.5 $g/(m^2 \cdot d)$
	2-2 Chemical fertilizers	Generally, for filter feeder, saprophagous, and omnivorous species aquaculture; limiting factor is natural food production; fish productivity is about 1.0–1.5 $g/(m^2 \cdot d)$
	2-3 Organic fertilizer	Generally for filter feeder, saprophagous, and omnivorous species aquaculture; limiting factor is natural food production and saprophagous chain efficiency; fish productivity is about 3.0–3.2 $g/(m^2 \cdot d)$
3. Oxygen-dependent systems	3-1 Feeding without aerator	Generally, for fed species aquaculture; limiting factor is dissolved oxygen (DO) and feed quality; fish productivities are 3.0–4.0 $g/(m^2 \cdot d)$ for plant feeds, 4.0–5.0 $g/(m^2 \cdot d)$ for pelleted feeds
	3-2 Feeding plus aerator	Generally, for fed species aquaculture; limiting factor is DO and feed quality; fish productivity can increase 2.0–3.0 $g/(m^2 \cdot d)$
	3-3 Outdoor facilities	Generally, for fed species aquaculture; limiting factor is DO; fish productivity can increase 14.6–27.9 t/m^2 at t/s water condition
4. Multi-environment factor-dependent systems		Generally for fed species aquaculture; fish productivity is limited by O_2, NH_3, temperature, etc.
5. Heterotrophic food web-dependent systems		Mainly for shrimp and tilapia culture, which can take advantage of natural productivity in the systems, their productivities are mainly restricted by the stability of microbial community; the seasonal yield of shrimp is 1–10 kg/m^2.
6. Species or subsystem coupling-dependent systems		Fish productivity is limited by degree of coupling between culture species or subsystems

also important. For example, when feed is fully satisfied, the factors limiting the productivity of aquaculture waters will be some environmental factors, such as dissolved oxygen and concentration of metabolites. Therefore, from the limiting factor point of view, aquaculture system can be divided into six types, namely inorganic nutrient-dependent system, food-dependent system, oxygen-dependent system, multi-environment factor-dependent system, heterotrophic food web-dependent system, and species or subsystem coupling-dependent system (Table 2.3).

2.1.6.1 Inorganic Nutrient-Dependent Systems

This type of system mainly includes commercial aquatic plant cultivation, such as kelp culture. Areas rich in nutrients with moderate water current are often selected for seaweed culture. The main limitations of this type of aquaculture system are nutrients and light. In some cases, temperature is also important. In many cases, proper application of chemical fertilizers can increase algae yield.

2.1.6.2 Food-Dependent Systems

This aquaculture type using natural diets to culture economic aquatic species can be further divided into three categories:

The first category: stocking without feeding and fertilization (2-1). Examples of this type of system are raft farming of scallops, stocking of filter-feeding fish in lakes and reservoirs, and extensive pond farming of tilapia and sea cucumber. The yield of this types of system depends on the feeding habits of farmed species and the primary productivity of farming waters. Under certain composition and quantity of natural diets in the waters, the yield of the system will dependent on the feeding habits of farmed species. Generally speaking, the yield will be high for species with shorter food chain and wider food spectrum. Boyd and Tucker (1998) reported that the seasonal yield of channel catfish was 50–100 kg/hm^2 in nonfeeding and nonfertilizing ponds in the United States, while the single-seasonal yield of tilapia was 200–500 kg/hm^2 under the same conditions. The relationship between stocking densities and productions under different aquaculture models is shown in Fig. 2.2.

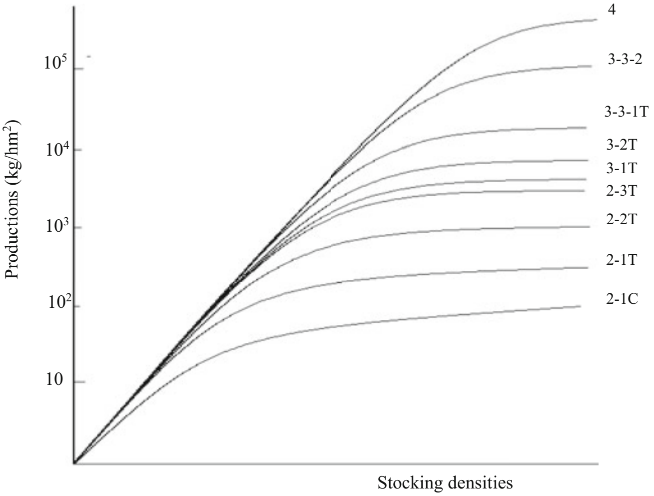


Fig. 2.2 Relationship between stocking densities and productions under different aquaculture models (from Dong 2015b). 2-1C, channel catfish extensive farming; 2-1T, tilapia extensive farming; 2-2T, tilapia extensive farming with chemical fertilizers; 2-3T, tilapia extensive farming with organic fertilizer or mixed fertilizers; 3-1T, tilapia farming with feeding without aerator; 3-2T, tilapia farming with feeding and aerator; 3-3-1T, tilapia in raceway or silver carp and bighead carp farming in pen in large waters; 3-3-2, silver carp in net cages; 4, tilapia farming in indoor facility

The second category: applying chemical fertilizers (2-2). This category is based on the fact that the amount of nutrients in the water restricts the production of natural diet, which in turn restricts the production of farmed animals. Therefore, it is possible to increase the production of farmed fish by applying chemical fertilizer to the waters. If filter-feeding fish such as silver carp or tilapia are stocked, phytoplankton and zooplankton are good diets for the fish. In the United States, a single-season production of tilapia will increase more than two times in the system with chemical fertilizers used compared with extensive culture. Choosing the right fertilizer, suitable compatibility and application are the key points to increase the production of fish in this type of system.

The third category: applying organic fertilizer or mixed application of organic and inorganic fertilizers (2-3). Besides the function of inorganic fertilizer, organic fertilizer can directly produce a large number of organic particles (debris) and a huge number of microorganisms, which can be directly fed by filter-feeding fish or zooplankton. Hence, the application of organic fertilizer or mixed application of organic and inorganic fertilizers can better meet the diet demand of fish. In general, the fish production is higher in this type of system than in the system with only chemical fertilizer used. In the United States, the production of tilapia in a single season can approach 3000 kg/hm^2 in ponds with mixed application of organic and inorganic fertilizers. According to Liu and Huang (2008), the yield of polyculture ponds with silver carp and bighead carp stocked can reach 5900 kg/hm^2, and the yield of polyculture ponds with silver carp, bighead carp, grass carp, and crucian carp stocked can reach 10,500 kg/hm^2.

2.1.6.3 Oxygen-Dependent Systems

In this type of system, sufficient amount of artificial feed is provided for farmed animals, and food is no longer the limiting factor to further increase the aquaculture production. As the stocking density increases (the feed input also increases accordingly), the dissolved oxygen (DO) in the water will decrease due to the respiration of farmed animals. Therefore, the DO content in water and the tolerance to low DO of the farmed species become the main limiting factors for continuing to increase the production. The strategy to manage DO in water to increase production will become the main basis for further classification.

The first category: feeding without aerator (3-1). Pellet feed or other kind of food is provided to the farmed animals in this type of system. However, no artificial measures are provided to increase DO content in water, and DO content in the farming waters changes according to the natural circadian rhythm. In the United States, the single-seasonal yield of channel catfish cultured in this type of system is 1500–2500 kg/hm^2, while that of tilapia can reach 3000–4000 kg/hm^2 (Boyd and Tucker 1998). The higher yield of tilapia results from its much wider food spectrum. The tilapia could not only feed on the pellet feed but also many natural organisms.

The second category: feeding plus aerator (3-2). In order to increase DO content in aquaculture systems (such as ponds), some equipment such as aerator is used. In some aquaculture waters, the stocking density is not very high, and the DO content in water is generally not low during daytime; therefore, the aerators only need to be operated at night. For example, in the United States, the single-seasonal yield of tilapia cultured in this type of system can reach 4000–6000 kg/hm^2. If the stocking density continues to increase, DO content in the daytime will be very low. In this case, the aerators need to be operated all day. The yield of tilapia can reach 6000–8000 kg/hm^2, and the yield for channel catfish, which can tolerate much lower oxygen level, will be higher.

The third category: outdoor facilities (3-3). In the case of high stocking density and large amount of metabolic waste produced, it is necessary to adopt aquaculture models that can better dilute these metabolites. Typical examples of this type of system include the net cage and pen farming in lakes and reservoirs, raceways, and in-pond raceways. In the United States, the single-season production of tilapia cultured in the systems with frequent water exchange can be as high as 15,000–20,000 kg/hm^2.

The net cage and pen farming in large waters are aquaculture models developed rapidly in the past 40 years. Net pen farming is suitable for shallow waters, while net cage farming is suitable for deep waters. The common point of net pen and cage is that water exchange inside and outside the facilities is frequent; therefore, the total and actual area or volume of the farming water body is dozens of times larger than the area or volume of the pen or cage. The metabolic waste of the farmed animals is diluted by the water volume of several dozen times larger than that of the net pen or cage. This type of aquaculture system has good water quality and less harmful predator of farmed animals. The movement of cultured animals in the system is greatly reduced due to limited space of the facilities.

In the United States, the channel catfish is cultured in small cages (1 m^3) with a yield of up to 600 kg/m^3. The size of cages used to culture Atlantic salmon in Norway is getting larger and larger, and the perimeter of large cages can exceed 100 m. In recent years, Norway has used a 250,000 m^3 semisubmersible steel frame cage (Ocean Farm) to culture Atlantic salmon. In China, a 50,000 m^3 submersible steel frame cage (Deep Blue 1) has been built. In 2017, the average production of large deep-water cages (used for water area >20 m in depth) in China was 11.1 kg/m^3, and the average production of ordinary cages was 11.6 kg/m^2. The net pens in China are divided into three types, i.e., large (greater than 7 hm^2), medium (2–7 hm^2), and small (less than 2 hm^2), and their productions are 2250, 3750, and 7500 kg/hm^2, respectively.

The production of the cage and pen varies greatly with farmed species, the size of the culture facility, and hydrodynamic conditions. The production will be higher with fed species, smaller facility, and better hydrodynamic conditions. This type of aquaculture activity usually has a great impact on water environment, which has drawn much attention of the public.

2.1.6.4 Multi-Environment Factor-Dependent Systems

Multi-environment factor-dependent systems can also be subdivided into flow-through system, semi-closed recirculating system, and closed recirculating system. Recirculating aquaculture systems (RAS) belong to the closed one, and many environmental factors such as DO, water flow, temperature, and even salinity are controllable in the production process of it. The production of the systems is high; moreover, the harvest time and size of their products will be more controllable.

In the Netherlands, the annual production of tilapia cultured in RAS is around 200 kg/m^3, and production of European eel can reach more than 330 kg/m^3. In the United States, the annual production (including several crops) of channel catfish in super intensive system can reach 1500 kg/m^3. Aquaculture production is related to water exchange rate and oxygen supply. For example, when the water flow rate is 0.0035–0.016 t/(s·m^2), the annual production of common carp is 90.3–2195 kg/m^2; when DO is 70% saturated in water, and the water flow rate is 1.6 t/(s·m^2), the annual production can reach 20 t/m^2; if DO is 100% saturated in water, the water flow rate is 0.9–1.0 t/(s·m^2), the annual production can reach 60 t/m^2 (Liu and Huang 2008).

The water requirement for producing 1 kg fish in water flow-through system is 200–300 kg, while that in closed recirculating aquaculture system is 2.5–8.0 kg (Liu and Huang 2008). The closed RAS is more complex in technological design, and the water reuse rate of the system is higher. Of course, the energy consumption per unit weight of product will be more in the closed RAS.

There is an appropriate temperature range for the growth of farmed aquatic animals. The temperature of outdoor waters varies with the season. In order to prolong the growing season and keep the animals in the optimum growing temperature range, underground hot (cool) water, hot water discharged from power plants, and heating devices are often used to regulate the water temperature of closed RAS. Recent studies have shown that rhythmic fluctuations of certain environmental factors (e.g., temperature) near the "optimum growth point" can promote the growth of farmed animals and more efficient use of feed (see Chap. 6 for detail). Therefore, the application of the optimal fluctuation rhythm control for some environmental factors will become one of the important development directions of RAS in the future.

In sum, fish productivity in aquaculture waters increases with the increase of human intervention (management). The fish productivity in natural pond is about 0.5 g/(m^2·d), is 1.0–1.5 g/(m^2·d) with chemical fertilizer, is 3.0–3.2 g/(m^2·d) with organic fertilizer, is 3.0–4.0 g/(m^2·d) with plant feed, and is 4.0–5.0 g/(m^2·d) with pellet feed. With aeration the fish productivity in pond can increase 2.0–3.0 g/(m^2·d) (Boyd and Tucker 1998). The fish productivity is 14.6–27.9 t/m^2 in the water flow-through system (Liu and Huang 2008).

2.1.6.5 Heterotrophic Food Web-Dependent Systems

Bioflocs or biofloc-based aquaculture systems are the typical heterotrophic food web-dependent system, developed in the recent 20 years. The heterotrophic food web is used to provide supplementary feeds for farmed animals in the system. Water quality is maintained by aeration and material circulation in the system. Pellet feed is still needed in biofloc-based aquaculture system, and additional carbohydrates are needed to promote the growth of beneficial microbial communities. More electricity is needed for aeration and keeping biofloc in suspension. Less or even zero water exchange can be realized in the system. Other advantages of the system including biological safety, environmentally friendly and high economic benefits (Browdy et al. 2012; see Chap. 10 for detail).

Biofloc technology can be applied in lined pond, raceway, or concrete pond. The main farmed species are tilapia and Pacific white shrimp, etc., which could use heterotrophic food web productivity efficiently. The production of the shrimp is 1–2 kg/m^2 per crop, and in some system, it can reach 10 kg/m^2. The production of tilapia is 10–20 kg/m^2 in the system.

2.1.6.6 Species or Subsystem Coupling-Dependent System

The abovementioned five types of aquaculture systems refer monoculture systems, while polyculture belongs to species coupling-dependent system or integrated aquaculture. Integrated aquaculture refers to the simultaneous culture of several aquatic species or culture of aquatic species together with other productive activities (See Chap. 9). The productivities of these systems are affected by the degree of coupling between multiple species or subsystems. In addition, aquaponics and some land-based intensive aquaculture systems are also integrated aquaculture systems. The characteristics of these types of aquaculture systems will be elucidated in Chap. 10.

2.2 Major Physical Environment in Aquaculture System

Similar to general aquatic ecosystem, aquaculture ecosystem consists of six parts: water environment (light and temperature, etc.) and substrate; inorganic substances (inorganic minerals, oxygen, carbon dioxide, nitrogen gas, etc.); organic compounds (protein, carbohydrate, fat, humus, etc.); producers or plants (macrophyte, phytoplankton, photosynthetic bacteria, and chemosynthetic bacteria, which use inorganic substances to produce organic matter); phagotrophs or consumers (animals that feed on other organisms or particle organic matter); and saprotrophs or decomposers (mainly bacteria and fungi, which obtain energy mainly by absorbing soluble organic matter extracted from plants or other organisms). This section will focus on the physical environment closely related to aquaculture organisms, such as water, temperature, light, and salinity.

2.2.1 Physical Characteristics of Water

The biggest difference between aquaculture and other agricultural production activities is that aquaculture activities are generally carried out in water, which is a special media. Therefore, some unique thermodynamic properties of water will have an important impact on aquaculture activities. Important physical properties of water include the following:

1. The maximum mass of water is 1.000 g/cm^3 at 3.94 °C, and the mass of water is 0.9168 g/cm^3 at 0 °C. Therefore, the surface water of a deep lake freezes in winter, while there is still liquid water under the ice.

2. The specific heat (the amount of heat in calories that is required to raise the temperature 1 °C of a unit mass of a substance) of water is very high, which is 1 cal/(°C·g) (1 cal = 4. 1868 J).
3. The latent heat of evaporation of water is very high, which is 540 cal/g, and the sublimation heat of ice is 679 cal/g. Therefore, the temperature of water is more stable than that of air and surface soil.
4. The freezing point of water is 0 °C, and the boiling point of water is 100 °C. The freezing point of water decreases with the increase of salinity.
5. Water has good thermal conductivity.

The above properties of water are very important for aquaculture production and even for the existence of life on earth. The water in aquaculture waters can move under the action of temperature and wind.

2.2.2 Light in Waters

Solar radiation is one of the most important factors in waters, which is not only the energy source of photosynthesis for primary producers, but also affects the behavior of aquatic animals and the state of water movement. The movement of water has directly or indirectly effects on some important ecological processes of aquatic ecosystems.

Solar radiation consists of visible light, ultraviolet light, and infrared light. The solar energy reaching the outer surface of the earth's atmosphere is 1.9 cal/(cm^2·min). However, due to the absorption of the atmosphere, the light reaching to the surface of aquaculture waters is almost the visible light and infrared light. On average, the solar energy absorbed by the atmosphere accounts for about 19% of the total solar radiation, 40% of the remaining part is visible light, and 60% is infrared light.

The solar radiation reaching to different aquaculture waters is different due to their different latitude. From Fig. 2.3, the average illumination intensity is stronger and the seasonal variation is smaller in low latitude region. Most regions in China are in middle latitude region, and seasonal variation of illumination intensity is large. The farther to the north, the larger the variation of illumination intensity.

2.2.2.1 Reflection and Absorption of Sunlight

The amount of solar radiation reaching to the surface of aquaculture waters is related to weather conditions, latitude, seasons, and time of the day. On a sunny day, the solar radiation is almost zero before dawn, increases rapidly then, and reaches its maximum at noon, and then decreases rapidly. The solar radiation is almost zero throughout the night. The solar radiation is shaped like a bell during the day.

Parts of the solar radiation reaching to the waters will be reflected by the surface of the waters, and the rest penetrates the water. The reflectivity is related to the incident angle, the nature of the water surface, and meteorological conditions. The smaller the incident angle, the greater the reflectivity. The wave can disturb the water

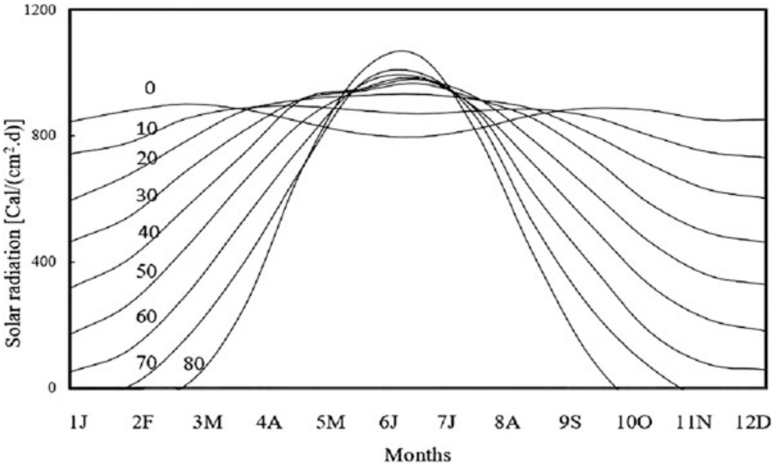


Fig. 2.3 Solar radiations in different months at different latitudes (from Wetzel 2001). 1J—January, 2F—February, 3M—March, 4A—April, 5M—May, 6J—Jun, 7J—July, 8A—August, 9S—September, 10O—October, 11N—November, 12D—December

Table 2.4 Light penetration through ice and snow cover of lakes under different conditions (from Wetzel 2001)

Ice-snow conditions	Thickness (cm)	Percentage transmission of surface insolation
Clear ice	43	72
Clear ice with vestige snow	39	53
Milky ice with bubbles	29	54
Wet ice with bubbles	39	41
Translucent ice ("snow ice")	25	11–18
Ice with irregular surface	29	58
New snow	0.5	34
	5.0	20
	10	9
	17–20	8.8–6.7
Compacted snow	17–20	5–1

surface. When the wave is large, the reflectivity will increase. Scattered light will also be partially reflected on the water surface, but its reflectivity is less affected by its incident angle.

In cold winter, the water surface of aquaculture waters may freeze. Ice and snow covered on ice can affect the penetration of light. The degree of influence is related to the nature and thickness of ice or snow (Table 2.4). Light can pass through the snow on the ice, but it attenuates quickly. Light intensity decreases by 66% after passing through 0.5 cm thick new snow, and only 9% is remained after passing through 10 cm snow.

Scattered light and direct light can penetrate the ice on the water surface, and the penetration percentage of scattered light is higher than that of direct light. Part of the sunlight can penetrate the ice of fish overwintering ponds, and phytoplankton in the pond water can use the light to carry out photosynthesis, which produces oxygen and ensure the safety of overwintering fish in ponds.

The ice on the surface of aquaculture waters sometimes is opaque, and such ice is called dark ice. The dark ice is usually formed on snowy or windy days and has a great influence on the transmission of light. Dark ice can seriously hinder the entry of light into water, resulting in weak photosynthesis in water. The DO content is low in the ponds covered with dark ice, which will threaten the survival of fish under the ice. In this case, aquaculture manager often breaks the dark ice to let the surface of the water freeze again to form transparent ice.

The sunlight entered water will be absorbed strongly by the water and will attenuate rapidly. The remaining intensity of light in water obeys Bill's law:

$$I_Z = I_0 \cdot \mathrm{e}^{-kZ}$$

In the formula, I_Z is the remaining intensity of light at Z depth, I_0 is the light intensity on the surface of waters, and k is the extinction (absorption) coefficient. The extinction coefficient is influenced by the nature of water itself, suspended particles, and dissolved substances.

In pure water, about 25% of the sunlight energy can be absorbed by the top 1 cm water layer, and about 50% of it will be absorbed by the top 10 cm water layer. Infrared light (wavelength >0.76 μm) will be absorbed rapidly, and most of infrared light will be absorbed at 1 m depth. As the wavelength decreases, the absorptivity decreases, and blue light has the lowest absorptivity. The visible light reaching 10 m depth is mainly blue and purple light.

Particulate matter suspended in water (phytoplankton, sediment, etc.) also absorbs light, thus affecting the incident depth of light at different wavelengths. Figure 2.4 shows the distribution of visible light in a shallow lake with a transparency of about 1.7 m. It is not difficult to see that only a small amount of blue light can reach below the Secchi depth, while green light can reach deeper water. This characteristic of green light is of great significance to the photosynthesis of phytoplankton distributed under the Secchi depth.

2.2.2.2 Transparency and Water Color

Transparency and water color are two important parameters representing the light transmittance and quality of water. Transparency can be measured by a Secchi disk 20 cm or 30 cm in diameter. Transparency represents the depth of light entering the water. The more suspended matter and dissolved organic matter in water, the smaller the value is. Generally, the Secchi depth of aquaculture ponds is about 10 cm, while those of reservoirs and lakes can be up to 1 m. The Secchi depth of bay area is higher, which can be up to 2 m. The Secchi depth of offshore ocean is over 10 m.

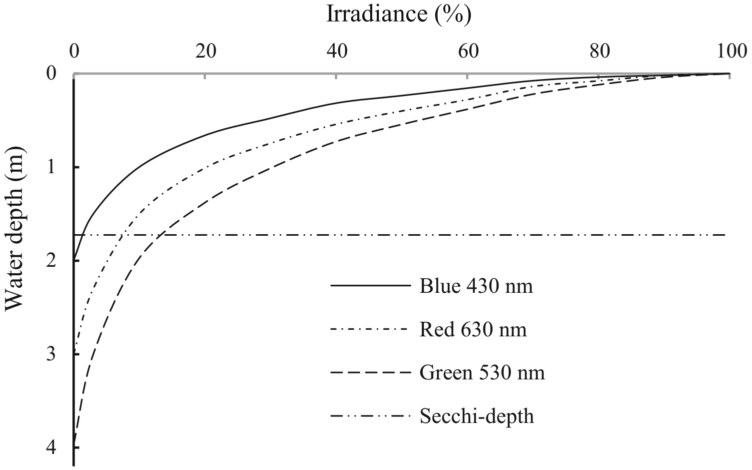


Fig. 2.4 Vertical distribution of visible light in a shallow lake (from Scheffer 1998)

There is a certain correlation between the transparency measured by the Secchi disk and the light intensity underwater. The empirical formula for calculating extinction coefficient *k* given by Idso and Gilbert (1974) is as follows:

$$k = 1.7/Z_{\mathrm{SD}}$$

In the formula, Z_{SD} is the transparency (*m*) measured by the Secchi disk. If the light intensity at water surface and *k* are obtained, the light intensity at a given depth can be roughly calculated by using Bill's law mentioned above.

Water color is the color of light reaches the observer eyes after scattered and reflected from water molecules and suspended particulate matter. It does not include reflected light from the water surface. The water color of No. 1 measured by water color meter is blue and No. 21 is yellow. In general, the smaller the number, the better the water quality.

2.2.2.3 Biological Effects of Light

When sunlight is absorbed by water, the water will be warmed up, which will result in water movement. This aspect will be introduced in detail later. The biological role of light will be briefly introduced in this section.

Sunlight is an important energy source of aquaculture ecosystem, especially for the inorganic nutrient-dependent and food-dependent aquaculture systems. For each molecule CO_2 consumed by photosynthesis of phytoplankton or large aquatic plants in water, 4–9 photons are utilized and a molecule glucose is synthesized.

Because of the attenuation characteristics of sunlight, intensity of photosynthesis also presents a specific distribution pattern. Intensity of photosynthesis is sometimes inhibited on the surface of water due to too strong illumination. As the water depth increases, photosynthesis will increase and gradually reach its maximum value.

After that photosynthesis will gradually decrease to zero. For freshwater water in China, the maximum photosynthesis usually occurs at the water depth around half of the Secchi depth. The water depth with the equal rate of photosynthesis and respiration is called compensation depth, which is also the lower depth of the euphotic zone. The compensation depth generally occurs at 1.7–2 times of the Secchi depth, where the light intensity is about 1% of the water surface light. The depth at which photosynthesis is zero is generally near three times of the Secchi depth. Other types of vertical distribution of photosynthetic intensity may occur in some waters or under special conditions. Readers may refer to "*Limnology*" (Wetzel 2001) for more information.

The intensity of photosynthesis determines the DO content in aquaculture waters. When wind is mild, the vertical distribution of DO in the waters at daytime is mainly affected by photosynthesis and respiration (see Sect. 2.3 of this chapter for more information).

Another important biological function of light is to influence behavior and physioecological characteristics of aquatic animals. The circadian rhythm of many animals is related to the changes in light intensity. It has been found that salmon larvae are more sensitive to green light and less sensitive to red light, while silver perch and golden perch larvae are sensitive to yellow-orange light. Some studies have found that silver carp grow better under white and green light. The sensitivity of these species to different light colors generally corresponds well to the light colors in the water layer, where those species live naturally. Different photoperiod also has significant effects on ovarian maturation, growth, and reproduction of animals.

There are two types of photosensitive cells in the visual organs of *Fenneropenaeus chinensis*. And these two types of cells are sensitive to blue light (0.48 μm) and yellow light (0.58 μm), respectively. Different light colors have obvious effects on the growth and metabolism of *F. chinensis*. As shown in Table 2.5, the order of growth rate of *F. chinensis* under four light colors was white light > green light > yellow light > blue light.

F. chinensis feeds and moves actively under blue light. The ingestion rate is also highest under blue light, which indicates that the shrimp is sensitive to short-wave blue light. However, the proportion of energy consumed for growth decreases due to its active movement under blue light (Wang et al. 2003).

Blue light has strong penetrating power in clean water; therefore, the sunlight reaching pond bottom with clean water is often blue. Some aquaculture activities

Table 2.5 Energy allocation of *Fenneropenaeus chinensis* at different light color (%) (from Wang et al. 2003)

Light color	R/C	G/C	E/C	U/C	F/C
White	65.15	12.94	1.42	5.76	14.73
Yellow	68.43	11.56	1.72	6.06	12.24
Green	69.99	10.81	1.36	6.16	11.69
Blue	76.11	8.07	1.52	7.05	7.25

Note: C is energy consumed, E is energy lost in exuvia, F represents energy of feces produced, G is energy for growth, R stands for energy lost as respiration, U is energy lost in excretion. The following tables are the same to present these parameters such as feeding and fertilization will change the color of aquaculture waters, because the input of nutrients increases the phytoplankton and dissolved organic matter in water. With the increase of dissolved organic matter and particulate matter, the amount of solar radiation entering deep water decreases rapidly, and the light spectrum changes from short-wavelength blue light to longer-wavelength green light. Due to human activities, nearshore or aquaculture pond water usually shifts from blue-green to green-orange (McFarland 1986). Clean blue water in aquaculture ponds is not necessarily better than yellow-green water for the growth of *F. chinensis*. The growth of *F. chinensis* under green light is slightly faster than that under blue light, and more ingested energy is deposited to growth under green light than under blue light (Table 2.5).

2.2.3 Water Temperature

Water temperature is a measure of heat intensity in water. The high specific heat of water (when the temperature of 1 g water rises or falls by 1 °C, 1 cal energy is consumed or released) makes it absorb a large amount of incident light energy and stores it in the water system in the form of heat. The heat storage, distribution, and change of waters not only directly affect the primary production and decomposition process of aquaculture ecosystems, but also affect the growth of farmed organisms.

The heat income to aquaculture waters is mainly direct absorption from solar radiation, transfer of heat from the air, transfer of heat from sediment to the water, heat transfer from terrestrial sources via precipitation, surface runoff, and groundwater input. The heat losses of aquaculture waters are mainly evaporation, heat radiation to the air (mainly in autumn and winter), outflow or discharge water, etc.

Most of the aquaculture animals and plants are ectotherm organisms, and their physioecological processes will change significantly with the change of water temperature. Aquaculture organisms can be divided into stenothermobionts and eurythermophils based on their ability of temperature adaptation. They can also be divided into cold-temperature species, warm-water species, and tropical species.

The water temperature in aquaculture systems has temporal and spatial variations. As mentioned in the previous section, solar radiation energy will be strongly absorbed at upper layer of waters. Less than half of the solar radiation energy could reach more than 2 m depth even in clean water. Therefore, the nonuniformity distribution of heat energy will result in a series of special phenomena. Understanding the changing rule of water temperature is important for aquaculture management.

2.2.3.1 Thermal Stratification and its Ecological Significance

2.2.3.1.1 Inverse Stratification of Water Temperature in Winter

The vertical distribution of water temperature in temperate zone varies from season to season. In winter, the water temperature of the waters will be inversely stratified (i.e., the water temperature is high at the top and low at the bottom) (Fig. 2.5a). Because the mass or density of water is highest at 3.94 °C (hereinafter referred to as

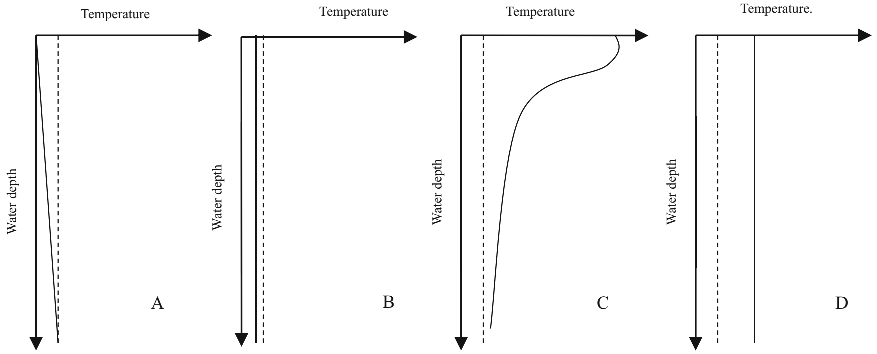


Fig. 2.5 Thermal stratification of a typical temperate water. (**a**) Winter; (**b**) Spring; (**c**) Summer; (**d**) Autumn. The dotted line is 4 °C

4 °C), and the mass of water will be smaller than the highest value when its temperature is higher or lower than 4 °C. Taking a typical deep freshwater reservoir in northern temperature zone as an example, when the surface water temperature drops below 4 °C, the water density of upper layer water begins to be lighter than that of bottom water. When the surface water temperature drops to 0 °C, it begins to freeze. The mass of ice is only 0.9168 g/cm^3, which is lighter than that of the water beneath the ice. Therefore, the ice will float on the surface of water, which can slow down the rapid dissipation of heat energy of the waters. This important physical characteristic of water is of great significance to the existence of life in water. Otherwise, primitive aquatic organisms could not overwinter in water, and there will be no such colorful lives in the world.

2.2.3.1.2 Isothermal in Spring

When the ice cover melts due to the rise of temperature in spring, the density of the surface warming water will be greater than that of the water below, which will cause the phenomenon of convection. The convective motions last until the whole water column reaches 4 °C. The water temperature distribution at this time is called spring isothermal (Fig. 2.5b). Because of the effect of wind, the mixture of the waters might occur even when water temperature is below 4 °C.

The spring isothermal period is thermal instable and mild wind is sufficiently enough to mix the water. The duration of spring isothermal is determined by many factors. It lasts only a few days for the deep and small surface area of waters, but lasts several weeks for shallow and large surface area of waters. Spring mixing in deep lakes and reservoirs can transport nutrients accumulated at the bottom of the waters to the upper water layer which is relatively nutrient-deficient, which will promote the rapid reproduction of phytoplankton. A peak of phytoplankton biomass is usually reached in this period.

2.2.3.1.3 Stratification in Summer

In the process of warming up in spring, the temperature of the waters may be stratified after several sunny and mild wind days. When the surface water temperature increases, its density decreases. The corresponding mixing resistance increases obviously, and the difference of several degrees Celsius between the top and bottom water is enough to prevent the occurrence of vertical circulation of water. Entering summer, the stratification will be further strengthened and will continue until autumn (Fig. 2.5c). The water body can be vertically divided into three layers, i.e., epilimnion, metalimnion, and hypolimnion. Convection or even circulation occurs within the upper layer (epilimnion) at night when the temperature drops or the wind blows, but the exchange process between the upper layer and the lower layers seldom occurs. The water layer near the bottom of the waters is hypolimnion, and its temperature is low and stable. Between the epilimnion and hypolimnion, it is the metalimnion or thermocline, which is the water layer with fast temperature change with the increase of water depth. It is generally recognized that the change of water temperature in thermocline should be more than 1 °C/m. The classical definition of a thermocline is not applicable to ponds, because even in winter, temperature gradients often exceed 1 °C/m of depth (Boyd and Tucker 1998).

The thermocline also exits in offshore ocean. The thermocline of ocean is usually located at 100–200 m beneath the sea surface, but the thermocline in the center of the Yellow Sea is shallow, which is at -20 to -30 m. There is a huge volume of cold-water mass (about 500 billion m^3) under the thermocline of the Yellow Sea. The bottom water temperature in summer is 4.6–9.3 °C, and the DO near bottom water is no less than 5 mg/L. Chinese have begun to use the cold-water resources to culture cold-water fish (Dong 2019b).

The formation of thermocline in summer will hinder the exchange of heat energy and materials between epilimnion and hypolimnion of the waters. The inorganic nutrients in epilimnion are quickly absorbed by phytoplankton, and part of plankton sinks into hypolimnion gradually, resulting in the decrease of phytoplankton biomass in epilimnion in summer. Epilimnion water is rich in DO due to photosynthesis, but is lack of inorganic nutrients. However, DO content is low in epilimnion water due to strong decomposition and weak photosynthesis. For the eutrophic waters with dense phytoplankton, DO in epilimnion is usually very low, and a very thick anaerobic zone will appear near bottom, resulting in the reduce of the adsorptive capacity of the sediment. As a result, NH_4^+ and PO_4^{2-} concentrations of the hypolimnion increase (Wetzel 2001).

A common phenomenon is that phytoplankton biomass is lowest in summer in deep waters of mid-latitude. Although the water temperature in summer may be suitable for fish growth, the low phytoplankton biomass results in slow growth of stocked filter-feeding fish. There will still be a certain level of DO in the water below the thermocline in oligotrophic waters in summer and aerobic organisms such as fish can survive. However, in the hypolimnion of eutrophic waters, fish and other animals will asphyxiate or escape due to anoxia.

In summer, the water temperature of water discharged from the lower layer of the reservoir with thermocline is lower, which will have a certain impact on the downstream ecosystem. For example, some dams built on large rivers, such as Gezhouba Dam, may change the growth and reproduction of the fish and other organisms downstream by discharging low-temperature water in summer. The low-temperature water discharged by some dams in southern China in summer can also be used to culture cold-water fish. For example, rainbow trout is cultured under the dam of Xin anjiang Reservoir.

2.2.3.1.4 Isothermal in Autumn

In late summer or early autumn, the temperature of the surface water begins to decrease. Because of the sinking and convection of the low-temperature or low-dense surface water, the thickness of thermocline is gradually thinned until it disappears. As the water temperature continues to drop, the surface water begins to exchange with the deep water, i.e., convection. In theory, when the water temperature reaches 4 °C, the temperature of the whole waters will be the same, which is called autumn isothermal (Fig. 2.5d). In fact, a strong wind could mix the whole water body, when water temperature is greater than 4 °C. The specific temperature of the mixed water is related to the water area, depth, topography, meteorology, and other conditions.

During the isothermal period in autumn, nutrients and DO are exchanged between the upper and lower water layers, and the anaerobic zone in the hypolimnion of eutrophic waters will gradually disappear. The abundant nutrients in the hypolimnion water can be supplemented upward to promote the reproduction of phytoplankton in the epilimnion. The second peak of phytoplankton biomass will be reached in the year. In the temperate zone, seasonal variations of phytoplankton biomass in deep waters are usually saddle-shaped (Fig. 2.6). The abundant food sources in the water in autumn are the natural diets to fatten the farmed fish before overwintering.

When the temperature drops below 4 °C in winter, the water body begins to have inverse stratification of water temperature. Before freezing, the whole water body is easy to be mixed even by weak wind because the temperature difference between the upper and lower water layer is small.

In temperate zone, the shallow waters, such as aquaculture ponds and shallow lakes in the middle and lower reaches of the Yangtze River, generally do not have an

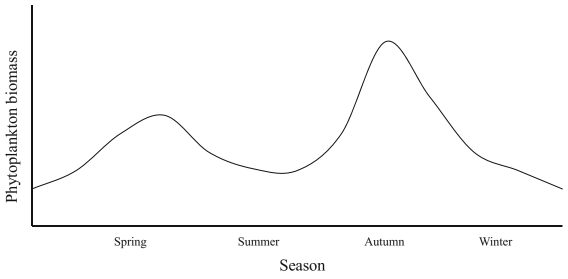


Fig. 2.6 Seasonal variation of phytoplankton biomass in typical temperate waters

obvious and stable summer thermocline. The phytoplankton biomass has only one peak, i.e., a single peak in summer.

2.2.3.2 Thermal Mixing Types of Water

The types of the thermal stratification and circulation of waters around the world are diverse. Generally speaking, temperate waters have the maximum densities (4 °C) for two times (positive stratification in summer and inverse stratification in winter) in a year. In the tropic areas, water temperature is always higher than 4 °C. There is positive stratification of temperature throughout the year, and the overturn of waters occurs only in winter. In the polar regions, water temperature is always lower than 4 °C. There is always an inverse stratification of temperature in water except the summer overturn.

It is reasonable to name water types according to their thermal mixing types. The thermal mixing types are classified as follows:

Amixis: Some waters never circulate. These are the amictic waters, permanently ice-covered, and immune throughout to the stirring effects of wind. This type of water mainly exists in the Antarctic, and there are a few records of this type of water in some high mountains or Arctic regions.

Cold monomixis: Cold monomictic waters are frozen over during winter months when the water is shielded from the mixing effect of wind. The temperature of this type of water is always below 4 °C. This type of water is mostly distributed in the Arctic and alpine regions. The annual temperature is inversely stratified, and mixing occurs in summer.

Warm monomixis: The temperature of warm monomictic waters is always over 4 °C. This type of water is mostly distributed in tropical and subtropical areas. The annual temperature is stratified, and mixing occurs in winter.

Dimixis: Dimictic waters are a typical temperate waters. It is distributed in temperate zone and subtropical zone with high altitude. As mentioned above, it is characterized by inverse stratification in winter, positive stratification in summer, and two overturn periods in spring and autumn.

Oligomixis: Oligomictic waters mostly exist in the tropical windless zone, and the annual water temperature is more than 4 °C. This kind of water is usually small or deep, and the mixing of water occurs in abnormal cold weather.

Polymixis: Polymictic waters are generally large in area and shallow in depth and are influenced more by the changing diel fluctuations in temperature than by seasonal changes. They are more common in tropical areas with strong wind and high altitude. The water temperature rises rapidly due to solar radiation received during the day, and the temperature drops rapidly at night, leading to convection and mixing. In addition, wind or rainfall process can also lead to the mixing. This type of water is also called warm polymictic waters.

2.2.3.3 Wind Drift and Circulation

In aquaculture waters, the upper and lower water layers often mix under the action of wind drift (Fig. 2.7). Under the action of well-directed wind, a wind drift will form

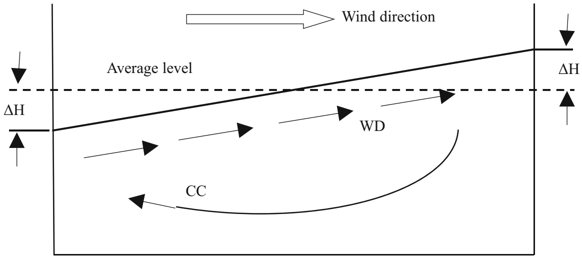


Fig. 2.7 Wind-driven water circulation. *CC* compensatory current, *ΔH* water level change, *WD* wind drift

on the surface of the waters, and the surface water will move from the leeward bank to the windward bank, resulting in the water level difference between the two sides. During a typhoon in the 1980s, the water level difference between the windward bank and leeward bank of Lake Taihu reached 1.48 m. Because of this water level difference, a compensatory current opposite to the direction of wind drift is formed in the lower layer of the waters, which makes a large amount of water at the bottom move from the windward bank to the direction of the leeward bank. The wind drift and the compensatory current constitute the wind-driven circulation, and various substances in the waters can be mixed by this circulation. The intensity of wind-induced circulation depends on the force, duration of wind, surface area, depth, thermal stratification, and topography of the waters.

In addition to the regular seasonal mixing and wind-induced circulation, heavy rain often causes convective mixing of aquaculture waters. When there is unstable thermal stratification of aquaculture waters (ponds, small reservoirs or lakes, etc.) and existence of thick anoxic zone at the bottom of the waters, anaerobic asphyxia of fish may happen due to sudden mixing of waters. This phenomenon often occurs after heavy rain in windless and muggy weather.

2.2.3.4 Requirements for Water Temperature in Aquatic Animals

Most of the aquatic animals are ectotherms and the change of water temperature will directly affect the metabolism, growth, and even survival of them. The effect of water temperature on their metabolism is basically in accordance with van Hoff’s law; that is, the rate of biochemical processes roughly doubles for every 10 °C increase in temperature. However, extremely high temperature can have a negative impact on their metabolism. Effect of water temperature on relative oxygen consumption rates (ROCR) of aquatic animals is illustrated in Fig. 2.8. Before reaching the maximum ROCR, the ROCR of the animals increases with the increase of temperature. The peak value of ROCR is only maintained in a very narrow temperature range. As the temperature continues to rise, the ROCR of the animals will drop rapidly. The animals will finally stop breathing when the lethal temperature is reached.

The relationship between water temperature and the growth of aquatic animals is similar to the curve illustrated in Fig. 2.8. Generally speaking, aquatic animals can grow in a wide temperature range, but the optimum growth temperature range is narrow. For example, the shrimp *F. chinensis* can tolerate temperatures ranging from

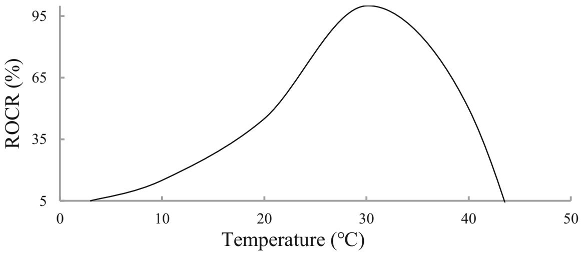


Fig. 2.8 Effect of water temperature on relative oxygen consumption rates (ROCR) of aquatic animals (from Boyd and Tucker 1998)

4 to 38 °C, and the temperature range that is suitable for growth is 18–30 °C. The optimum growth temperature range is 20–28 °C, and the species grow fastest at 25 °C (Zhang 1998; Wang 2008a).

The optimum growth temperature of cold-water species is generally below 20 °C, and when the water temperature is above 25 °C, the species cannot survive. Tropical and subtropical species will not grow well when water temperature falls below about 25 °C, and water temperature below 10 °C or 15 °C may kill them. Warm-water species which are native to temperature climate grow best at temperature between 20 °C and 28 °C, but they can survive at temperature near 0 °C.

Daily and seasonal fluctuations of temperature may have a certain impact on the growth of aquatic organisms. Previous studies indicated that suitable temperature fluctuations can promote the growth of fish, shrimp, and sea cucumber, etc. (Diana 1984; Dong et al. 2006; Tian and Dong 2006; Tian et al. 2006). More information about the effects of temperature fluctuations on the growth of aquatic organisms is available in Chap. 6.

2.2.4 Salt Content of Water

Salt content is an important index of aquaculture waters, which influences on the growth of aquatic organisms and the ecological process of aquaculture waters. Salt content can be represented by the total concentration of all ions in water. Salinity and chlorinity are often used in mariculture.

2.2.4.1 Chemical Classification of Salt Content in Water

According to the FAO Yearbook of Fishery and Aquaculture Statistics, the freshwater is waters with a consistently negligible salinity. The brackish water is waters with appreciable salinity but not to a constant high level. It is usually characterized by regular daily and seasonal fluctuations in salinity due to freshwater and full-strength marine water influxes. Enclosed coastal and inland water bodies, in which the salinity is greater than freshwater but less than marine water, are also regarded as brackish. The marine water is coastal and offshore waters with maximal salinity and not subject to significant daily and seasonal variation. However, according to the total amount of ions in water, the International Society of Limnology divided natural waters into four following categories:

Freshwater		<0.5 g/kg
Mixohaline	Oligohaline water	0.5–5 g/kg
	Mesohaline water	5–18 g/kg
	Polyhaline water	18–30 g/kg
Euhaline water		30–40 g/kg
Hyperhaline water		>40 g/kg

There are many other methods to classify water based on its salt content. Former Soviet Union scholar Arliekin classified water into different water types according to the ionic equivalent of eight major anions and cations in natural water, namely Cl^-, SO_4^{2-} , CO_3^{2-} ,HCO_3^- , K^+, Na^+, Ca^{2+}, and Mg^{2+} (Fig. 2.9).

In Arliekin's classification, the eight major ions were considered as the main ion composition of water body (i.e., $Ca^{2+} + Mg^{2+} + K^+ + Na^+ = HCO_3^- + CO_3^{2-} + SO_4^{2-} + Cl^-$), while concentrations of other trace ions are ignored. Table 2.6 lists the chemical composition of several typical waters. Sanmenxia Reservoir (Henan Province, China) is a typical freshwater body. Daluhu Lake (Shandong province,

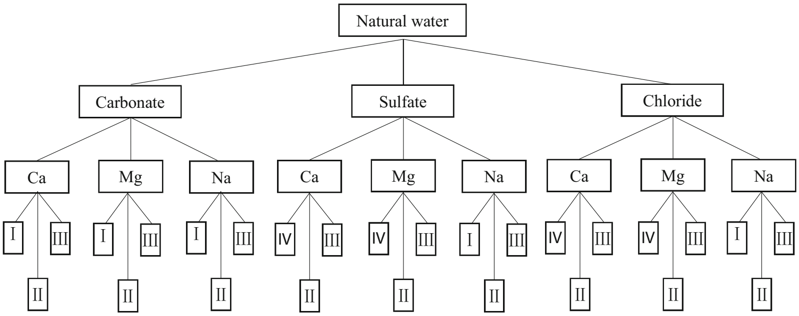


Fig. 2.9 Classification of natural water based on chemical compositions

Three categories:	Bicarbonate category C:	$HCO_3^- + CO_3^{(2-)} > SO_4^{(2-)} + Cl^-$
	Sulfate category S:	$SO_4^{(2-)} > HCO_3^- + CO_3^{(2-)} + Cl^-$
	Chloride category cl:	$Cl^- > SO_4^{(2-)} + HCO_3^- + CO_3^{(2-)}$
Three groups:	Ca group:	$Ca^{2+} > Na^+(K^+) + Mg^{2+}$
	Mg group:	$Mg^{2+} > Na^+(K^+) + Mg^{2+}$
	Na group:	$Na^+(K^+) > Ca^{2+} + Mg^{2+}$
Four types:	Type I:	$HCO_3^- \left(CO_3^{2-}\right) > Ca^{2+} + Mg^{2+}$
	Type II:	$HCO_3^- < Ca^{2+} + Mg^{2+} < HCO_3^- + SO_4^{2-}$
	Type II:	$HCO_3^- + SO_4^{2-} < Ca^{2+} + Mg^{2+}$ or $Cl^- > Na^+$, seawater
	Type IV:	$HCO_3^- \left(CO_3^{2-}\right) = 0$

Table 2.6 Chemical compositions of several typical waters (me/L)

Waters	Ca^{2+}	Mg^{2+}	$K^{+}+Na^{+}$	HCO_3^-	SO_4^{2-}	Cl^-	Salt contents	Water types
Sanmenxia reservoir (Henan)	2.13	1.27	3.18	3.65	1.32	1.61	0.489	C_{II}^{Na}
Daluhu Lake (Shandong)	2.31	5.86	12.72	6.18	2.08	12.6	1.44	C_{II}^{Na}
Dali Lake (Inner Mongolia)	0.29	1.89	63.0	44.5	5.44	33.4	5.56	C_{II}^{Na}
Seawater	20.6	106	477	2.33	56.5	545	35	C_{III}^{Na}

China) is a saline–alkali lake in waterlogged areas. Dalaihu Lake (Inner Mongolia Autonomous Region, China) is a typical saline–alkali waters. The ratios of monovalent cations to bivalent cations ($K^{+}+Na^{+}$ /$Ca^{2+}+Mg^{2+}$) for Sanmenxia Reservoir, Daluhu Lake, Dalai Lake, and seawater are 0.94, 1.55, 28.9, and 3.67, respectively. The monovalent and bivalent cations are not well balanced in Dalai Lake, which is harmful to fish.

Salt content in water body is mainly affected by precipitation, runoff, and drainage basin conditions such as geology, soil type, geomorphology, and human activities. The salt contents of waters in China are quite different, and it tends to increase gradually from southeast to northwest. There is abundant rainfall in the southeastern coastal region of China. The rainfall could leach the soluble salts out of the soil; therefore, the salt contents of rivers in the region are usually below 0.05 g/L, and most of them belong to bicarbonate category, Na group, or Ca group. In the middle and lower reaches of the Yangtze River, the salt contents of the rivers in the region are less than 0.2 g/L. In the region north of Huaihai River and Qinling Mountains in China, the salt contents of rivers are more than 0.2–0.3 g/L. In addition to bicarbonate category, sulfate and chloride categories also appear. The salt contents of the rivers in the south of the Loess Plateau in China can reach 0.3–0.4 g/L, and it rises to 0.5–1.0 g/L in the northwest of the region.

There are many saline–alkali ponds for aquaculture in the waterlogged areas along the Yellow River in China. Since people used the technology of Digging pond and raising land (planting crop at the raised bed and culturing fish in pond) to exploit the waterlogged and saline–alkali land, about three million hectares of pond-based aquaculture–agriculture system have been exploited for fish or shrimp farming. These saline–alkali ponds are characterized by high salt content, high alkalinity, high pH, and high Na^{+}/K^{+} ratio. The principles of aquaculture utilization of saline–alkali land will be introduced in Chap. 11.

2.2.4.2 Effects of Salt Content on Aquaculture

The fish, crustaceans, and shellfish living in water have different osmoregulation ability. Osmoregulation is an energy-consuming process. Each species has an optimum salinity or salt content range. Outside of this range, the aquatic animal must expend considerable energy for osmoregulation at the expense of other

Table 2.7 Upper limits of salt content or salinity that permit growth and survival of some cultured fish (from Boyd and Tucker 1998)

Species	Salt contents or salinities (mg/L)
Catla *Catla catla*	Slightly brackish
Rohu *Labeo rohita*	Slightly brackish
Grass carp *Ctenopharyngodon idella*	12,000
Silver carp *Hypophthalmichthys molitrix*	9000
Channel catfish *Ictalurus punctatus*	11,000
Blue tilapia *Oreochromis aureus*	18,900
Nile tilapia *Oreochromis niloticus*	24,000
Java tilapia *Oreochromis mossambicus*	30,000
Gray mullet *Mugil cephalus*	14,500
Common carp *Cyprinus carpio*	32,000
Milkfish *Chanos chanos*	9000
Bigmouth buffalo *Ictiobus cyprinellus*	9000
Goldfish *Carassius auratus*	15,000

processes, such as growth. The destruction of osmotic pressure of the body fluid will affect other physiological and biochemical processes. Therefore, if aquatic species could not adapt to the hypersaline or hyposaline environment, they will die because of their inability to maintain ion balance of the body fluid. The upper limits of salt content or salinity of some cultured fish are listed in Table 2.7.

Many aquaculture species, such as *Penaeus vannamei*, *F. chinensis*, *Eriocheir sinensis*, *Oncorhynchus mykiss*, *Lateolabrax maculatus,* and *O. mossambicus*, could live in a wide range of salt content. This is related to their living environment and evolutionary history. In recent years, these euryhaline species are cultured in inland freshwater or brackish areas in China. However, it is not advisable to artificially add salt to freshwater waters for aquaculture from the perspective of environmental protection.

2.3 Major Chemical Environment in Aquaculture System

2.3.1 Dissolved Oxygen

Besides water, oxygen is the most basic requirement for aquatic animals in aquaculture system. DO is essential for the metabolism of all aerobic aquatic animals. Therefore, the concentration and variation of DO in water determine the distribution, behavior, and growth of many aquatic animals. In addition, DO also affects many ecological processes in aquatic ecosystems and is a comprehensive indicator of water quality. Water saturated with oxygen contains 20–40 times less oxygen than air by volume, and the energetic costs of breathing in water are greater than in air because water is much denser.

2.3.1.1 The Solubility of Oxygen in Water

Under standard atmospheric conditions (0 °C at sea level, atmospheric pressure 760 mmHg), the partial pressure of oxygen in a dry air accounted for 20.946% of the atmospheric pressure, and it is 159.2 mmHg. When air comes into contact with water, the oxygen in the air continues to diffuse into the water until the partial pressure of oxygen in the water equals to the partial pressure of the oxygen in the air. If the partial pressure of the oxygen in the water is greater than the partial pressure of the oxygen in the air, the oxygen in the water will escape from the water.

The solubility of oxygen in water is mainly affected by temperature, salinity, and altitude. The solubility of oxygen in water decreases with increase of temperature, but the relationship between solubility of oxygen and temperature is nonlinear. As the salinity increases, the amount of DO in the water also decreases. With the altitude rises, the atmospheric pressure and the absolute partial pressure of oxygen decrease, and the DO in water will also decrease. For example, rainbow trout cultured in the cages of Longyangxia Reservoir, a high-altitude waters in Qinghai Province, China, are suffering from the problem of low DO, especially in summer.

In deeper water bodies, the hydrostatic pressure generated by the overlying water layer increases with depth. Under the combined effects of atmospheric pressure and hydrostatic pressure, the saturation concentration of DO increase in a certain depth of water. The hydrostatic pressure of water at the bottom of a dam or a deep pool of waterfall is great. Accordingly, the amount of nitrogen and oxygen dissolved in the water and in the blood of fish is much great. While the fish at the bottom of the dam or the pool are carried by current to the surface of the waters, the sudden disappearance of the hydrostatic pressure will cause the dissolved gas in the blood to escape as bubbles, which may result in bubble disease. It can be fatal to the fish in severe cases.

2.3.1.2 The Budget of DO in Water

The sources of DO in aquaculture waters are mainly air diffusion (reaeration), photosynthesis, water exchange, aeration, etc. The main consumptions of dissolved oxygen in the waters include air diffusion (degassing), respiration of cultured animals, microorganisms in water and sediment, water discharge, chemical oxygen consumption, etc.

2.3.1.2.1 Reaeration and Degassing

When the partial pressure of O_2 in air is equal to that in the water, the O_2 in the water and the air is in equilibrium, and the net transfer of O_2 between the air and the water is zero. When the partial pressure of O_2 in water is less than that in the air, the O_2 in the air will diffuse into the water (reaeration). When the partial pressure of O_2 in the water is greater than that in the air, the oxygen in the water will diffuse from the water to air (degassing).

When the DO content of the water body is lower than the saturated DO concentration, it is called oxygen deficit (D). When the DO content of the water body is higher than the saturated DO concentration, it is called oxygen surplus (S), and D and S can be calculated by the following formulas

$$D = (DO_{\mathrm{s}} - DO_{\mathrm{m}})/DO_{\mathrm{s}}$$
$$S = (DO_{\mathrm{m}} - DO_{\mathrm{s}})/DO_{\mathrm{s}}$$

where DO_{s} is the theoretical saturated DO concentration in water, and DO_{m} is the measured DO concentration in water. The rate of oxygen transfer is related to the D and S values, and the greater the D or S value, the greater the rate of reaeration or degassing.

The greater the D or S values, the faster oxygen will enter or leave a water body from air–water interface. The net transfer of oxygen will depend on the degree of undersaturation or supersaturation, temperature, and the time of contact for an undisturbed waters (Boyd and Tucker 1998). Oxygen transfer is greatly accelerated by wind turbulence.

In the daytime, when the dissolved oxygen in the pond is supersaturated, oxygen will degas from the pond. The amount of oxygen degassing accounts for about 1.5% of the total oxygen consumption in the pond with low stocking density of fish.

2.3.1.2.2 Photosynthesis

Photosynthesis of aquatic plants is the major source of DO in water and one of the major causes of diurnal fluctuation of DO in water. The process of photosynthesis can be expressed as follows:

$$\begin{gathered}1{,}300{,}000\ \text{cal radiation energy} + 106\mathrm{CO_2} + 90\mathrm{H_2O} + 16\mathrm{NO_3^-} + 1\mathrm{PO_4^{3-}} \\ + \text{mineral elements} = 13{,}000\ \text{cal thermal energy in 325 g protoplast} \\ (106\mathrm{C}, 180\mathrm{H}, 46\mathrm{O}, 16\mathrm{N}, 1\mathrm{P}, 815\ \text{g mineral ash}) + 154\mathrm{O_2} \\ + 1{,}287{,}000\ \text{cal diffusion of thermal energy}\ (99\%)\end{gathered}$$

The simplified expression for photosynthesis is

$$6\mathrm{CO_2} + 12\mathrm{H_2O} \xrightarrow{\text{Chlorophyll and light}} \mathrm{C_6H_{12}O_6} + 6\mathrm{O_2} + 6\mathrm{H_2O}$$

The rate of photosynthesis is related to the sunlight intensity received by the waters, water temperature, nutrient supply, and aquatic plant types. In general, the oxygen production rate by photosynthesis in the upper water layer of river and lake is 0.5–10 g/($m^2 \cdot d$). The phytoplankton biomass and oxygen production in ponds are generally higher than those in rivers and lakes. For example, the oxygen production rate of photosynthesis in productive aquaculture ponds in Wuxi, Jiangsu Province, China, is 17.82 ± 2.77 g/($m^2 \cdot d$), and the rate in Harbin, Heilongjiang Province, China, is 20.3 ± 7.43 g/($m^2 \cdot d$) (Lei et al. 1983; Jin et al. 1984). In general, the photosynthetic oxygen production in a bay is low, while the production in waters with flourishing seaweed beds or vascular plants is high.

2.3.1.2.3 Oxygen Consumption in Water

The oxygen consumption in aquaculture water is mainly caused by the respiration of farmed animals, plankton and microorganisms in water, and microorganisms in sediments. The process of respiration can be expressed as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Heat}$$

The consumption rate of oxygen in aquaculture water is related to the size of farmed animals, stocking density, the biomass of plankton and microorganisms in water, water temperature, and sediment quality.

Zooplankton respiration and the decomposition of organic matter by microorganisms in aquaculture water consume a large amount of DO, which is often called "water respiration." Water respiration often constitutes the most important part of the oxygen consumption in aquaculture pond. Phytoplankton also respirates. Previous studies demonstrated that the amount of oxygen consumed by respiration of phytoplankton in farming season accounts for 10%– 20% of its daily oxygen production.

According to previous studies, the water respiration of fish farming ponds with algal blooms is 5.3–13.5 mg/(L·d), while that without algal blooms is 2.4–5.3 mg/(L·d). The surface water respiration of productive fish farming ponds in Wuxi, China, from April to August is 6.68 ± 0.19 mg/(L·d), while that for the middle layer water is 4.96 ± 0.66 mg/(L·d). In northern China, the water respiration of fish farming ponds in winter is only 0.63 ± 0.52 mg/(L·d). Since the phytoplankton, microorganisms and dissolved organic matter in lakes, reservoirs, and bays are less than those in aquaculture ponds, and the water respiration of them is also weaker.

Oxygen consumption of cultured animals is related to their developmental stages, size, stocking density, feeding status, movement, and water temperature, etc. Oxygen consumption rate of fish ranged from 63.5 to 665 mg/(kg·h) under different conditions.

2.3.1.2.4 Oxygen Consumption in Sediment

The oxygen consumption in sediments is mainly composed of benthic organisms' respiration, decomposition of organic matter by heterotrophic bacteria, and oxidation of reductive inorganic compounds by autotrophic bacteria. The biomass of zoobenthos in aquaculture ponds increases with the increase of input nutrients. The season, species, and stocking density of cultured animals might also affect the biomass. The dry weight of zoobenthic biomass in the sediments of fertilized ponds is 10–12 g/m^2 and that without fertilization is 3–9 g/m^2, while that in saline and alkaline ponds in China is only 0.14–0.54 g/m^2 (Boyd 1995; Zhao et al. 2001c).

The decomposition of the organic matters in the sediment consumes a large amount of dissolved oxygen. According to previous studies, the oxygen consumption rates of the pond sediments in northern China in summer were 0.67–2.01 $gO_2/(m^2{\cdot}d)$, with an average of 1.31 $gO_2/(m^2{\cdot}d)$; the rates in the United States were 0.19–2.74 $gO_2/(m^2{\cdot}d)$, with an average of 1.46 $gO_2/(m^2{\cdot}d)$; and the rates in Japanese ponds were 1.1–13.2 $gO_2/(m^2{\cdot}d)$; while in winter, the oxygen consumption rate of the pond sediments in northern China was 0.4 $gO_2/(m^2 \cdot d)$. There is often anoxic zones within the sediment or in the overlying water as a result of this intense oxygen consumption.

Fish respiration, water respiration, and sediment oxygen consumption accounts for 20%, 71% and 9% (degassing is neglected), respectively of the total oxygen consumption in productive freshwater ponds in Wuxi, China. In the other freshwater fish pond, fish respiration, water respiration, sediment oxygen consumption, and degassing accounts for 16.1%, 72.9%, 0.6% and 10.4%, respectively of the total oxygen consumption. The oxygen consumption of shrimp in seawater ponds is 25.2%, water respiration is 58.2%, and sediment oxygen consumption is 16.2% of the total oxygen consumption. It is clear that water respiration is the major part of oxygen consumption in aquaculture ponds, and the sediment oxygen consumption cannot be neglected. Water quality management and sediment improvement are necessary to provide sufficient dissolved oxygen for cultured animals.

2.3.1.3 Distribution and Dynamics of DO in Water

In aquaculture water bodies, especially in aquaculture ponds, the change of DO is mainly affected by the two opposite processes: photosynthesis and respiration. Reaeration and degassing processes have apparent effects on DO concentration in relatively clean water with low stocking density of fish.

2.3.1.3.1 Diurnal Variation of DO in Aquaculture Waters

The DO in aquaculture waters has obvious diurnal variation. As shown in Fig. 2.10, after daybreak, the oxygen produced by photosynthesis is greater than that of oxygen consumed by respiration in euphotic zone of the waters, and the DO concentration begins to increase. The DO concentration will reach its maximum at about 3 p.m. Then, the oxygen produced by photosynthesis is less than the oxygen consumed by respiration, and the DO concentration in the waters begins to decrease. The tendency of decrease will last until the next daybreak. After daybreak, the DO in the waters begin to increase again.

The diurnal variation range of DO is large in the upper water layer water due to the strong incident light and photosynthesis in the layer. The photosynthesis of the bottom water is weak, so its diurnal variation range of DO is relatively small

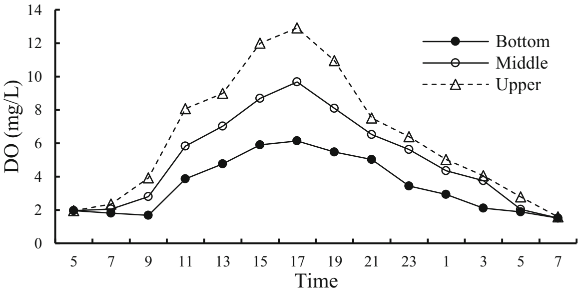


Fig. 2.10 Diurnal variation of dissolved oxygen (DO) in aquaculture waters (from Boyd and Tucker 1998)

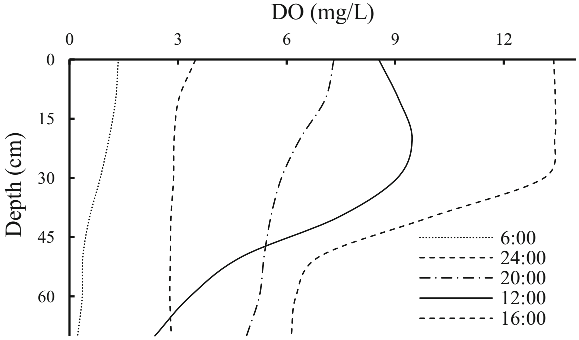


Fig. 2.11 Vertical distribution of dissolved oxygen in aquaculture pond (from Boyd and Tucker 1998)

(Fig. 2.10). In addition, the reaeration and degassing processes at air–water interface in windy weather are relatively strong; therefore, the diurnal variation of DO in waters is relatively small.

2.3.1.3.2 Vertical Distribution of Dissolved Oxygen in Aquaculture Waters

The vertical distribution of DO in aquaculture system is closely related to water depth, phytoplankton intensity, meteorological conditions, etc. For shallow, nutrient-rich ponds, the vertical distribution of DO is shown in Fig. 2.11. In general, the DO concentration in the upper layer water is higher than that in the bottom layer water. The difference of DO concentrations between the two layers is small in the morning, and large at 2 or 3 p.m. There is obvious light suppression on the photosynthesis in phytoplankton of water surface at noon, which causes the DO in the surface water to be slightly lower than that in the subsurface water.

In bottom waters with heavy phytoplankton bloom and low transparency, the respiration is greater than photosynthesis due to the self-shadow effect, resulting in a thick anaerobic zone on pond bottom. In summer, cold dense rain falling on the surface may sink through the warm upper layer water causing upwelling and destratification. The sudden mixing of the bottom anaerobic water with upper layer water may result in suffocation of farmed fish.

The DO concentration of the bottom water is higher than that of the upper layer water in some deep, nutrient-poor, and windless waters. The DO dynamics of such waters are mainly restricted by physical factors, such as water temperature and hydrostatic pressure.

2.3.1.3.3 Horizontal Distribution of DO in Aquaculture Waters

Aquaculture ponds are more shallow, more protected from wind, and have a smaller surface area than lakes. When the wind is weak, there is usually no obvious horizontal difference of DO in aquaculture waters. However, when the wind is strong, the horizontal distribution of DO of surface water will be uneven. Due to the action of wind-driven circulation, the DO concentration on the upwind side is significantly higher than that on the leeward side.

The diurnal variation of DO at littoral area with abundant aquatic plants is greater than that at pelagic area because of the photosynthesis and respiration of the aquatic plants.

2.3.1.4 Tolerance of Cultured Animals to Dissolved Oxygen

Fish and aquatic invertebrates mainly rely on gills to absorb DO from water. When the DO concentration in water is too low, the cultured animals will asphyxiate because they cannot absorb enough oxygen to maintain their metabolism. When the DO concentration in water is higher than the critical concentration of asphyxiation but lower than the optimum concentration, the feeding, growth, and development of cultured animals will be affected.

When the DO concentration is low, the hemoglobin of warm-water fish usually has stronger ability to combine with oxygen and release a higher proportion of oxygen in tissues than cold-water fish. Therefore, warm-water fish are generally more tolerant to hypoxia than cold-water fish. DO conzentration of warm-water fish habitats must not be less than 5 mg/L during at least 16 h of any 24-h period. It may be less than 5 mg/L for a period not exceed 8 h of any 24-h period, but at no time shall the DO concentration be less than 3 mg/L. For salmonid culture system, DO concentration should not be less than 4 mg/L at any time except frozen season.

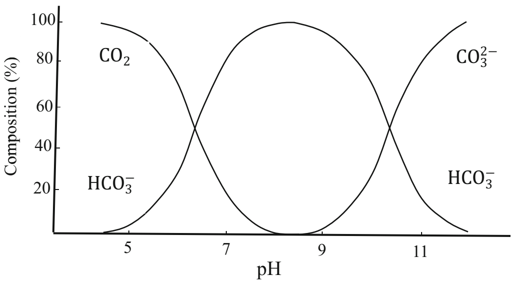
Supersaturated DO in water can cause gas bubble trauma in fish and shrimp. The disease is mainly due to the degassing of dissolved oxygen or other gases and formation of bubbles in the blood, which can lead to vascular thrombosis. Such phenomena may occur in the pool of waterfall, the water under dam, and waters in summer when photosynthesis of aquatic plants is strong.

2.3.2 pH and Carbonate Buffering System

pH is the negative logarithm of hydrogen ion concentration in water. The pH of natural water is generally between 4 and 10. The pH of seawater is between 8 and 8.5. The pH of natural waters is the result of the integrated effects of chemical and biological processes in it. Its diurnal, vertical, and horizontal variations pH are similar to those of dissolved oxygen in water. For example, its highest value often occurs at 2 or 3 p.m., and the pH of surface water is higher than that of the bottom water.

Aquaculture animals have a certain range of tolerance to water pH. Low or high pH is harmful to them. According to the *Water Quality Standard for Fisheries in China*, the pH of freshwater should be 6.5–8.5 and that of seawater should be 7.0–8.5. The pH of aquaculture water, especially in ponds with high phytoplankton biomass, tends to exceed the upper limit of the standard around noon due to photosynthesis and to exceed the lower limit of the standard in the early morning due to respiration. Short-term fluctuations of pH generally do not have a significant impact on farmed organisms. However, if the aquaculture waters are in a high or low pH value for a long time, it might slow growth of farmed organisms. When pH is

Fig. 2.12 Effects of pH on the proportion of H_2CO_3, free CO_2, HCO_3^-, and CO_3^{2-}



lower than four or higher than 11, even short-term exposure can cause certain damage to farmed organisms.

The change of pH in aquaculture water will cause the change of the existing forms of some compounds in water, which will sometimes enhance the toxicity of some compounds. For example, at high pH, the toxicity of alkalinity will increase due to the increase of toxic CO_3^{2-}.

The solubility of CO_2 in water is very high, but because the partial pressure of CO_2 in atmosphere is small, the concentration of CO_2 in water is usually not high. In water, an equilibrium system forms between different forms of CO_2.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$$

As shown in Fig. 2.12, when pH is less than 6.4, CO_2 and H_2CO_3 are dominant in the equilibrium system; when the pH is greater than 6.4 and less than 10.4, HCO_3^- is dominant; when the pH is greater than 10.4, CO_3^{2-} is dominant. Moreover, the change of the proportion of each component in the CO_2 equilibrium system will also alter the pH of the water.

When the pH of water is weak alkaline, the above CO_2 equilibrium relationship can be expressed by the following formula

$$2HCO_3^- \leftrightarrow CO_3^{2-} + CO_2 + H_2O$$

From the above formula, it is not difficult to see that photosynthesis and respiration in water can significantly affect water pH. Photosynthesis consumes CO_2, and then, the equilibrium system is going to shift to the right, producing more CO_3^{2-} and increasing water pH. Respiration produces CO_2 and decreases water pH. Therefore, the variation tendency of pH in natural water is similar to that of dissolved oxygen.

If Ca^{2+} concentration in water is near saturation, white precipitation may be formed in water when photosynthesis is intense at daytime. The process can be illustrated as:

$$CO_3^{2-} + Ca^{2+} \leftrightarrow CaCO_3 \downarrow$$

This reaction consumes CO_3^{2-} and slows down the rate of pH rise. When photosynthesis is inactive at night, respiration in water will reduce the concentration of CO_3^{2-}, and the $CaCO_3$ precipitation will dissolve again. The CO_2 equilibrium system and the presence of Ca^{2+} can effectively buffer the change of pH in water.

If the alkalinity in waters is mainly composed of HCO_3^- and CO_3^{2-}, higher alkalinity is harmful to farmed fish. Lei et al. (1985) showed that the harm of alkalinity to fish was mainly caused by CO_3^{2-}. When the alkalinity in aquaculture waters is 10 mmol/L, it is dangerous for four major carps (black carp, grass carp, silver carp, and bighead carp).

In summer, the pH increases rapidly around noon because of the strong photosynthesis in aquaculture waters with low hardness (low Ca^{2+}, Mg^{2+} concentration in water). In some waters with high alkalinity and low Ca^{2+} concentration, strong photosynthesis can cause rapid increase of pH and CO_3^{2-}. This phenomenon is often found in low-lying saline–alkali ponds, and it is very harmful to farmed animals. Artificially increasing the buffer capacity of the waters to the change of pH is an important management strategy for effectively exploring of this type of water (see Chap. 11 for details).

Burnt lime is usually used in freshwater ponds for disinfection. The pH of water and sediment in pond will rapidly increase to a very high level where most of harmful organisms cannot survival. Because the Mg^{2+} concentration in seawater is high, thus, larger amount of burnt lime will be consumed in the seawater pond than freshwater pond.

2.3.3 Ammonia and Hydrogen Sulfide

Ammonia and hydrogen sulfide are two important inorganic compounds in aquaculture water. The concentrations of ammonia and hydrogen sulfide in water are mainly affected by temperature and pH. Higher concentration of the two compounds is harmful to farmed animals.

2.3.3.1 Ammonia

Ammonia exists in water in both un-ionized and ionic forms, namely NH_3 (UIA) and NH_4^+. These two forms of ammonia exist in a pH- and temperature-dependent equilibrium

$$NH_4^+ + H_2O \leftrightarrow NH_3 + H_3O^+$$

When pH and temperature increase, the concentration of NH_3 increases. The NH_4^+ is not very toxic, but the UIA is very toxic to aquatic animals. The acute toxicity concentration of UIA for salmon, noncyprinid fish, and common carp are 0.083–1.09 mg/L, 0.14–4.6 mg/L, and 1.5 mg/L, respectively. According to the Water Quality Standard in Fisheries in China, the concentration of UIA in aquaculture water should not exceed 0.020 mg/L.

Ammonia in water mainly comes from the decomposition of nitrogen-containing organic matter and the excretion of aquatic animals. Ammonia is the main component of nitrogen excretion of aquatic animals except cartilaginous fish. The nitrogen-containing organic matter, such as biodebris, can be decomposed by microorganism to produce ammonia. Ammonia can be directly absorbed and utilized by aquatic plants and can also be converted into nitrite or nitrogen gas under the action of anaerobic organisms.

The processes mentioned above will lead to the change of ammonia concentration in water. In aquaculture waters, the ammonia concentration in the upper water layer is usually low because of the absorption of aquatic plants. The ammonia concentration in the lower water layer is usually higher than that in the upper water, especially in waters with thermostratification.

Inorganic nitrogen fertilizers, such as $(NH_4)_2CO_3$ and NH_4Cl, are sometimes applied to waters where nitrogen is the limit factor to promote the growth of phytoplankton. However, the application of these fertilizers can sometimes harm farmed animals, especially around noontime. The main reason is that more UIA will be formed soon after fertilization when temperature and water pH are high around noontime. Therefore, when ammonium fertilizer is applied, it should be used in small amount with multiple applications in morning.

In the Netherlands, there is a recirculating aquaculture system (RAS) to culture European eel in high density, in which the ammonia concentration in its water is very high, and the pH is around 5. Although low pH can reduce the proportion of UIA in total ammonia in water, low pH is also detrimental to fish growth. Modern RAS is beginning to employ denitrification to reduce the accumulation of inorganic nitrogen in RAS (see Chap. 10).

2.3.3.2 Hydrogen Sulfide

SO_4^{2-} is an anion commonly found in natural water, and SO_4^{2-} concentration is very high in sulfate type of waters. Under hypoxia condition, SO_4^{2-} can be reduced to H_2S by microorganisms. In water rich in organic matter, the decomposition of the organic matter may produce a large amount of SO_4^{2-}. In bottom water layer or in sediment where is anoxic, SO_4^{2-} reduction is strong especially in brackish water or mariculture ponds.

H_2S solubility in water is very high. 3.8 g H_2S can dissolve in a liter of water at 20 °C and 7.1 g at 0 °C. H_2S dissolves in water with weak acidity and can ionize in two steps to form the following equilibrium system

$$H_2S \leftrightarrow H^+ + HS^- \leftrightarrow 2H^+ + S^{2-}$$

There is almost no S^{2-} in natural water. With the decrease of water pH, the proportion of H_2S increases. When the pH is 7.2, the proportion of H_2S and HS^- is almost the same. The proportion of nonionic H_2S in total H_2S is related to pH and temperature. The lower the pH and temperature, the higher the proportion of nonionic H_2S.

The nonionic H_2S is harmful to aquatic animals. H_2S has the odor of rotten eggs. Human olfaction can detect H_2S with air volume fraction of 2×10^{-9}. It is generally believed that when H_2S concentration in water is below 2.0 μg/L, it is harmless to most fish species. The Water Quality Standard of Fisheries in China stipulates that sulfide in fishery waters should be less than 0.2 mg/L.

Maintaining the aquaculture water in an aerobic state can inhibit the process of reducing SO_4^{2-} to H_2S by microorganism. Therefore, aeration is an effective way to avoid the harm of nonionic H_2S to farmed organisms.

2.4 Biological Environment of Aquaculture Organisms

Compared to natural aquatic ecosystem, one of the important characteristics of aquaculture systems is that the biodiversity of the system is artificially significantly reduced. For example, the carnivores that prey on farmed animals are eliminated to improve the survival of farmed animals. However, microorganisms and food organisms are still present in most aquaculture systems, and these organisms are important for maintaining a stable and good water environment and a higher ecological efficiency.

2.4.1 Microorganisms of Aquaculture Waters

Like other aquatic ecosystems, there are a large number of microorganisms in aquaculture ecosystems. Some of these microorganisms are planktonic in water, but more are distributed on the surface or inside of organisms, planktonic debris, and sediments. The microorganisms generally include all the tiny life forms in water, such as bacteria, archaea, fungi, protozoa, cyanobacteria, and viruses. In the narrow sense, microorganisms only include bacteria, fungi, and viruses. The role of microorganisms in material recycling and pathogenicity in aquaculture waters has been an important issue.

Bacteria and fungi are the main decomposers of ecosystems. Bacteria mainly decompose carcasses, while fungi mainly decompose dead plants. In recent years, the role of virus as mediators in natural mortality of microalgae attracted scientists' attention (Liu et al. 2009a).

Bacteria in water have been studied broadly. According to the statistics of Wetzel (2001), the average number of bacteria in oligotrophic, mesotrophic, and eutrophic waters are 0.50×10^6, 1.00×10^6, and 3.70×10^6 ind./mL, respectively, and their average biomass is 0.15, 0.70, and 3.30 g/m^3, respectively. The number and biomass of bacteria in fertilized reservoirs can be as high as 20×10^6 ind./mL and 25 g/m^3, respectively. The number of bacteria in polluted water will be even greater. According to Liu et al. (1999a), the number of planktonic bacteria in semi-intensive seawater ponds of shrimp varies from 0.63×10^6 ind./mL to 10.6×10^6 ind./mL. The numbers of microorganisms parasitized on the surface and in the body of aquatic animals are also very large, and its biomass can reach 1.5% of the parasitized animals (Karlsson et al. 2013).

In thermally stratified lakes, bacterial biomass is commonly highest in the epilimnion, decreases to a minimum in the metalimnion and upper hypolimnion, and increases in the lower hypolimnion.

Bacteria in water can be divided into photoautotrophic, chemoautotrophic, and heterotrophic types, which play a key role in the material circulation and energy flow of aquatic ecosystem. In the presence of light photoautotrophic bacteria, such as sulfur bacteria, use H_2S as hydrogen donor, and complete three important chemical processes (hydrogen production, nitrogen fixation, and decomposition of organic matter) in water. Sulfur bacteria are ubiquitous in natural waters, but they are not abundant in general. Their photosynthetic production only accounts for 3–13% of the total primary production.

Chemoautotrophic bacteria, such as nitrite bacteria, nitrate bacteria, hydrogen bacteria, and iron bacteria, can grow and reproduce without any organic nutrients. Instead of obtaining energy from sunlight or organic matter, they obtain chemical energy by oxidizing simple inorganic compounds and assimilate carbon dioxide for cell synthesis. The number of chemoautotrophic bacteria is usually not high. But in the transitional areas of aerobic and anaerobic zone, the number of chemoautotrophic bacteria is high, and these bacteria play an important role in maintaining the circulation of nitrogen, sulfur, and other elements in the ecosystem. According to Wetzel (2001), the organic carbon synthesized by chemoautotrophic bacteria in Lake Michigan and Lawrence accounts for 3.1% of the total organic carbon production in the waters.

Heterotrophic bacteria, including saprophytic bacteria and parasitic bacteria, proliferate and obtain energy from a variety of organic substances (such as proteins and carbohydrates). Saprophytic bacteria, which rely on the carcass and dead plants, play a key role in the material circulation and energy flowing of waters. The respirations, production, and decomposition of humid carbon by planktonic bacteria in semi-intensive seawater shrimp ponds are 349 ± 167, 180 ± 86 and 529 ± 253 μgC/(L·d), respectively. The respirations of planktonic bacteria account for about 40% of the total respirations of plankton (Liu et al. 1999a).

2.4.2 Food Web Structure of Aquaculture Waters

2.4.2.1 Food Chain and Food Web

The organisms in the ecosystem form a food chain and food web through the food or trophic relationship. Each aquaculture system has a specific ecological structure and function. For example, the phytoplankton in a pond is the food of some zooplankton. The zooplankton is the food of small fish or filter-feeding fish, and the small fish is the food of large predatory fish. Thus, a food chain is formed: phytoplankton → zooplankton → small fish → large fish. There are two basic forms of food chain in an aquaculture ecosystem: (1) Grazing food chain, which begins with green plants (such as phytoplankton) and ends with herbivores (such as grass carp) or carnivores (such as mandarin fish); (2) detritus food chain, which starts with lifeless organic matter, and is followed by microorganisms, detritus consumers, and predators

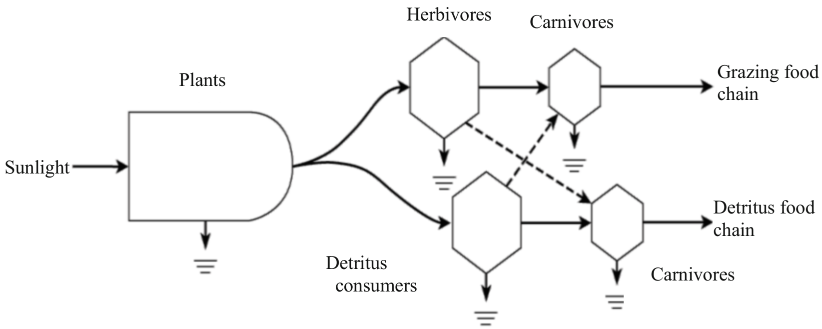


Fig. 2.13 Energy flow model showing linkages between grazing and detritus food chains (from Odum and Barrett 2005)

(Fig. 2.13). For fed aquaculture systems, pelleted feeds can be ingested directly by cultured animals, which is the key linkage between allochthonous organic matter and consumers in the system.

The food chains in the ecosystem do not exist in isolation, but relate to each other to form a complex network, i.e., food web. Most animals have several food sources. It is common that food chains interlace with each other to form a network structure.

The first function of aquaculture system is to produce food for human. Its optimum state is maximizing the flow of energy to aquaculture products (increase production) and reducing operation costs without negative impact on the environment. Therefore, clarifying the structure of food web and the energy flow process in aquaculture system is the basic work to optimize the species composition and improve the production efficiency of aquaculture system.

2.4.2.2 Food Web Structure in Aquaculture Ponds

In general, there is more species in less intensive aquaculture systems. The more species included in an ecosystem, the more complex of food web structure in ecosystems. In order to quantitatively elucidate the energy flow in ecosystems, biological species in the same level of the food chain are often considered as the same trophic level in ecology research. There are not only cultured animals but also wild species in open or semi-open aquaculture systems. Species with the trophic level lower than that of the cultured animals are the food sources of cultured animals. On the contrary, cultured animals are the prey of the animals with the trophic level above them. Therefore, within the limit of environmental carrying capacity, the ideal species structure of an aquaculture system is that there are more biomass with lower trophic level and there less biomass with higher trophic level. That is, the predators of cultured animals in aquaculture waters should be reduced or eliminated.

Feng et al. (2014) calculated the trophic structure of integrated aquaculture pond of sea cucumber (*Apostichopus japonicus*) based on the $\delta^{13}C$ and $\delta^{15}N$ values of primary producers (phytoplankton, benthic microalgae, and macroalgae) and

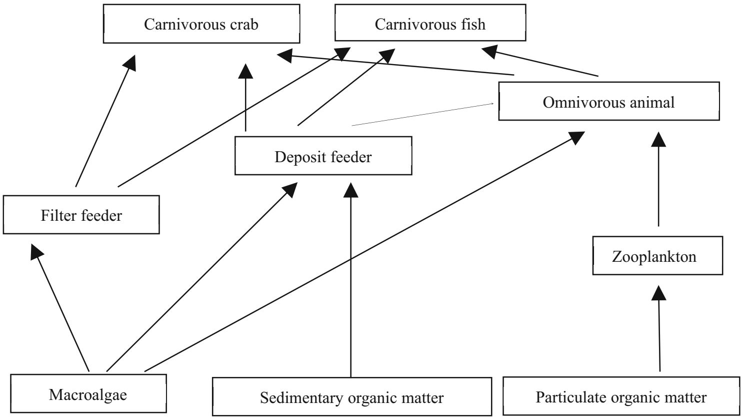


Fig. 2.14 Food web structure of the sea cucumber farming ponds in Jinhai Bay, Shandong Province (Feng et al. 2014)

consumers (zooplankton, shellfish, sea cucumber, and fish) in the intertidal aquaculture pond. Results showed that $\delta^{15}N$ values increased from producer to consumer. The trophic levels of bivalves were less than 2.0, and those of sea cucumber and *Leptosynapta ooptax* were about 2.0. The trophic levels of predatory gastropods, cephalopods, and omnivorous crustaceans were 2.2–2.7. The trophic level of fish ranged from 2.2 to 3.33. The sea bass (*Lateolabrax maculatus*) had the highest trophic level and was the only consumer with the trophic level over 3.

Based on mathematical model of mixed carbon and nitrogen stable isotopes, the main structure of the food web in the sea cucumber pond is illustrated (Fig. 2.14). There are two main energy flow processes in the pond: (1) macroalgae debris/benthic microalgae → filter feeder/deposit feeder → omnivorous animals → carnivorous crabs and fish; (2) phytoplankton → zooplankton → omnivorous fish and crustaceans → carnivorous crabs and fish.

The food components of the sea cucumber cultured in the ponds were identified by Sun et al. (2013). The seasonal changes of the contributions of different food sources to the growth of sea cucumber were calculated by using the $\delta^{13}C$ and $\delta^{15}N$ values. The results showed that the main food sources of the sea cucumber include particulate organic matter, benthic microalgae, macroalgae, and small benthic animals such as copepods and nematodes.

Due to the seasonal succession of primary producers and changes in the physical and chemical environment of the pond, the contribution of different food sources to sea cucumber also exhibited obvious seasonal changes. Macroalgae were the main food sources of sea cucumber, and its annual contribution to sea cucumber was 27.7%–63.4%. The annual contribution of copepods, nematodes, particulate organic matter, and benthic microalgae to the sea cucumber were 16.9%–33.6%, 8.1%–23.3%, 4.3%–6.2%, and 4.2%–9.2%, respectively.

2.4.2.3 Waste Utilization in Aquaculture System

Some organisms are often cocultured or intercultured in aquaculture waters, one purpose of which is to reuse aquaculture waste and reduce the impact of aquaculture on the adjacent waters (see Chap. 9 for details). Trash fish is the main food sources for grouper in cage farming in Guangdong, Hong Kong, and some other southern areas of China. Residual feed and feces are deposited on the bottom of the aquaculture area, which has a significant impact on the water and sediment quality. In order to reduce the environmental impact caused by grouper cage culture, green mussels (*Perna viridis*) are cocultured around the grouper farming cages. Using fatty acid and stable isotope analysis, Gao et al. (2006) investigated the utilization efficiency of residual feed and feces from grouper by the green mussel. The results indicated that there is no significant difference in fatty acid composition of particulate organic matter between grouper aquaculture area and adjacent area without grouper aquaculture. However, there is significant difference in fatty acid composition of the green mussel between grouper aquaculture area and adjacent area. Moreover, compared with the adjacent area, the fatty acid composition of green mussel collected in grouper aquaculture area is closer to that of residual feeds and group feces. This result indicated that green mussel cocultured with grouper ingested a large amount of residual feed and grouper feces, resulting in significant changes in fatty acid composition of its body tissues.

Based on the carbon and nitrogen stable isotope mathematical model, the particulate organic matter, residual feed, and grouper feces contributed to 68.3%, 27.5%, and 4.2%, respectively, of the ingested food of the green mussel. Based on the amount of waste discharged from grouper culture cages and the feeding rate of green mussel, it is estimated that the waste discharged from 1 m^2 grouper culture cage can be reused by 1506/m^2 green mussels (70 mm in body length) cocultured around the cage (Gao et al. 2008).

Grass carp (*Ctenopharyngodon idella*) is one of the most important cultured fish species in China. In intensive aquaculture pond of grass carp, a large amount of pellet feed is used, and the accumulation of residual feed and feces will result in water and sediment quality deterioration. By using experimental enclosures, Xia et al. (2013) studied the feasibility of silver carp reusing the wastes in grass carp integrated aquaculture system. The biomass ratio of grass carp to silver carp was 8:2, 7:3, 6:4, 5:5, 4:6, and 0:10, respectively. The results showed that the contribution of grass carp waste to silver carp ingested food decreased with the increase of the proportion of silver carp to grass carp. When the biomass ratio of grass carp to silver carp was 8:2 and 7:3, the feeding efficiency of silver carp to aquaculture waste was the highest, ranging from 38.0% to 38.5%.

Filter-feeding silver carp in intensive aquaculture ponds can directly feed on particulate organic matter such as residual feed and feces, reduce the concentration of particulate organic matter in water, and improve water quality. In addition, phytoplankton in the ponds can absorb and utilize nutrients such as C and N excreted by fishes. Silver carp can refilter these phytoplankton, which improves the utilization efficiency of dissolved nutrients in the aquaculture system.

2.5 Ecological Differences Among Aquaculture Waters

Because of the application of net cage technology, aquaculture waters have been greatly expanded. Nowadays, fish farming activities are carried out in rivers, reservoirs, lakes, ponds, coastal waters, and offshore areas. These water bodies differ greatly in ecology, but in general, they are gradually changing continuous ecological types. Their ecological characteristics are the results of combined effects of hydrological characteristics, natural succession, and human influence.

2.5.1 Ecological Efficiency of Different Types of Reservoirs

Reservoir, also known as artificial lake, is an ecological type between river and lake. The ecological characteristics of river-type reservoirs (such as the Sanxia Reservoir) are close to rivers, while plain-type reservoirs (such as the Jihongtan Reservoir in Qingdao) are closer to lakes, and hilly-type reservoirs are between rivers and lakes. Therefore, studying the ecological characteristics of different types of reservoirs is helpful to understand the relationship among different types of aquaculture waters.

In the 1980s, 45 reservoirs in Liaoning province, China were studied, and 13% of them belonged to oligotrophic–mesotrophic type (1–3 mg/L of phytoplankton biomass), 36% of them were mesotrophic–eutrophic types (3–6 mg/L), 24% of them belonged to eutrophic type (6–10 mg/L), and 27% of them were hypereutrophic type (>10 mg/L). No oligotrophic reservoirs were found (Dong et al. 1989b).

The compositions of phytoplankton in these reservoirs are different. In terms of phylum composition, the proportions of diatoms in oligotrophic–mesotrophic type of reservoirs increase by 15% comparing with eutrophic reservoirs and hypereutrophic reservoirs, while the proportions of Euglenophyta and Cyanobacteria decrease by 50% and 300%, respectively. In addition, compared with eutrophic and hypereutrophic reservoirs, protozoa and rotifers in oligotrophic–mesotrophic reservoirs decrease by 150% and 62%, respectively, while cladocera and copepods increase by 52% and 38%, respectively.

Taking 13 different types of reservoirs as examples, the conditions of these reservoirs are quite different (Table 2.8). Precipitation is less in Daqinggou Reservoir and Dongfanghong Reservoir in the west of the Liaoning Province, but more in Tiejia Reservoir and Helong Reservoir in the southeast of the province. The solar radiation weakens from the west to the east of the province. The Hunjiang and Dahuofang reservoirs are river valley reservoirs. The Helong, Dongfanghong, Gedalou, and Tuanjie reservoirs belong to plain reservoirs, while the others belong to hilly reservoirs (Shi et al. 1988).

The phytoplankton biomass varies greatly among the 13 reservoirs (Table 2.9). Because of the turbid water, the phytoplankton biomass in shallow reservoirs is not great, while the biomass of Daqinggou Reservoir with small area and medium water depth is the greatest. The range of zooplankton biomass change is small among the reservoirs, and the shallow and clear Tuanjie Reservoir with large number of aquatic plants has the largest zooplankton biomass. The biomass of planktonic bacteria

Table 2.8 Natural conditions of the 13 reservoirs in Liaoning Province, China (from Dong et al. 1989b)

Reservoirs	Areas (km^2)	Depths (m)	Watershed areas (km^2)	Precipitation (mm)	Transparencies (cm)	Solar radiation[a] (kcal/cm^2)
Hunjiang	97.6	22.5	10,400	876	238	69
Dahuofang	82.1	14.3	5437	840	164	71
Qinghe	46.0	8.7	2376	722	116	72
Chaihe	20.8	13.0	1355	735	104	73
Tanghe	31.6	10.5	1228	791	303	70
Tiejia	17.3	8.4	241	1040	246	67
Zhuweizi	17.3	6.2	260	785	118	70
Daqinggou	1.0	9.3	15	442	87	75
Sandaoling	3.3	4.5	133	780	68	76
Helong	4.5	1.2	38	996	88	67
Dongfanghong	14.6	2.3	28	486	48	75
Gedalou	13.5	1.6	0	651	14	84
Tuanjie	8.4	1.5	1782	641	112	74

[a] Total solar radiation is the solar radiation from May to September in the reservoir area

Table 2.9 Biomass and primary productivities of the 13 reservoirs in Liaoning Province, China (from Dong et al. 1989b)

Reservoirs	Phy (mg/L)	Zoo (mg/L)	PB (mg/L)	B (g/m^2)	PP ($gO_2/(m^2 \cdot d)$)	FY (kg/hm^2)
Hunjiang	5.92	2.07	–	2.72	2.98	19.5
Dahuofang	5.33	3.28	0.8	2.40	4.83	60.0
Qinghe	5.05	1.21	0.05	0.69	3.74	51.0
Chaihe	9.81	2.17	0.14	8.40	6.05	42.0
Tanghe	5.99	2.16	–	0.39	2.88	39.0
Tiejia	2.08	0.83	0.34	1.24	1.56	28.5
Zhuweizi	2.46	3.24	2.60	1.06	1.12	39.0
Daqinggou	13.94	1.10	0.85	2.73	6.02	220.5
Sandaoling	7.17	2.00	0.83	4.68	3.80	43.5
Helong	7.99	2.26	0.59	1.91	2.35	90.0
Dongfanghong	3.99	2.78	2.79	4.29	2.07	79.5
Gedalou	3.88	1.25	0.75	0.58	1.05	11.0
Tuanjie	3.73	4.12	0.61	3.94	3.89	85.5

Note: *B* benthos, *BP* planktonic bacteria, *FP* fish yield, *Phy* phytoplankton, *PP* primary productivity, *Zoo* zooplankton

varies greatly among the reservoirs, and the Qinghe Reservoir has the smallest biomass. The Dongfanghong Reservoir and Zhuwaizi Reservoir with abundant organic matter sources have the greatest biomass. The benthic biomass of Tuanjie, Dongfanghong, and Sandaoling reservoirs with shallow mud bottom and the deeper Chaihe Reservoir is much great. Aquatic vascular plants are rarely found in reservoirs except in shallow plain reservoirs. There are a large number of aquatic plants in Tuanjie Reservoir, with an average wet weight of 3381 g/m^2 and dry weight of 273 g/m^2. The primary productivity of Chaihe and Daqinggou reservoirs with medium water depth and great phytoplankton biomass is higher, while that of Jilonglou Reservoir, Zhujinzi Reservoir, and Tiejia Reservoir with shallow and turbid water or small phytoplankton biomass is very low.

Ecological efficiencies of the 13 reservoirs during May and September are listed in Table 2.10. The *P/B* value of phytoplankton is closely related to the average depth of the reservoir ($n = 13$, $r = -0.85$, $P < 0.01$). This is because water depth not only affects the concentration of inorganic nutrients in water, but also affects the ratio of photic zone to disphotic zone in water column and the turbidity of water.

The *P/B* coefficients of phytoplankton in each reservoir vary greatly, ranging from 16 to 512, with an average of 110. The value is mainly related to water depth. The gross production of phytoplankton and *P/B* coefficient are important indicators of water production performance. It is reported that the *P/B* coefficients of phytoplankton are mainly influenced by latitude and phytoplankton biomass. As the latitude difference among reservoirs in Liaoning province is not great, the influence of water depth on the coefficient is greater. Water depth will affect the transparency of water and the ratio of photic zone to disphotic zone in water column. Shallow

Table 2.10 Ecological efficiencies of the 13 reservoirs during May and September in Liaoning Province, China (%) (from Dong et al. 1989b)

Reservoirs	P_G/I	P_G/B	P_Z/P_G	P_B/P_G	P_D/P_G	F/P_G
Hunjiang	0.23	16	45	–	0.87	0.30
Dahuofang	0.36	46	28	27	0.47	0.56
Qinghe	0.27	81	8.0	1.3	0.17	0.62
Chaihe	0.44	35	13	3.4	1.3	0.32
Tanghe	0.22	34	22	–	0.13	0.62
Tiejia	0.12	65	13	21	0.75	0.84
Zhuweizi	0.08	54	51	164	0.90	1.58
Daqinggou	0.42	34	4.8	15	0.43	1.66
Sandaoling	0.26	86	6.7	11	1.2	0.52
Helong	0.18	174	3.3	3.4	0.77	1.74
Dongfanghong	0.15	164	8.8	35	2.0	1.74
Gedalou	0.07	123	5.4	13	0.52	0.48
Tuanjie	0.40	512	4.6	1.6	0.57	0.06
Average	0.25	110	16.4	27	0.77	0.85

Note: B, phytoplankton biomass, F fish yield, I solar radiation, P_B production of planktonic bacteria, P_D benthos production, P_G primary production, P_Z zooplankton production

water generally has a large *P/B* coefficient, but the gross production per unit of water surface is not necessarily high.

Silver carp and bighead carp are the main fish species stocked in the 13 reservoirs. The growth season of the reservoirs for the fishes is 150 days (5 months), and the average fixation rate of total solar radiation energy (P_G/I) in growth season is 0.25%. The values are less than 0.1% in Gedalou and Zhuwaizi reservoirs, which have high turbidity and low phytoplankton biomass. And the values are more than 0.4% in Chaihe Reservoir and Daqinggou Reservoir, which have great phytoplankton biomass and a certain depth. The fixed solar radiation energy by aquatic plants in Tuanjie Reservoir is about 40% of the total fixed energy.

The average ratio of zooplankton production to primary production (P_Z/P_G) is 16.4%. The ratio of large hilly reservoirs is higher than that of small shallow reservoirs. The P_Z/P_G value of Zhuwaizi Reservoir is 51%, because oak trees are planted for silkworms in the watershed area of the reservoir. A large amount of allochthonous organic matter enters the reservoir, which promotes the growth of planktonic bacteria and provides rich food for zooplankton in the reservoir. The ratio of production of planktonic bacteria to primary production (P_B/P_G) averaged 27%, while that of Zhuwaizi Reservoir is as high as 164%.

The ratio of benthos production to primary production (P_D/P_G) (average 0.77%) in the reservoirs is not significantly different. The ratio of fish production to primary production (F/P_G) (average 0.85%) in the reservoirs is quite different. The F/P_G of Daqinggou, Zhuwaizi, Helong, and Dongfanghong reservoirs exceeded 1.5%. The F/P_G of reservoirs in China is higher than those of the reservoirs or lakes around the world, because filter-feeding silver carp and bighead carp stocked in the reservoirs have short food chains and high ecological efficiency.

2.5.2 Ecological Differences Among Various Aquaculture Waters

2.5.2.1 Ecological Continuum

Cummins (1977) proposed the concept of “river continuum,” i.e. the ecological variables within a river system present a continuous gradient of ecological conditions from headwaters to mouth. Headwater is ravine stream and often shaded with little direct sunlight. The consumers mainly feed on the leaves of terrestrial plants or other organic debris entering from the basin. There are some large coarse particulate organic matters (CPOM) and aquatic insects in it. The ecosystem is heterotrophic with the community production/respiration (P/R) value much less than one. However, the middle reaches of the river are generally much wider than the upper reaches and headwaters. Large aquatic plants and phytoplankton provide the primary production of the system, and aquatic animal is less dependent on organic matter entering the basin. Fine particulate organic matter (FPOM) and filter feeders predominate in water. The ecosystem is autotrophic with P/R value greater than or equal to one, and the species diversity is the highest. In the lower reaches of the river, the flow rate decreases and the waters are usually deep and silty. Transparency and photosynthesis of aquatic plants are reduced. The rivers become heterotrophic again ($P/R < 1$), and the species diversity decreases.

2.5.2.2 Ecological Differences Among Inland Aquaculture Waters

Similar to river continuum, the ecological differences among rivers, river reservoirs, hilly reservoirs, plain reservoirs, lakes, and ponds also represent certain regularity (Table 2.11).

The water velocity and dissolved oxygen (DO) concentrations of rivers are high, and diurnal variation of DO is small. The water transparency in the upper reaches of a river is higher than that in the middle and lower reaches of the river, because there

Table 2.11 Ecological differences among various aquaculture waters

Ecological factors	Types of waters			
	River	Reservoir	Lake	Pond
Current	Strong	Relatively strong	Week	Much week
Transparency	Deep	Relatively deep	Shallow	Much shallow
Macrophyte	Less	Less	More	Less
Phytoplankton biomass	Small	Relatively small	Relatively great	Great
Biodiversity	Low	Relatively low	High	Relatively low
Respiration	Week	Relatively week	Relatively strong	Strong
DO	High, less daily variation	High, less daily variation	Greater daily variation	Greater daily variation
COD	Low	Relatively low	Relatively high	High
Organic matter	Allochthonous	More allochthonous	More endogenous	Endogenous pluses exogenous feed and fertilizer

is more phytoplankton and sediment in the middle and lower reaches of the river. Some rivers in China have relatively high sediment content and low transparency, such as the Yellow River (average sediment content is 37 kg/m^3).

In general, there are fewer large aquatic plants and phytoplankton in the upstream of rivers, more benthic plants and anticurrent nektons. Allochthonous organic matters from watershed area are important nutrient sources of the river system.

The water velocity of lakes is slower than that of rivers. Large aquatic plants are generally abundant along lakeshore. The biomass of phytoplankton in open waters is high (1–10 mg/L). The change of dissolved oxygen in lakes is mainly affected by photosynthesis and biological respiration of aquatic plants and plankton, and the diurnal variations of dissolved oxygen are obvious. The transparency of the lake is closely related to its depth, area, and biomass of plankton. Deep-water lakes have higher transparency, while small lakes and the lakes mightily affected by wind have lower transparency. The salt contents of the lakes in China vary greatly. Salt contents of the lakes in the eastern plain are lower than 200 mg/L, while those in Yunnan–Guizhou plateau are slightly higher than 200 mg/L. The salt contents of lakes in Meng-Xin plateau range from 1.0 to 20 g/L. In general, endogenous nutrition has become an important nutrition source of lake systems.

Reservoirs are the intermediate ecological type between rivers and lakes, and their ecological characteristics lie between them. The ecological features of river type of reservoirs are similar to a river, while those of plain type of reservoirs are similar to a lake.

Aquaculture ponds are semi-artificial ecosystems, which are greatly affected by fertilization and feeding. The ecological characteristics of aquaculture pond are related to pond size, depth, and intensification. The ecological characteristics of extensive ponds are similar to those of small lakes, while intensive ponds are similar to hypereutrophic waters. There are usually fewer large aquatic plants in the aquaculture pond system, but the biomass of phytoplankton is very high. The diurnal variation of DO content is large, COD and total ammonia nitrogen are high in the system.

2.5.2.3 Ecological Differences Among Mariculture Waters

The mariculture waters discussed here include seawater ponds, estuaries, coastal waters, and offshore areas. Estuary ecosystem is the intersection zone of saltwater and freshwater. Tidal action is an important physical regulation and energy supplement process. Estuary ecosystem is very special not only in hydrology, but also in periodic horizontal and vertical changes of salinity. The isohaline can move upward at high tide and downward at low tide. The turbidity of the estuary is high, and the sedimentation is very strong. The sediment of the estuary is mostly soft mud. Estuaries are the most nutrient-rich waters in the world. Despite their high turbidity, estuaries are still the areas with high primary productivity. Generally, estuaries are not rich in biodiversity, but there are many euryhaline species.

Like estuaries, coastal waters are also affected by periodic tides, but the diurnal variation of salinity is not significant. The dominant groups of phytoplankton in coastal waters are diatoms, dinoflagellates, and microflagellates. The benthic communities of sandy sediment and rock reef sediment differ greatly. The former is mainly composed of buried molluscs, shrimp, and crab, while the latter is mainly composed of seaweeds, oysters, barnacles, and mussels. Because of the effect of tides and coastal currents, the water exchange in coastal waters is good, and it is a good area for mariculture. The coastal area is also a place of tourism and other activities, so there is contradiction between coastal mariculture and other industries.

Compared with the coastal waters, the offshore area has deeper water and stronger wind and currents. Due to the application of large antiwind and wave cages and other offshore aquaculture facilities, offshore area is expected to become a new area for aquaculture. Strong currents and winds in offshore area can damage mariculture facilities, but they can also help to quickly dilute mariculture pollutants, so its water quality is excellent for mariculture.

Similar to deeper lakes and reservoirs, thermocline may be formed in offshore waters in summer. The thermocline would lead to significant differences in ecology between upper and lower water layers.

Seawater ponds and freshwater ponds are similar but with the following differences: The salinity of seawater ponds is high, and only the seawater and euryhaline species can be cultured in it; the water exchange of intertidal ponds could be realized by tide; the sulfate content is high, and the potential threat of H_2S is greater while DO is low; the sediment of seawater ponds cannot be directly used as the fertilizers for crops.

2.5.2.4 Coastal Mariculture, off-the-Coast Mariculture and Offshore Mariculture

There is no uniform standard for the regional division of mariculture in the world because of the great differences in the slope and coastline conditions of the continental shelf among countries. According to location, environment, access, operation, and exposure, mariculture is classified into three categories: coastal mariculture, off-the-coast mariculture, and offshore mariculture (Lovatelli et al. 2013). The coastal mariculture refers to the mariculture in sheltered sea areas, <0.5 km away from the coast, and <10 m in water depth at low tide. Off-the-coast mariculture refers to the mariculture in partly exposed sea areas with a depth of 10–50 m, 0.5–3 km away from the coast. The offshore aquaculture refers to the mariculture in exposed sea areas, >2 km away from the coast, and >50 m in water depth. The off-the-coast and offshore mariculture can also be called open ocean mariculture.

The scale of mariculture in China is the largest around the world. The continental shelf in some provinces in China is flat. The floating raft culture has extended to the open sea area 19 km away from the coast. In China, the aquaculture in the shallow or sheltered sea area with a water depth of less than 10 m and <2 km from the coast is generally called coastal mariculture; the aquaculture in the open sea area with a depth of 10–50 m and a distance of more than 2 km from the coast is called offshore mariculture; and the mariculture using modern equipment in open sea area with a depth of more than 50 m or in the exclusive economic zone (>12 miles) is called deeper-offshore aquaculture (Dong 2019a).

2.5.3 Limiting Nutrient Element in Aquaculture Water

There are about 20 elements that are essential for phytoplankton, and 11 (C, H, O, N, P, S, K, Mg, Ca, Na and Cl) of them are abundant in phytoplankton and called macroelement. Silicon is also a macroelement for diatoms, because there is a large amount of Si in the cell walls of silicon. Phytoplankton cells need additional eight trace elements, such as Fe, Mn, Cu, Zn, B, Mo, V, and CO. Phytoplankton absorb these essential nutrients from water for growth. The concentration of these elements in water varies greatly with time and place and can significantly affect the productivity and growth of phytoplankton populations and community. The amount of these elements in the aquatic environment is not unlimited for the growth demand of phytoplankton. The productivity of phytoplankton communities is usually restricted by one or two elements which are relatively scarce, and these one or two elements are called limiting nutrients.

The relative proportion of various elements in phytoplankton cells is relatively stable, and the phytoplankton absorbs nutrients from the aquatic environment in this proportion to meet their growth demand. The ratio of nitrogen to phosphorus of phytoplankton cells is about 16:1 (Redfield value). Compared with the element composition of phytoplankton cells, element with the lowest relative proportion in measured waters is the first limiting nutrient element, and element with the second lowest relative proportion is the second limiting nutrient element. In fact, P in freshwater is usually the first limiting nutrient, and N in seawater or brackish water is the first limiting nutrient.

The N and P contents of marine macroalgae and vascular plants are similar to those of fresh water ones. In general, the first limiting nutrient of phytoplankton, macroalgae, and aquatic vascular plants is often N in seawater systems and P in freshwater systems.

The potential strength of limiting nutrient elements in Laizhou Bay of Shandong Province follows the order: $N > P > Si > Fe$, while that in Sanggou Bay of Shandong Province is $N > Si = Fe > P$ (Liu et al. 2003a). According to the survey (Wen et al. 1999), both N and P are limiting elements in saline–alkali fish farming ponds along low-lying land of the Yellow River in Shandong Province, which should be the transitional type between freshwater and seawater.

2.5.4 Ecological Succession of Aquaculture Waters

Ecosystem succession is a process including the change of biological community structure and energy allocation with time. The basic trends of ecosystem succession in natural waters include the increase of community biomass and species diversity, change of dominant species from *r*-selective opportunistic species to *K*-selective species, *P/R* value (production/respiration) approaching to 1, and the role of detritus food chain increasing. Figure 2.15 is the 100 days' succession of a microcosm system in a flask, which is much similar to the centenary succession pattern of forest ecosystems (Odum and Barrett 2005).

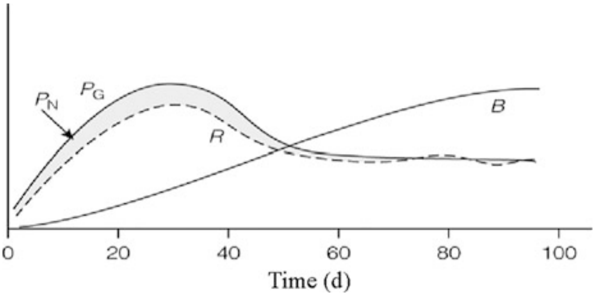


Fig. 2.15 One hundred days' succession of a microcosm system in a flask (from Odum and Barrett 2005). *B* biomass, P_N net primary productivity, P_G gross primary productivity, *R* respiratory

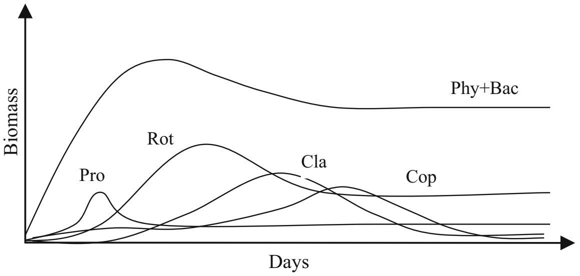


Fig. 2.16 Succession of plankton community in pond after liming. *Bac* bacterioplankton, *Cla* cladocera, *Cop* copepods, *Phy* phytoplankton, *Pro* protozoa, *Rot* rotifer

The differences between the river continuum and aquaculture waters introduced earlier in this chapter are similar to the ecological succession here. In aquaculture practices, people are very concerned about the changes of the production of microorganisms, plankton, and fish in water after the stabilization or disturbance of aquaculture water body, because it is directly related to the occurrence of diseases, the amount of bait supply, and fish catch.

2.5.4.1 Succession of Plankton Community after Disinfection

The succession of biological community in aquaculture waters happens in days and years. For example, the succession of plankton community in ponds after water exchange or disinfection happens in days, and the succession of fishery resources after dam closure happens in years.

Quick lime is often used in pond aquaculture to kill harmful organisms and oxidize sediment. When fresh water is added into the pond after disinfection using quick lime, the succession of plankton in the pond happens in days. After fresh water is pumped into the pond, the biomass peak of plankton appears in the order of bacterioplankton and phytoplankton → protozoa → rotifer → cladocera → copepods (Fig. 2.16). Finally, a stable and mixed population is formed. Because the seawater pond lacks cladocera, the succession of plankton in seawater pond is bacterioplankton and phytoplankton → protozoa → rotifer → copepods, and finally a stable mixed population is formed (Li 1983; Li et al. 2002).

Juvenile fish (about 3 cm in body length) is often cultivated following the plankton succession in ponds in China. For example, while water temperature is

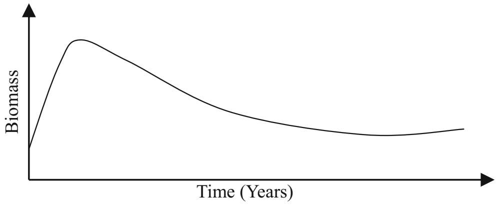


Fig. 2.17 Changes in plankton biomass in reservoir after dam closure

20 or 25 °C in spring, water is pumped into the pond after disinfection, and organic fertilizer is applied. Bacterioplankton and phytoplankton will first appear in the pond in large quantities; then, protozoa feeding on bacterioplankton and phytoplankton will appear in large quantities. Rotifers will appear in large quantities in the pond 8–10 days after disinfection, and fish fry should be stocked at this time. Cladocera will appear a few days after fish stocking, and they can be good food sources for the fish and then the copepods. The succession of plankton is affected by several factors such as number of dormant eggs of zooplankton, time required for germination, and competition for food sources among the plankton.

In the past, in order to prolong the duration of rotifer peak, people sometimes used 0.05 ppm trichlorfon (now prohibited in aquaculture in China) to inhibit the growth of cladocera. In this way, the fish fry can have adequate natural food and growth of the fry will be accelerated.

2.5.4.2 Changes in Plankton Biomass in Reservoir after Dam Closure

Plankton biomass in the reservoir exhibits certain interannual variations after dam closure (Fig. 2.17). Water level rises rapidly after dam closure, and large area of land is submerged. Because of the decomposition of a great amount of submerged terrestrial plants, the nutrients in the water of the reservoir increased rapidly and continuously in a few years after dam closure, resulting in the rapidly growth of plankton. When the decompositions of the submerged terrestrial plants finish, the nutrient concentration in the reservoir begins to decrease gradually. The plankton biomass will decline. After that, the reservoir enters the normal process of natural eutrophication.

With the explosive growth of plankton biomass after dam closure, fish production will also increase. A dominant generation of some species will sometimes appear and occupies a large proportion of capture production in the following years.

2.6 Ecological Pyramid of Aquaculture Ecosystems

The ecological pyramid is the arrangement of the number of individuals, biomass, or energy in an ecosystem according to the order of trophic levels. If using this information to draw a figure, the figure is similar to a pyramid. Generally speaking, the energy pyramid is a regular pyramid, while the biomass pyramid and the quantity pyramid may be reversed or partially reversed. For example, in forest ecosystems and macroalgae ecosystems, the number of primary producers is often less than that

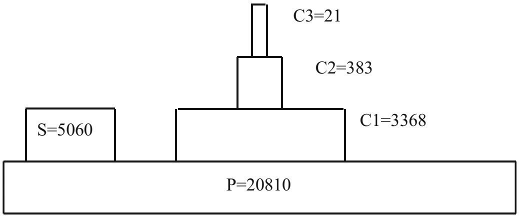


Fig. 2.18 Energy pyramid of Silver Spring ecosystem [kcal/(m^2·yr)] (from Odum 1957). *C1* primary consumer, *C2* secondary consumer, *C3* third consumer, *P* primary producer, *S* bacteria and fungi

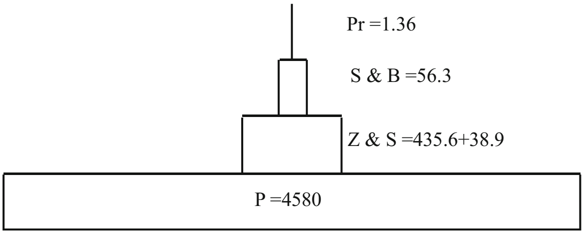


Fig. 2.19 Energy pyramid of East Lake, Wuhan, China [kcal/(m^2·yr)] (from Wang 1999a). *P* primary production, *Pr* predators, *S and B* silver carp and bighead carp, *Z and S* zooplankton and silver carp

of their consumer because of the larger body volume of primary producers. The ecological pyramid of natural ecosystem is regular cone if it is expressed by energy. In the process of energy flow in an ecosystem, the total energy is reduced when it is transferred at each trophic level. Energy transformation rate at each trophic level is only a few percent to 20 percent. While studying on lake ecosystems, Lindeman found that the transformation rate of energy among different trophic levels was about 10%, which is called “1/10 rule” later.

Silver Spring in the United States is a typical aquatic ecosystem, and the energy flow in the system roughly conforms to the “10% rule” (Fig. 2.18). The energy in secondary and third consumers (C2 + C3) is 1.94% of the primary production (P). The East Lake in Wuhan, China, is a shallow lake, in which many filter-feeding silver carp and bighead carp are stocked. Therefore, its ecological efficiency is greatly improved, and commercial fish production accounts for 2.108% of its primary production (Fig. 2.19).

Most of the aquaculture systems are seminatural ecosystems with high degree of artificial intervention. The functions such as natural production, consumption, and decomposition are still playing an important role or leading role in the system. However, due to the large number of stocking animals, artificial intervention (such as feed delivering to compensate for the shortage of natural food for farmed fish) is important to maintain the structure and function stability of aquaculture ecosystem. Figure 2.20 is an energy pyramid of semi-intensive shrimp culture system (stocking density 7.2 individuals/m^2, fertilization, supplementary feeding, no artificial aeration). Shrimp production accounts for 2.88% of its primary production. Because of the long food chain of shrimp, energy transferred from primary production is not enough to maintain the growth of the shrimp; therefore, it is necessary to supplement a certain amount of feed.

Figure 2.21 is the energy pyramid of integrated aquaculture pond (shrimp, tilapia, and razor fish; stocking density of shrimp is 7.2 individuals/m^2) with organic

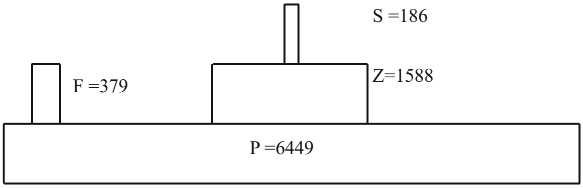


Fig. 2.20 Energy pyramid of a shrimp farming pond, Shandong province [kJ/(m^2·crop)] (from Yan 1999). *F* feeds, *P* primary production, *S* shrimp, *Z* zooplankton and zoobenthos

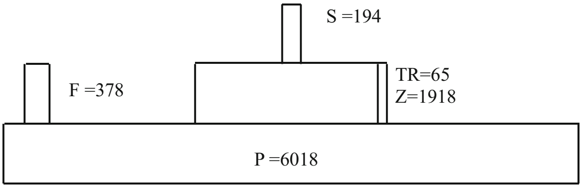


Fig. 2.21 Energy pyramid of an integrated shrimp farming pond, Shandong province [kJ/(m^2·crop)] (from Yan 1999). *F* feeds, *P* primary production, *S* shrimp, *TR* tilapia and razor fish, *Z* zooplankton and zoobenthos

fertilizer. The utilization ratio of primary production and secondary production is improved greatly in this integrated system. The production of commercial products reaches 4.30% of the primary production of the system.

Because of the high stocking density of farmed animals in an intensive system, the system not only receives a large amount of solar radiation energy, but also receives the energy contained in the seedlings, feed, electricity, etc., resulting in a serious deformity of its energy pyramid. With the intensification of aquaculture system, more and more industrial auxiliary energy (including feed, aeration) is inputted to meet various demand of farmed animals and aquatic community. Artificial aeration becomes necessary, and the role of natural ecosystem regulation is becoming less and less important. In an indoor recirculating aquaculture system, the primary producers are almost zero, and all the nutrition and most of the DO in the system are from pelleted feed and aeration.

According to Bao et al. (2006), in shrimp intensive monoculture system (30 individuals /m^2), the net yield of shrimp, primary productivity, and feed input are 2.25 MJ/(m^2·crop), 2.56 MJ/(m^2·crop), and 2.62 MJ/(m^2·crop), respectively. The net yield of shrimp is 87.9% of the primary production, and its conversion rate of total input energy (primary production plus feed) is 43.4%, which is much greater than the rates of Silver Spring in the United States, East Lake of Wuhan, China, and semi-intensive ponds.

In the shrimp (30 individuals/m^2) intensive integrated aquaculture system, the net primary production and feed input are 5.45 MJ/(m^2·crop) and 2.86 MJ/(m^2·crop), respectively, and the net yields of shrimp, clam, and Gracilaria are 2.62 MJ/(m^2·crop), 1.98 MJ/(m^2·crop), and 8.92 MJ/(m^2·crop), respectively. The net commercial product yield is 93.8% of the primary production (phytoplankton and Gracilaria), and 77.7% of the total input energy (primary production, feed, and Gracilaria) is converted to the total commercial biomass. If the Gracilaria is excluded, and the conversion ratio is 55.4%. It can be seen that the efficiency of integrated aquaculture (55.4%) is higher than that (43.4%) of shrimp monoculture. Please see Chap. 9 for the detail on integrated aquaculture.

2.7 Ecosystem Services of Aquaculture Ecosystems

Ecosystem services are processes or conditions that lead to directly and indirectly benefits for humans and can be classified into four categories: provision, regulation, support, and culture (Daily 1997). In food production ecosystems, including aquaculture systems, the target subjects are farmed organisms (Willot et al. 2019). Therefore, ecosystem services of aquaculture ecosystems should include humans and farmed organisms (indirectly related to humans). The boundary of an aquaculture ecosystem is the extent of a farm or water area, including aquaculture waters, ancillary land, and the available space above them.

Ecosystem services can be divided into provision, regulation, support, and culture services. Provision services of aquaculture ecosystems provide direct food, raw materials, biochemical resources, energy, and so on for humans and inorganic nutrients, water, and organic sediment for farmed species. Regulation and support services are crucial for healthy aquaculture ecosystems. Culture services of aquaculture ecosystems provide tourism, educational opportunities, and cultural significance of the ecosystems for many coastal communities (Table 2.12).

In general, mariculture not only consumes but also provides ecosystem services far beyond the provision of goods (Alleway et al. 2019); however, for the aquatic ecosystem where aquaculture is highly developed, the proportion of provision services will be higher in value.

The boundary of an aquaculture ecosystem is the extent of a farm, including aquaculture waters, ancillary land, and the available space above them. Various ecosystem services (provision, regulation, support, and culture) can be integrated into aquaculture ecosystems to improve their productivity, comprehensive benefit, and sustainability.

In fact, the development process of fisheries and aquaculture is just a process in which mankind gradually deepen their understanding and utilization of ecosystem services. Two million years ago or so, people knew that the water body could provide us with aquatic products, i.e., the provision services of aquatic ecosystems, so the fishing emerged in human history (Fagan 2017). Eight thousand years ago, the recognition that water could be used for fish farming, the support services of aquatic ecosystems, led to the carp and tilapia domestication by the Chinese and Egyptians (Nash 2011; Nakajima et al. 2019). In the TANG Zhao Zong Dynasty (889–907 AD), grass carp's roles in weeding and fertilization, i.e., regulation

Table 2.12 Major ecosystem services of aquaculture ecosystem

Ecological services	Carriers	Examples
Provision services	Food for humans	Harvest of aquatic food products (fish, shrimp, molluscs, etc.)
	Raw materials	Alginate industry, fish skin for fashion goods
	Natural primary productivities	Food for farmed animals directly or indirectly
	Inorganic nutrients	Seaweeds
	Water and organic sediment	Irrigation and fertilizer for agriculture
	Air space above	Wind turbines, solar power generation
	Land space	Aquaculture–agriculture systems
	Energy	Solar energy for photosynthesis
		Wind and wave energy for electricity generators
Regulation services	Biodiversity	Trophic synergism, mutualism in polyculture, commensalism for disease prevention in polyculture
		Self-purification of water quality
	Photosynthesis	Aquaponics
	Bivalves	Carbon sequestration
Support services	Water environment	Environment of all aquaculture animals
	Nutrient cycling	Environment maintenance of aquaculture waters
	Physical purification	Water exchange in large aquaculture waters
Culture services	Ecotourism	
	Education	
	Game fishing	

services of aquatic ecosystem, were known; therefore, rice–grass carp farming became popular. At present, there are dozens of integrated aquaculture models in China, major rationale of which is to make full use of various ecosystem services of aquaculture ecosystems, including provision services, regulation services, support services, and cultural services, in order to improve their aquaculture efficiency and ecological efficiency (see Sect. 9.2). Ecological intensification of aquaculture systems (ELIAS) is the integration of anthropogenic inputs with aquaculture ecosystem services (see Sect. 15.7).

Brief Summary

1. Compared with natural aquatic ecosystems, aquaculture ecosystems have four characteristics: First, the energy and material input of the system is not entirely dependent on solar radiation, precipitation, runoff, etc., but partly controlled by human beings; second, in order to maximize the production of target organisms (farmed animals), the biodiversity of the system has been artificially reduced; third, biological communities in the system are not naturally formed, and the dominant organisms are usually artificially stocked. Moreover, some aquaculture systems will exert negative impacts on the adjacent environment when the wastewater from the system is discharged.

2. Compared with general agricultural ecosystem, trophic levels of aquaculture organisms are more diverse; most of the aquaculture animals are poikilotherms and sensitive to water temperature changes; most of the aquaculture animals have a certain degree of osmotic pressure regulation ability; the life habit of aquaculture animals is more diverse; and aquatic animals are more fecund than livestock and poultry.
3. Based on the energy structure of the system, the aquaculture system can be divided into four types: (1) natural aquaculture system, whose energy structure is maintenance energy $(M) \approx 0$, such as silver carp and bighead carp stocking or releasing in lakes or reservoirs without feeding; (2) subnatural aquaculture system, whose energy structure is $M > 0$ and $M <$ solar radiation (S), such as fertilized pond aquaculture, scallop aquaculture, and kelp plantation in open sea; (3) artificial replenished aquaculture system, whose energy structure is $S > 0$ and $M > S$, such as intensive aquaculture in ponds; and (4) fully artificial replenished aquaculture system, whose energy structure is $S \approx 0$, such as indoor recirculating aquaculture system.
4. Based on the metabolism characteristics of the system, aquaculture system can be divided into autotrophic and heterotrophic systems. The autotrophic system, such as kelp plantation system, mainly relies on solar radiation for photosynthesis and obtains inorganic nutrients from the water environment. The operation of the system can reduce the nutrient load of the waters. The heterotrophic system, such as fed fish cage culture system, mainly relies on artificial feeds for fish growth. The operation of the system will discharge pollutants to adjacent environment or deposit organic matters on the bottom of the system.
5. Based on the material budget of the system, the aquaculture system can be divided into fed system (such as shrimp or Atlantic salmon culture system) and extractive system (such as oyster or kelp aquaculture systems).
6. Based on the ecological restriction factors of fish productivity, aquaculture system can be divided into inorganic nutrient-dependent (aquatic plant plantation) system, food-dependent system, dissolved oxygen-dependent system, multi-environmental factor-dependent system (such as recirculating aquaculture system), heterotrophic food web-dependent system (biofloc culturing system), species coupling-dependent (integrated aquaculture) system, and so on.
7. Light is one of the most important factors in aquaculture waters, which is not only the energy source of photosynthesis for primary producers, but also affects the behavior of aquatic animals and water movement. The movement of water will affect directly or indirectly on some important ecological processes of aquatic ecosystems.
8. Because of a high specific heat, waters absorb a large amount of incident light energy and stores it in the aquatic system in the form of heat. The heat storage, distribution, and change in water affect directly not only the primary production and decomposition process of aquaculture waters, but also affect the growth of farmed organisms.

9. The types of the thermal stratification and circulation of waters around the world are diverse. Generally speaking, in deep temperate waters, there are isothermal periods in spring and autumn, positive stratification in summer, and inverse stratification in winter. During the isothermal period, nutrients and DO are exchanged between the upper and lower water layers, and the anaerobic zone in the hypolimnion of eutrophic waters will gradually disappear. In the tropic areas, water temperature is always higher than 4 °C. There is positive stratification of temperature throughout the year, and the overturn of waters occurs only in winter.
10. Dissolved oxygen (DO) is a comprehensive index of water quality. It is the most basic requirement of farmed animals besides water. The content and variation of DO determine the distribution, behavior, and growth of farmed animals and also affect many ecological processes in aquatic ecosystems.
11. The change of pH in aquaculture water is the integrated result of chemical and biological activities of water, which has obvious effects on the metabolism and growth of aquaculture organisms.
12. Ammonia and hydrogen sulfide are two important inorganic compounds in aquaculture water. Concentration of the two compounds in water is affected mainly by temperature and pH. Higher concentration of ammonia and hydrogen sulfide are harmful to aquaculture animals.
13. Although rivers, river reservoirs, hilly reservoirs, plain reservoirs, lakes, and ponds differ greatly in ecology, on the whole, they are ecological continuum with gradual changes of physical, chemical, and biological factors. Their ecological characteristics are the integrated result of their hydrological characteristics, natural succession, and human influence.
14. Generally speaking, the first limiting nutrient element that limits the productivity of primary producers in waters is often N in seawater systems and P in freshwater systems.
15. In freshwater ponds after liming, the biomass peaks of plankton appear in the order of bacterioplankton and phytoplankton→protozoa→rotifer→cladocera→copepods, and finally, a stable community is formed. In seawater ponds after liming, the corresponding order is as follows: bacterioplankton and phytoplankton→protozoa→rotifer→copepods, and finally a stable community is formed. These succession patterns of plankton in ponds can be used to cultivation of fish fry in ponds.
16. There are two basic forms of food chain in an aquaculture ecosystem: (1) grazing food chain, which begins with green plants, and ends with herbivores or carnivores; (2) detritus food chain, which starts with lifeless organic matter, and is followed by microorganisms, detritus consumers, and predators. For fed aquaculture systems, pelleted feeds can be ingested directly by cultured animals, which is the key linkage between allochthonous organic matter and consumers in the system.
17. Most of the aquaculture systems are seminatural ecosystems with high degree of artificial intervention. The functions such as natural production, consumption, and decomposition are still playing an important role or leading role in the

system. However, due to the large number of stocking animals, artificial intervention (such as feeding and aeration) becomes necessary to maintain the structure and function stability of aquaculture ecosystem.

18. Generally speaking, with the intensification or integration of aquaculture systems, the utilization rate of the total energy input of the aquaculture system increases.
19. Ecosystem services are processes or conditions that lead to directly or indirectly benefits for humans and can be divided into provision, regulation, support, and culture services. The development process of fisheries and aquaculture is just a process in which mankind gradually deepen their understanding and utilization of ecosystem services.

Productivity and Carrying Capacity of Aquaculture

3

Shuang-Lin Dong

Productivity and carrying capacity of aquaculture are the two important parameters of aquaculture ecology and are affected by factors such as primary productivity and so on. While for carrying capacity, it is also affected by social factors. Clarifying these two parameters can help us to understand the production characteristics of certain farmed organisms in a specific water and provide targeted guidance for aquaculture operation, such as the determination of stocking quantity of farmed organisms and daily management in order to achieve the goals of rational use of resources and improvement of economic benefits.

3.1 Productivity and Influence Factors of Aquaculture Waters

3.1.1 Productivity of Aquaculture Waters

The productivity of aquaculture waters is the ability or performance of aquaculture waters to produce commercial aquatic products, which is mainly affected by the primary productivity of the waters, farming models, and the ability of farmed organisms to use inorganic nutrients or feeds. Productivity of aquaculture waters can be expressed as productivity potential, maximum daily gain, and actual productivity.

The productivity potential of aquaculture waters refers to the production under the conditions of optimal stocking density and zero mortality of farmed organisms. As a matter of fact, in the early stage of aquaculture season, the standing crop of farmed organisms is low, which will result in waste of a certain amount of natural

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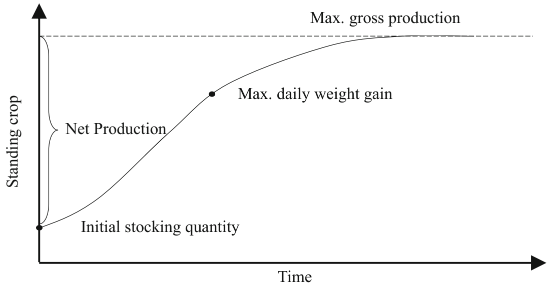
Fig. 3.1 Standing crop dynamic of stocking animal in aquaculture waters



feed and space in the water; in the later stage, the respiration consumption of farmed organisms is high due to their high-standing crop (Fig. 3.1). Therefore, the index of productivity potential expresses only the natural properties of aquaculture waters in an ideal state.

In the process of aquaculture, the standing crop or biomass of the farmed organism in the water has been increasing and its growth is similar to a S-shaped curve; that is, the specific growth rate (SGR) of individual or stock reaches the maximum at the inflection point (Fig. 3.1). Therefore, the maximum daily weight gain at this time can be used as a parameter to characterize the productivity of the waters. Actual production is generally far less numerically than the theoretical value of maximum daily gain rate multiplied by the cultivation days.

When the standing crop of the farmed organism exceeds the inflection point, the daily weight gain of the individual or school begins to slow down, but the individual size and standing crop of the farmed school continue to increase until the maximum gross production is reached. The actual productivity of the waters is the maximum net production of fish, shrimp, or other commercial aquatic products that the waters can produce, that is, the maximum gross production minus the initial stocking quantity.

Individual size of farmed organism is an important economic indicator in aquaculture. In general, the larger in size the higher in price, but the larger in size the less in feed efficiency. In order to obtain greater economic benefits, the farmed organism is usually harvested when the standing crop has exceeded the inflection point but approaching the point of maximum gross production. Therefore, the maximum economic net yield is also taken as a parameter of actual productivity sometime.

3.1.2 Influence Factors on Productivity

The productivity of an aquaculture waters can also be divided into natural productivity and artificial productivity. The former refers to the inherent natural productivity of aquaculture waters, i.e., the productivity formed by feeding on natural diet organisms or absorption of inorganic nutrients in natural water. The latter refers to the productivity formed by artificial intervention, such as fertilization productivity, feeding productivity, etc. Aquaculture productivity usually refers to the total productivity, that is, the natural productivity plus artificial productivity.

The productivity of aquaculture waters is affected not only by various objective factors such as the environmental conditions, but also by some artificial factors. Different from natural waters, the structure of intensive aquaculture ecosystem is usually simple, and its productivity is greatly influenced by stocking species and density, the quality and quantity of feeds, fertilization and so on.

3.1.2.1 Stocking Species

The productivity of aquaculture waters is related to the stocking species. In general, the species with a shorter food chain and a wider diet spectrum are more productive; conversely, the species with longer food chain and narrower diet spectrum are less productive. For example, without feeding and fertilization, the pond productivity of channel catfish is 50–100 kg/(hm^2·per crop), while that of tilapia is 200–500 kg/(hm^2·per crop) under the same conditions (Table 3.1). The difference in productivity between the two species is due to differences in their feeding habits or trophic levels. Both the species feed on zooplankton and aquatic insects in the pond, but the tilapia also feeds on phytoplankton and debris in large quantities in pond (Boyd and Tucker 1998). As a result, the tilapia has lower trophic level or shorter food chain, wider diet spectrum, and can more efficiently utilize the primary production in pond. The common carp yield in fertilized pond in Israeli is 4300 g/(hm^2·d), while that of tilapia is 8380 g/(hm^2·d), because the carp mainly feeds on zoobenthos (He 1985).

The macroalgae is not only the economic organism but also the primary producer of aquaculture waters, so its natural productivity is much higher than those of aquatic animals. Filter-feeding bivalves and silver carp filter phytoplankton directly, so their ecological efficiency and productivity are also high. In 2014, the average yield of kelp plantation in China was 34.1 t/(hm^2·yr) (dry weight), and the average yield of oysters was 32.6 t/(hm^2·yr).

3.1.2.2 Aquaculture Models

As mentioned in Chap. 2, aquaculture systems can be divided into six types: inorganic nutrient-dependent systems, food-dependent systems, multi-environment

Table 3.1 Productivity of channel catfish and tilapia with different culture systems [kg/(hm^2·per crop)] (from Boyd and Tucker 1998)

Aquaculture models	Net production Channel catfish	Tilapia
Extensive	50–100	200–500
Fertilization	200–300	1000–3000
Fertilization and supplemental feeding	–	3000–4000
Feeding	1500–2500	3000–4000
Feeding and emergency aeration	4000–4500	4000–6000
Feeding and continuous aeration	4000–5000	6000–8000
Feeding, continuous aeration, and water exchanges	12,000–15,000	15,000–20,000

factor-dependent systems, heterotrophic food web-dependent systems, species, or subsystem coupling-dependent systems. They are different in intensification level and the key factors restricting their production, so are the aquaculture productivity (see Tables 2.3). It can be seen from Table 3.1 that the productivity of Nile tilapia with natural diet organisms in ponds is 200–500 kg/(hm^2·per crop), increases to 1000–3000 kg/(hm^2·per crop) with fertilization, and reaches to 6000–8000 kg/(hm^2·per crop) with feeding and continuous aeration.

The productivity of Chinese shrimp (*Fenneropenaeus chinensis*) varies greatly under extensive and semi-intensive models, ranging from 0.19 to 1.24 g/(m^2·d) (Li et al. 1999). The net production of shrimp (*Litopenaeus vannamei*) in an intensive integrated aquaculture systems with *Cyclina senensis* and *Gracilaria lichevoides* is 2.1–2.7 g/(m^2·d) (Wang et al. 2006a).

3.1.2.3 Natural Conditions

The fish productivity in natural waters is determined mainly by the autogenous primary productivity, the amount of exogenous organic matters, and the ecological characteristics of the fish species. The primary productivity of different aquatic ecosystems varies greatly around the world, and so does the corresponding fish productivity. Even in the lakes within the same region in China, there are great differences in fish productivity (Table 3.2). The natural conditions that affect the quantity of primary productivity and exogenous organic matters include mainly latitude, climatic conditions, composition of primary producers, watershed conditions, soil characteristics, and morphology of waters.

1. Latitude of aquaculture waters. Latitude determines the quantity of solar radiation received by the waters, and in turn affects directly the primary productivity of the waters. In general, the waters in regions with high latitudes have lower primary productivity.
2. The characteristics of soil, rock, and vegetation in watershed. If the watershed area has fertile soil, luxuriant vegetation, more land for agriculture, high-density population, or high ratio of watershed area to water volume, there will be a large amount of organic matter and inorganic nutrient input into the waters, and the primary productivity will be high; otherwise, the primary productivity will be low.
3. The morphological characteristics of waters. The average depth of waters, the slope and width of coastal zone, the curvature of lakeshore and so on will affect the fish productivity of the waters. Deeper water makes it difficult for nutrient circulation due to the isolation between euphotic and hypolimnion zones, and primary productivity is low. However, if the water is too shallow, it is easy to be turbid due to the influence of wind, and its primary productivity is also low. When the coastal zone is flat and wide, the aquatic plants are usually abundant, and the primary productivity is high. The more branches or bays along lakeshore the larger the interface between the water and the land soil, and the more nutrients will be dissolved and released into the water, which is more conducive to the growth of natural diet organisms in the water.

Table 3.2 Fish productivity in lakes with different conditions in China (kg/667 m^2)

	Northwest region		Yangtze river region		South region	
Trophic condition	M-S	L	M-S	L	M-S	L
Eutrophic type	20–45	4–10	30–75	6–15	40–90	8–18
Mesotrophic type	10–25	1.5–4	15–45	2–6	20–50	3–8
Oligotrophic type	< 10	< 1.5	< 20	< 2	< 25	< 3

Note: *L* stands for large size, *M-S* stands for middle and small sizes

4. Climatic and hydrological conditions. In warm regions, there is a long growing season, high-nutrient circulation rate, and generally high-primary productivity. The waters in the regions with moderate precipitation own more exogenous nutrients from watershed and own higher primary productivity. However, too much precipitation may lead to persistent loss of inorganic nutrients from the watershed soil and decrease in primary productivity, just as some waters in Southeast China. Stable water level, with annual variation of 0.5–1.0 m, is beneficial to the growth of aquatic vascular plants and benthos.
5. Tides and currents. Tides and currents affect the productivity of mariculture significantly. Tidal range has a great influence on the productivity of intertidal ponds, and larger tidal range can make the pond fully exchange of water. Appropriate velocity of current can bring abundant dissolved oxygen and nutrients to farmed organisms, and effectively dilute harmful metabolic wastes. The primary productivity is usually higher in the areas with upwelling.

In addition, water quality of aquaculture waters has a significant impact on both the primary and secondary productivity of aquaculture waters (see Chaps. 2 and 5).

3.2 Evaluation of the Productivity of Aquaculture Waters

There are many approaches to evaluate the productivity of aquaculture waters. However, they can be divided basically into two categories: one is based on the reductionism and the other is based on the holism. The reductionism approaches usually calculate the productivity of a specific aquaculture waters based on the natural diet quantity, food conversion efficiency, and some influencing factors; while the holism approaches, on the other hand, estimate the productivity according to the growth status of farmed organisms or the statistical correlativity between influencing factors and the productivity. Both the approaches have their own advantages and complementary characteristics, so they are used in combination to better estimate the productivity of aquaculture waters sometimes.

3.2.1 Productivity Evaluation of Aquaculture Ponds

Pond productivity can be expressed as net production per year or per crop, or daily maximum production. The followings are some cases to evaluate the productivity of shrimp farming in seawater ponds.

The productivity of semi-intensive (feeding without aeration) polyculture ponds (zero discharge) with Chinese shrimp (*Fenneropenaeus chinensis*) and red tilapia (*Oreochromis mossambicus* × *O. niloticus*) was studied using 26 land-based enclosures (25 m^2 each) in Shandong Province, China (Wang et al. 1998b). The experimental results showed that the net production of the shrimp was affected significantly by the stocking density of the shrimp itself. When the density of the shrimp was 6.0 ind./m^2, the average net production was the highest, 513.5 kg/hm^2 (Table 3.3).

The shrimp was also affected significantly by the stocking density of the tilapia. When the density of shrimp was 6.0 ind./m^2, the growth rate, survival rate, and production of shrimp increased with the density increase of tilapia. When tilapia stocking rate was 0.32 ind./m^2, net production of the shrimp was the highest, 575.7 kg/hm^2 (Table 3.4).

The daily net gain is an important ecological index of aquaculture ponds. During the experimental period, the daily net gain of each treatment was lower in the early stage of the experiment because of lower standing crop or size of the shrimp, and the maximum occurred on August 25. The maximum daily net gain was 1.11 g/(m^2·d) in the treatment of 6.0 ind./m^2 shrimp and 0.32 ind./m^2 tilapia.

Table 3.3 Effects of stocking densities of shrimp on the sizes, productions, and survival rates of the shrimp (from Wang et al. 1998b)

	Shrimp yields			
Shrimp stocking densities (ind./m^2)	Lengths (cm)	Weights (g)	Net productions (kg/hm^2)	Survival (%)
4.5	9.59 ± 0.61	10.41 ± 0.57	337.9 ± 27.97^a	80.20 ± 4.13
6.0	9.88 ± 0.42	10.62 ± 0.92	513.5 ± 40.09^b	89.02 ± 6.80
7.5	9.42 ± 0.27	9.64 ± 0.71	440.2 ± 165.50^c	65.50 ± 21.70

Table 3.4 Effects of stocking densities of tilapia on yield sizes, productions, and survival rates of the shrimp (from Wang et al. 1998b)

	Shrimp yields			
Fish stocking densities (ind./m^2)	Lengths (cm)	Weights (g)	Net productions (kg/hm^2)	Survival rates (%)
0.16	9.50 ± 0.36	10.47 ± 0.76	385.9 ± 122.2	75.68 ± 17.90
0.24	9.17 ± 0.35	9.23 ± 1.61	334.8 ± 157.3	79.52 ± 18.60
0.32	9.48 ± 0.55	9.90 ± 1.69	414.0 ± 168.5	86.71 ± 12.91
0.32	9.96 ± 0.62	10.74 ± 1.32	575.7 ± 13.9	88.50 ± 11.56

Table 3.5 Shrimp productivities in different integrated modes [g/(m^2·d)] (from Dong 2015b)

Integration models	Intensification level	Shrimp productivities [g/(m^2·d)]
Chinese shrimp–tilapia (*O. mossambicus* × *O. niloticus*)	Fertilization without feeding	0.19–0.33
Chinese shrimp–tilapia (*O. mossambicus* × *O. niloticus*)	Feeding without aeration	1.11
Chinese shrimp–bay scallop (*Argopecten irradians*)	Feeding without aeration	1.03
Chinese shrimp–tilapia–sea bass (*Lateolabrax japonicus*)	Fertilization without aeration	0.43
Chinese shrimp–tilapia–razor clam (*Sinonovacula sinensis*)	Feeding without aeration	1.24
Whiteleg shrimp–clam (*Cyclina sinensis*)–seaweeds (Gracilaria)	Feeding and aeration	2.68

The maximum daily net gain of shrimp in some integrated aquaculture ponds is shown in Table 3.5 (Li et al. 1999). It can be seen that the pond productivity is closely related to the integration models and intensification levels. The daily net gain of the optimal proportion (optimal structure) of shrimp, tilapia, and razor clam could reach 1.24 g/(m^2·d) under the condition of semi-intensive farming (feeding without aeration). The daily net gain of whiteleg shrimp (*Litopenaeus vannamei*) integrated with clam (*Cyclina sinensis*) and seaweed (*Gracilaria*) under the condition of feeding and aeration was 2.68 g/(m^2·d) (Wang et al. 2006a).

It should be noted that the productivity mentioned above is the sole shrimp productivity. For the integration aquaculture model of Chinese shrimp + tilapia + sea bass, the total productivity could reach 3.59 g/(m^2·d).

3.2.2 Productivity Evaluation of Large Aquaculture Waters

It is difficult to precisely evaluate the productivity of large aquaculture waters, because it is hard to know the actual net production of lakes or reservoirs comparing with ponds. Therefore, fish productivity of large aquaculture waters is usually estimated according to the primary productivity or the biomass of natural diet organisms. It can also be estimated through correlativity between the actual fish yield and some environmental variables in past years.

By referring to the fish production of two well-managed and fully stocked reservoirs, Li et al. (1993a) used a ranking method to classify the fish productivity of 36 large- and middle-sized reservoirs in Shandong Province, China, into five types: 440, 370, 290, 220, and 150 kg/hm^2, respectively. The results of regression analysis showed that the key factors affecting fish productivity of these reservoirs were soil fertility, population density, and vegetation rate of watershed area in turn.

Fish productivity can also be estimated by empirical formulas. For example, fish productivity can be obtained through statistical analysis based on the correlation between fish production in typical waters and some abiotic variables. The morphoedaphic index (MEI) proposed by Ryder (1965) belongs to this kind of approach.

Another kind of approach to estimate fish productivity is dynamic models. The common feature of the approach is to build models from the perspective of energy flow and material conversion of aquaculture ecosystem.

Some of the methods mentioned above have been used to evaluate the productivity of natural fish population in large waters, while aquaculture in large waters is dominated by stocked fish, that is, stocking-based aquaculture in large waters or culture-based fisheries (De Silva 2003). Therefore, the following will mainly introduce some study cases without recruitment stock except of the case with MEI (Ryder 1982).

3.2.2.1 Morphoedaphic Index

In Ryder's study, 34 north-temperate lakes were investigated, in which 23 lakes were moderately to intensively fished and 11 lakes had restricted catches or incomplete records. Based on the information of the 34 lakes, a mathematical model for predicting fish productivity using the MEI was proposed (Ryder 1982):

$$Y = a\mathrm{MEI}^{b}$$

It is a power function and becomes a log-linear one after taking the logarithm on both sides

$$\log Y = \log a + b \log \mathrm{MEI}$$

where Y is fish productivity, a and b are constants depending on the conditions of the lakes studied. MEI is the ratio of total dissolved solids (TDS) to mean depth ($\overline{Z}$) of the lake, i.e., MEI = TDS/$\overline{Z}$.

The model for predicting the fish productivity of the 23 well-managed lakes is

$$Y = 2.094\mathrm{MEI}^{0.446} \quad r^2 = 0.73$$

In the model, the unit of fish productivity is pound/acre (1 pound = 453.59 g, 1 acre = 4046.86 m^2), the unit of TDS is mg/L, and the unit of depth is foot (1 foot =0.3048 m). The simplified expression of the above model is

$$Y \approx 2\sqrt{\mathrm{MEI}}$$

If all the parameters use metric units, namely kg/hm^2, mg/L, and m, then

$$Y \approx \sqrt{\mathrm{MEI}}$$

The model is based on the correlativity between some abiotic environmental variables and fish productivity, so it is an empirical model to estimate fish productivity. The success of this approach is that it selects two simple parameters (TDS and $\overline{Z}$) that are closely related to the production performance of the waters. However, its disadvantage is that the precision is not high. When MEI is used to estimate fish productivity in natural waters in other regions of the world, the constants should be modified depending on the conditions of the waters studied.

3.2.2.2 Productivity of Herbivorous Fish

Grass carp (*Ctenopharyngodon idella*) is one of the most important farmed fish species in the world, 5.5 mt in 2019 in China. Its natural diet is mainly aquatic vascular plants; however, pellet feed now has been widely used in China for feeding the fish.

In 1975, Mr. Chen from Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, China, proposed an approach for evaluating the production potential of herbivorous fish in lakes (Cui and Li 2005) as follows:

$$F = B \times P / (K \times 100)$$

where F is the fish productivity, B is the highest biomass of aquatic plants in a lake, P is the aquatic plant availability to grass carp, and K is the feed coefficient of grass carp. Later, Liang and Liu (1995) also proposed an approach to estimate the productivity potential of grass carp based on the growth model of aquatic vascular plants, and the growth and feeding model of grass carp.

In 2005, Dr. Cui's team combined the bioenergetics model of herbivorous fish with the dynamic model of aquatic vascular plants biomass and proposed an approach for predicting the productivity of grass carp in lake (Cui and Li 2005). The specific models are as follows:

3.2.2.2.1 Bioenergetic Models for Grass Carp

The maximum ration level of grass carp ($RL_{\max}$, %/d) is a function of water temperature (T, °C)

$$RL_{\max} = 0.04T^{2.32}$$

The relationship between the maximum ration level and body weight of the fish is a power function

$$RL_{\max} = 0.09W^{-0.25}T^{2.32}$$

There was a constant ratio between feces (F, kJ/d) and consumption rate (C, kJ/d)

$$F = fC$$

Constant f is related to the type of feed.

The function of excretion rate (U_S, kJ/d), body weight (W, g) and water temperature for hungry fish is

$$U_s = 0.001W^{0.71}e^{0.077T}$$

There is a constant ratio of excretion rate (U_f, kJ/d) to consumption rate of feeding fish:

$$U_f = 0.049C$$

Metabolism includes starvation metabolism and feeding metabolism. Starvation metabolism (R_{fa}, kJ/d) is a function of body weight and water temperature:

$$R_{fa} = 0.00926W^{0.753}e^{0.077T}$$

The ratio of feeding metabolism to metabolizable energy ($C - F - U$) of grass carp is not related to ration level and is 67.2% in average. Therefore, the feeding metabolism (R_{fe}, kJ/d) is

$$R_{fe} = 0.672(C - F - U)$$

The energy content of fish body (E, kJ/g wet weight) is a function of ration level (RL, % body weight/d):

$$E = 2.767 + 0.0111RL$$

Meanwhile, the energy content of fish body is related to its body weight:

$$E = 1.706W^{0.179} + 0.111RL$$

Based on the above bioenergetic models, the weight gain, food intake, and energy budget of the fish during the whole growth season can be calculated by inputting the parameters of the initial body weight, initial energy content, ration level, water temperature, energy content of food, food digestibility, and growth period of grass carp.

3.2.2.2.2 Growth Model of Aquatic Vascular Plant

The growth model of aquatic vascular plants, diet organism of grass carp, also needs to be established. The models vary from case to case due to their differences in water temperature, solar radiation, and life stages of the aquatic plants in each month. The growth rate of aquatic plant [G, mg/(g·month)] and initial biomass (M, g/m^2) is as follows:

$$G = a + bM$$

where a and b change with the month and species of aquatic plants.

3.2.2.2.3 Productivity Estimation of Grass Carp

By combining the bioenergetics model of grass carp with the growth model of aquatic vascular plants, the relationship model of grass carp and aquatic plants can be established. The input variables of the model include the stocking quantity of grass carp, the initial body weight of the fish, the grazing rate of the fish, the start month of fish stocking, the initial biomass of aquatic plants, and the initial energy content of the fish, the digestibility of aquatic plants, the energy content of aquatic plants and so on. According to the water temperature of each month, the growth gain of aquatic plants, the ration level, and growth of grass carp can be calculated. Since grass carp prefer to grazing on the tender shoots of aquatic plants, it can be assumed that the mortality rate of the aquatic plants caused by fish grazing is twice as high as the grazing rate.

The stocking quantity of grass carp in Lake Baoanhu, Hubei Province, China, was estimated by above approach (Cui and Li 2005). Assuming that grass carp fingerlings (25 g/ind.) are released in March, the initial biomass of aquatic plants is 11 g/m^2, 90% of grass carp are captured 1 year later, and the remaining 10% continue to grow for another year, the reasonable stocking quantity of the grass carp fingerlings is 46 ind./hm^2 to ensure that the biomass of aquatic plants is not affected significantly. The yield of grass carp under this stocking condition can be regarded as the productivity of grass carp in the lake.

The above approach is based on reductionism, each step is scientific, but the aquaculture ecology of grass carp is more complex than the above situation. For example, grass carp is much selective about diet, tends to eat up the plants they prefer and then other species. In addition, grass carp prefers to grazing the tender shoots of aquatic plants, which can inhibit the growth of aquatic plant community especially during the germination stage of aquatic plants. Therefore, enough redundancy must be left when using the calculation results, that is, grass carp must not be overstocked, otherwise the aquatic plant community may be seriously damaged.

3.2.2.3 Productivity of Filter-Feeding Fish

Silver carp and bighead carp are typical filter-feeding fish and are important farmed species in inland waters in China. Chinese scholars often use plankton biomass or primary productivity of phytoplankton to estimate the productivity of the fish in lakes or reservoirs.

3.2.2.3.1 Productivity Estimation Based on Plankton Biomass

He and Li (1983a) estimated the fish productivity in Reservoir Qinghe using the indicator of plankton biomass. The calculation formula was as follows:

$$F = B \times (P/B) \times A \times \overline{Z} \times U \times FCR$$

where F is the fish productivity, B is the annual biomass of plankton, P is the plankton production, A is the area of waters, $\overline{Z}$ is the average depth of waters, U is the availability of plankton, and FCR is the feed coefficient rate.

According to an investigation, the *B* of phytoplankton and zooplankton in the reservoir were 7.4 mg/L and 2.5 mg/L, respectively; $\overline{Z}$ of the reservoir was 10 m. Assuming that *FCR* of silver carp on phytoplankton is 40, *FCR* of bighead carp on zooplankton is 10, *U* of phytoplankton is 20%, *U* of zooplankton is 25%, and *P/B* coefficients of phytoplankton and zooplankton are 50 and 20, respectively. Therefore, the productivity of silver carp and bighead carp in Reservoir Qinghe were 187.5 kg/hm^2 and 123.8 kg/hm^2, respectively.

This approach is simple and easy to implement. However, its precision is not high, because many parameters are selected from cited references, without measuring in situ.

3.2.2.3.2 Productivity Estimation Based on Primary Productivity

Wang and Liang (1981) calculated the productivity of silver carp and bighead carp in Lake Donghu, Wuhan, China, based on the primary productivity of the waters (measured by the black and white bottles). Phytoplankton (as diet of the fish) production capacity (F_{SC}) in the lake is

$$F_{\mathrm{SC}} = P_{\mathrm{O}} \times P_{\mathrm{Na}}/P_{\mathrm{Ga}} \times a \times 14.686$$

where P_{O} ($\mathrm{tO_2}$) is the oxygen production in the lake, $P_{\mathrm{Na}}/P_{\mathrm{Ga}}$ is the ratio of net primary production (P_{Na}) to gross primary production (P_{Ga}) of phytoplankton, generally choosing 0.8, *a* is the phytoplankton utilization rate by the fish, which is related to stocking density, etc., with a maximum value of 0.5; 1 $\mathrm{gO_2}$ = 14.686 kJ.

The productivity of silver carp (F_{Hy}) and bighead carp (F_{Ar}) was estimated by the following formulas

$$F_{Hy} = F_{\mathrm{SC}} \times E_{Hy} \times Hy/C$$
$$F_{Ar} = F_{\mathrm{SC}} \times E_{Ar} \times Ar/C$$

where *Hy* and *Ar* are the relative proportions of silver carp and bighead carp, respectively. For eutrophic Lake Donghu, $Hy = 0.7$ and $Ar = 0.3$ were recommended. *C* is the heat equivalent of fresh fish meat of silver carp and bighead carp, 5.021 kJ/g. E_{Hy} and E_{Ar} are the conversion rates of phytoplankton to silver carp and bighead carp, respectively.E_{Hy} = Annual meat gain×fish heat equivalent/food intake×fresh algae heat equivalent.E_{Ar} = Annual meat gain×fish heat equivalent/food intake×fresh algae heat equivalent.

In Lake Donghu, E_{Hy} and E_{Ar} were 0.032 and 0.072, respectively. Substituting the results with the preceding formulas

$$F_{Hy} = 0.0262 \times F_{\mathrm{SC}} = 0.154 P_{\mathrm{Na}}$$
$$F_{Ar} = 0.0253 \times F_{\mathrm{SC}} = 0.149 P_{\mathrm{Na}}$$

This approach looks scientific in form, but the selection of some parameters is also subjective. For example, $P_{\mathrm{Na}}/P_{\mathrm{Ga}}$ is affected significantly by water depth and phytoplankton biomass. In addition, the stocking proportion of silver carp and

Table 3.6 Conversion efficiencies of annual gross primary production (ΣPP) to areal fish yields for waters of different productivities (from Beveridge 2004)

ΣPP ($gC/(m^2{\cdot}yr)$)	Conversion efficiencies (%)	ΣPP ($gC/(m^2{\cdot}yr)$)	Conversion efficiencies (%)
<1000	1.0–1.2	3000–3500	2.1–1.5
1000–1500	1.2–1.5	3500–4000	1.5–1.2
1500–2000	1.5–2.1	4000–4500	1.2–1.0
2000–2500	2.1–3.2	>5000	1.0
2500–3000	3.2–2.1		

bighead carp is also related to the morphological and hydrological condition of the waters. The utilization rate of phytoplankton by filter-feeding fish is closely related to the stocking density of the fish and the composition of phytoplankton. In general, the stocking proportion of bighead carp should be higher in deep, large, oligotrophic, or mesotrophic waters, and the stocking proportion of silver carp should be higher in shallow, small, and eutrophic waters (see Sect. 2.5.1). Many factors should be considered to select the parameters when the approach is applied in practice.

Beveridge (2004) used a similar approach to assess the tilapia productivity of fertilized reservoirs in Southeast Asia. Three steps are as follows: first, determine the annual gross primary production (ΣPP, $gC/(m^2{\cdot}yr)$) of the waters; second, convert ΣPP to fish production, i.e., using the conversion efficiencies in Table 3.6 to convert plankton carbon content to fish carbon content assuming fresh fish carbon content = 10% net weight of fish; and third, production planning depends on several variables. The number of crops per year and the size of the fish at harvest should be decided.

For example, tilapia is farmed in a 100-hm^2 reservoir with 1200 $gC/(m^2{\cdot}yr)$ of total gross primary productivity. According to Table 3.6, 1.3% gross primary productivity can be converted into fish production, which is 15.5 gC/m^2, equivalent to 15.6 g fish/m^2, and the annual production of the whole reservoir is 156 t tilapia.

Assuming two crops per year, one from November to May and the another from June to October (fish grows faster in the warm season and needs less time to reach the harvest size), the total gross primary productivity during the periods is 570 gC/m^2 and 630 gC/m^2, respectively. If the stocking size of the fish is 25 g/ind. and the harvest size is 125 g/ind., then the weight gain is 100 g/ind. A total number of fingerlings required is 156 t/100 g = 1.56×10^6 individuals. According to the proportion of total gross primary productivity, the stocking quantity of the fingerlings should be 0.741×10^6 and 0.819×10^6 individuals, respectively (Beveridge 2004).

3.2.2.4 Productivity of Zoobenthivorous Fish

Using biomass of zoobenthos to estimate the productivity of zoobenthivorous fish can be also based on the parameters such as biomass, *P*/*B* coefficient, availability rate, and feed coefficient rate. Liang and liu (1995) estimated common carp productivity (F_Y) based on the biomass of benthic mollusks (B_M), aquatic insects (B_I), aquatic oligochaete (B_O), zooplankton (B_Z), and other parameters. Their simplified formulas were

$$F_Y = 0.032B_M$$
$$F_Y = 0.183B_I$$
$$F_Y = 0.235B_O$$
$$F_Y = 18.0B_Z$$

In recent years, studies on the *P*/*B* coefficient and feed coefficient of zoobenthos have been gradually deepened, and some more precise parameters are obtained. Therefore, some constants can be adjusted appropriately when the above formulas are applied.

3.2.2.5 Productivity Estimation Based on Stocking and Harvest Data

The stocking of silver carp and bighead carp in reservoirs and lakes, namely, stocking-based aquaculture in large waters, is an important aquaculture model in China. The silver carp and bighead carp reproduce drifting eggs which cannot normally complete their natural hatching process in ordinary rivers of reservoir watershed. Therefore, there will be no recruitment stock or increase in the individual quantity of the carps except for stocking year after year in the waters. Therefore, annually stocking of the fish fingerlings is essential for stocking-based aquaculture in large waters, except that it is more extensive and has a higher mortality than pond farming. It is important to estimate the natural productivity of the stocked carps for understanding the structure and function of aquaculture ecosystem.

3.2.2.5.1 Concept of Fish Production

Fish production belongs to the category of secondary production and refers to the biomass accumulated in a certain time and space, that is, the product of population or cohort quantity and biological growth. Fish production can be calculated by the following formula (Ricker 1975)

$$P = G \times Dt \times \overline{B}$$

where Δt is the time interval between the two samples, G is the instantaneous weight gain rate, and $\overline{B}$ is the average biomass of the fish.

$$G_i = (\ln W_{i+1} - \ln W_i)/\Delta t$$
$$\overline{B} = (B_{i+1} + B_i)/2$$

where W_i is the weight of the *i*th age fish. The biomass of each age group in the fish stock is $B_i = N_i \times \overline{W}_i$.

The fish survival rate (S) can be calculated by Robson–Chapman formula, that is

$$S = T/\left(\sum N + T - 1\right)$$

where

$$T = N_1 + 2N_2 + 3N_3 + \ldots$$
$$\sum N = N_1 + N_2 + N_3 + \ldots$$

N_1, N_2, N_3 ... represent the fish number of minimum fully catchable age of fish group and the numbers of fish above the fully catchable age groups. Survival rate can be used to calculate the existing quantities of N_i for each age group. For example, $N_2 = N_1 \cdot S_1$.

3.2.2.5.2 Catch Analysis of the Fishes in the Reservoir

Reservoir Qinghe is a large reservoir located in Liaoning Province, China, in which the silver carp and bighead carp are the major stocking and capture species. The production estimation of such a special stock with known stocking quantity and no natural recruitment has general implications for stocking-based aquaculture in large waters. 2663 individuals of silver carp and bighead carp were sampled and analyzed in the reservoir from 1982 to 1985. 556 samples were collected from the end of May to the beginning of June, their age compositions were identified by their scales (Dong 1992). Table 3.7 shows the composition of samples in the reservoir.

The silver carp and bighead carp in the catches were stocked from 1974 to 1984. During the 11 years, the average annual stocking quantities of the fish were 830 ind./hm^2 and 416 ind./hm^2, respectively. The fish stocked in 1974–1984 were captured from 1975 to 1985. The average annual catches of the fish during this period were 46.2 kg/hm^2 and 36.9 kg/hm^2, respectively.

3.2.2.5.3 Estimation of Survival Rates of the Fish in the Reservoir

The fully catchable age of silver carp and bighead carp in the reservoir was III-age. According to Robson–Chapman formula, the survival rates of III-age of silver carp and bighead carp were 0.344 and 0.452, respectively. The calculated survival rates of silver carp from IV- to VII-ages were 0.171, 0.411, 0.356, and 0.300, respectively, while the corresponding survival rates of bighead carp were 0.377, 0.258, 0.487, and 0.333, respectively.

Total I- and II-ages of silver carp and bighead carp accounted for 3.46% and 7.00% of total catch in weight, respectively.

According to the average weight of each age of the fish, the capture numbers of VII-age of silver carp and bighead carp were 0.150 ind./hm^2 and 0.176 ind./hm^2, respectively. Assuming VII-age is the final capture age, then.

Stocking number $\times S_1 \times S_2 \times S_3 \times S_4 \times S_5 \times S_6 \times S_7 =$ Capture number of VII-age.

The natural mortality rates of I-aged fishes were high, while the capture rates of II-age fishes were high. Assuming that the survival rates of I- and II-ages of the fishes were equal, the calculated survival rates of the silver carp were $S_1 = 0.204$, $S_2 = 0.344$, while those of bighead carp were $S_1 = 0.131$, $S_2 = 0.452$.

Table 3.7 Number, weight, and age compositions of silver carp and bighead carp in catches in Qinghe reservoir during 1982–1985 (from Dong 1992)

Species and quantity		Ages								Total
		I	II	III	IV	V	VI	VII	VII	
Silver carp	Numbers (ind.)	45	103	940	638	48	24	9	6	1813
	Mean weights (kg)	0.025	0.195	0.59	1.37	2.41	6.06	8.58	10.65	
	Samples	45	28	94	129	42	22	9	6	375
	Total weights (kg)	1.1	20.1	554.6	874.1	115.7	145.4	77.2	63.9	1852.1
Bighead carp	Numbers (ind.)	19	246	326	143	95	8	7	6	850
	Mean weights (kg)	0.015	0.415	0.89	1.80	3.79	8.95	13.0	14.7	
	Samples	16	30	43	48	19	22	7	6	191
	Total weights (kg)	0.3	102.1	290.1	257.4	360.1	71.6	91.0	88.2	1260.8

3.2.2.5.4 Production of the Fishes in the Reservoir

The stock quantity of N_i of each age group can be calculated based on the stocking quantity of N_1 for the fish and the survival rate of S_i at each age. The biomass of the fish at each age is $B_i = N_i \cdot W_i$. The calculated stocks, biomass, and productions of the fish are listed in Table 3.8. The stock quantity of silver carp and bighead carp was 1082 ind./hm^2 and 512 ind./hm^2, respectively, and the biomass was 130 kg/hm^2 and 104 kg/hm^2, respectively. The productions of the fish were 141 kg/hm^2 and 110 kg/hm^2, respectively, therefore, the actual yields of the fish were 33 and 34% of their production in the reservoir.

From 1975 to 1985, total capture rates of the stocking fish were 5.5% and 6.0%, respectively. Based on the survival rates of I-age and II-age of the fish, it can be figured out that only 6% of the stocking fingerlings could survive to III-age. Natural fish mortality occurred mainly in the first 2 years, and fish mortality was mainly due to fishing..

The average annual *P*/*B* coefficient or biomass turnover ratio of silver carp and bighead carp was 1.15 and 1.09 in the waters, respectively. Most of the silver carp and bighead in aquaculture ponds are young fish, so their *P*/*B* coefficient is normally as high as 1.7.

The stock of silver carp and bighead carp grew still faster, and the structure of the stocks was a little younger. If the capture age was delayed, such as fishing started from IV-age, and the fishing mortality coefficient of the silver carp was 0.6, natural mortality coefficient was 0.3, and the corresponding yield would be 65 kg/hm^2. For bighead carp if fishing started from IV-age, the fishing mortality coefficient was 0.5, natural mortality coefficient was 0.2, and the corresponding yield would be 64 kg/hm^2 (Wang and Dong 2003). For more information, see Ricker's works (Ricker 1975).

3.3 Carrying Capacity and Influence Factors of Aquaculture Waters

3.3.1 Carrying Capacity of Aquaculture

The term 'carrying capacity' was first proposed by Tomas Malthus in 1798 when studying populations and was used in aquaculture studies in the 1960s (Weitzman and Filgueira 2020). The concept of carrying capacity of aquaculture is evolved from the logistic curve of population growth in ecology. The S-shaped growth of the natural population basically conforms to the logistic model, that is, $dN/dt = rN(K-N)/K$. There are two important parameters in this model, namely, the carrying capacity (K) and the inflection point (Fig. 3.2). In an environment with limited resources, the individual number of a certain population cannot grow indefinitely and its growth will be inhibited by environmental resistance, such as restriction of food supply. The population growth will eventually oscillate around the environmental carrying capacity (K), at which time the population growth can be regarded as zero. It should be noted that there is no or negligible individual number increase of

Table 3.8 Stock, biomass, and productions of silver carp and bighead carp in Qinghe reservoir (silver carp/bighead carp) (from Dong 1992)

Ages	Average weights (kg)	Growth rates	Numbers (ind./hm^2)	Biomasses (kg/hm^2)	Average biomasses (kg/hm^2)	Productions (kg/hm^2)	*P*/*B*
I	0.015/0.10		830/416	12.5/4.16			
		2.48/3.72			22.8/13.4	56.6/47.9	2.48/3.72
II	0.196/0.415		169/54.6	33.0/27.7			
		1.11/0.763			23.8/22.4	37.4/17.1	1.11/0.77
III	0.59/0.89		58.2/24.7	34.4/21.9			
		0.893/0.702			30.9/21.0	26.0/14.7	0.84/0.70
IV	1.37/1.80		20.0/11.1	27.5/20.0			
		0.566/0.746			17.9/18.0	10.1/13.4	0.57/0.75
V	2.41/3.79		3.42/4.19	8.25/15.9			
		0.923/0.861			8.40/12.9	7.80/11.1	0.92/0.86
VI	6.06/8.95		1.40/1.08	8.55/9.75			
		0.349/0.373			6.41/8.25	2.25/3.15	0.35/0.37
VII	8.58/13.0		0.500/0.526	4.29/6.90			
		0.216/0.123			2.94/4.80	0.68/0.60	0.22/0.11
VII	10.65/14.7		0.150/0.177	1.68/2.55			
Total or average			1082/512	130/104	123/101	141/110	1.15/1.09

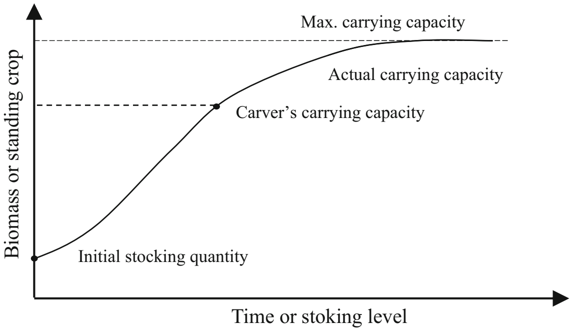


Fig. 3.2 Carrying capacity of farmed stock in aquaculture waters (modified from Dong 2015b)

farmed organisms in stocking-based aquaculture waters, but the biomass or standing crop of the farmed stock is increasing, similar to the S-shaped growth.

Since the research on carrying capacity of aquaculture involves many fields such as production, ecology, society, etc., there are also many different definitions about it. Hepher and Pruginin (1981) defined the standing crop at zero instaneous growth of farmed fish (weight gain/week) as carrying capacity of aquaculture ponds, that is, the maximum carrying capacity shown in Fig. 3.2. Some scholars also expressed standing stock at which the annual production of the marketable cohort is maximized (Bacher et al. 1998; Smaal et al. 1998).

The carrying capacity can also be expressed by the number of seedlings that should be stocked, therefore, the above-mentioned carrying capacity can be converted into the maximum or optimal stocking quantity of seedlings. McKindsey et al. (2006) described the carrying capacity as the stocking density at which production biomass is maximized. Carver and Mallet (1990) defined aquaculture capacity as 'the stock density at which production levels are maximized without negatively affecting growth rates', that is, the Carver's carrying capacity of aquaculture shown in Fig. 3.2.

The carrying capacity of aquaculture must be based on the premise of aquaculturists to obtain their due benefits. Usually, the larger the aquatic products harvested, the higher the price per product. Therefore, the 'actual' carrying capacity of aquaculture adopted in practice should be greater than the Carver's carrying capacity and less than the maximum carrying capacity in Fig. 3.2. When the 'actual' one is too close to the maximum one, the 'respiration' effect (i.e., waste of resources) of the farmed organisms is stronger than the 'growth' effect (i.e., resource utilization), resulting in waste of diet resources and environmental pollution (Li et al. 1994).

In addition to aquaculture activities, aquaculture waters may also have other functions, such as drinking water supply, irrigation, and tourism. When fish farming in cage is carried out in the reservoir with functions of drinking water supply, the effect of farming activities on water quality should be concerned. For this reason, Li et al. (1994) defined carrying capacity as the maximum aquaculture load that does not exceed the corresponding water quality standards.

Carrying capacity of aquaculture is not a simple biological term and it also involves the environmental, economic, and social factors of the waters. Therefore, generalized carrying capacity of aquaculture should be the optimum aquaculture load that meets the requirements of sustainable development in terms of protecting the environment, saving resources, and ensuring due benefits (Dong et al. 1998). McKindsey (2013) defines carrying capacity of aquaculture as the intensity of a practice that a given environment can sustain indefinitely given the availability of various necessities in that environment and the various pressures on them. The actual carrying capacity of aquaculture should be the optimum standing crop of farmed organisms or the optimum stocking level of seedlings that meet the demands of all stakeholders, especially the environmental protection requirement. Aquaculture productivity basically describes the natural attribute of the waters, while carrying capacity of aquaculture is the social value of the aquaculture waters (McKindsey 2013).

3.3.2 Influence Factors on Carrying Capacity

In intensive aquaculture systems, such as feed-feeding ponds and recirculating aquaculture systems, the number of farmed animals is known and the water quality is controllable, so the carrying capacity mainly depends on the assimilation ability of the animals. In large extensive aquaculture systems, such as lakes and bays, the carrying capacity is not only affected by the ecological characteristics of the aquaculture organisms, but also by the physical, ecological, economic, and social conditions of the waters.

The four functional categories of 'carrying capacity' as outlined by Inglis et al. (2000) and McKindsey et al. (2006) are used in bivalve culture: physical carrying capacity, production carrying capacity, ecological carrying capacity, and social carrying capacity. The physical carrying capacity is similar to the maximum carrying capacity as in Fig. 3.2, and the other three are the actual carrying capacity under different considerations.

Physical carrying capacity or natural carrying capacity actually is the maximum carrying capacity of a given species using a given method that can be supported by physical space and conditions (such as water body size, location, water depth, substrate type, hydrological conditions, diet organism resources, etc.) (Fig. 3.3). The physical carrying capacity of a specific water area depends greatly on farming species and farming methods.

The production carrying capacity of a water area is the stocking density at which harvests are maximized, which is less than the physical carrying capacity in quantity (Fig. 3.3). The production carrying capacity is a trade-off between the growth rates and market prices of farming species, therefore it is often not the greatest biomass. The production carrying capacity of a specific water area is strongly related to its physical carrying capacity. The models to predict production carrying capacity have three main components: (1) a hydrodynamic model that transports food, nutrients, and other wastes; (2) a biogeochemical component that describes processes that

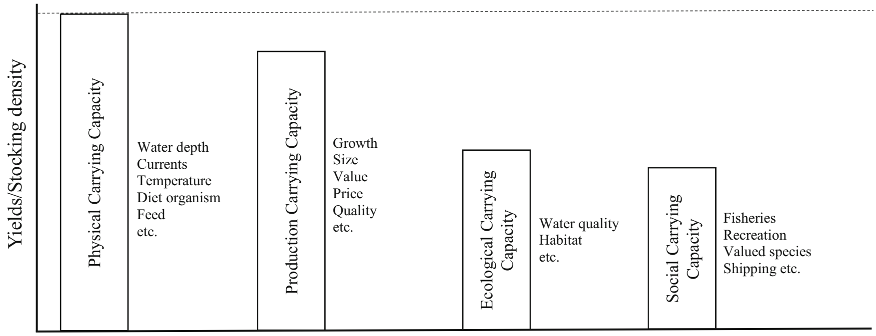


Fig. 3.3 Physical carrying capacity, production carrying capacity, ecological carrying capacity, social carrying capacity, and affecting factors

influence food production and consumption; and (3) a physiological component that determines the rate of food consumption and growth of the farmed bivalves (McKindsey 2013).

Ecological carrying capacity is the maximum harvest amount or the corresponding stocking density without significant change the major energy fluxes or structure of the food web. The ecological carrying capacity not only focus on the farmed organisms, but also pay attention to the non-farming organisms, habitats, and the function of ecosystem. Therefore, the ecological carrying capacity is not only closely related to the physical and production carrying capacities, but also related to the habitat or ecosystem. Since it is up to the society or its representatives to make a judgment on the acceptability of changes in an ecosystem, this capacity is related to the social values. From this point of view, the ecological carrying capacity overlaps following social carrying capacity in meaning.

The social carrying capacity of a water area depends on the trade-offs between stakeholders to meet the demands of both the population and the environment, and is the amount of aquaculture that can be developed at which the society as a whole is willing to accept. Communication between scientists and stakeholders is a key aspect of social carrying capacity to obtain the optimal outcome for sustainable management of resources and equity of all users. Social carrying capacity methods for evaluating aquaculture are still being developed.

In developed countries, social factors are normally the key considerations in determining carrying capacity and selecting aquaculture areas, while in developing countries, including most Asian countries, production factors are often the most important considerations, as production factors are more closely related to economic development and food security (Ferreira et al. 2013). Due to the environmental degradation caused by the expansion of aquaculture scale, China has begun to put environmental protection in a prominent position. Therefore, comprehensively considering social, ecological and production factors is the methodology to determine the carrying capacity in China. The carrying capacity with balanced consideration of production, ecological, and social objectives can be called integrated carrying capacity.

3.4 Evaluation of Carrying Capacity of Aquaculture Waters

Carrying capacity of aquaculture waters is the optimum standing crop or stocking quantity of farming organisms that meets the requirements of all stakeholders, especially environmental protection requirements. McKindsey et al. (2006) proposed a conceptual scheme where the impact is plotted as a function of production level. This allows quantifying the maximum production level that gives an 'acceptable' impact (Fig. 3.4).

The physical or natural carrying capacity of non-fed species (such as seaweed and filter-feeders) can be evaluated based on the supply of nutrient or diet organism and the absorption efficiency of nutrient or utilization rate of diet organisms by farmed organism. While the physical or natural carrying capacity of fed species (such as salmon) can be evaluated according to the energy or material budget models, or according to the relationship between environmental factor and growth condition of farmed animals. Then, considering market, ecological and social factors, the production, ecological, and social carrying capacities are determined. The followings are some examples of carrying capacity evaluation for different trophic levels of culture organisms. See Chap. 12 for the carrying capacity evaluation of fish cage in open seas.

3.4.1 Carrying Capacity of Shrimp Farming in Seawater Ponds

Shrimp is a fed species in seawater pond, therefore, the main factor that restricts the pond carrying capacity of the shrimp is no longer the supply and utilization rate of natural diet organism, but the environmental factors. Pond carrying capacity of shrimp in Shandong Province was evaluated using a holistic approach (Liu et al. 2000c). In their study, Chinese shrimp (*F. chinensis*) were co-cultured with red tilapia (*Oreochromis mossambicus* × *O. niloticus*) in 15 land-based encloses (5 × 5 × 1.2 m), with five density treatments and three replicates (Table 3.9). The

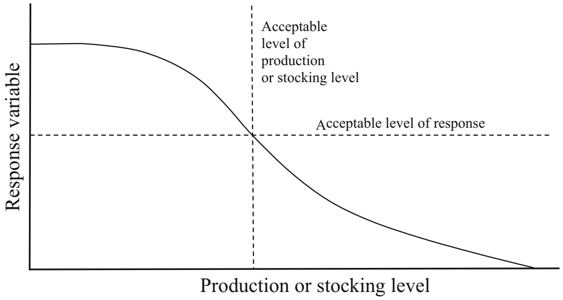


Fig. 3.4 Response curve of an environmental variable under the influence of varying levels of aquaculture production (modified from Smaal and van Duren 2019)

Table 3.9 Stocking of shrimp and tilapia in the experimental ponds (from Liu et al. 2000c)

Treatments	Shrimp sizes (cm)	Shrimp densities (ind./hm^2)	Tilapia sizes (g)	Tilapia densities (ind./hm^2)
A	3.61 ± 0.32	28,000	108.33 ± 62.92	400
B	3.61 ± 0.32	56,000	96.67 ± 20.21	800
C	3.61 ± 0.32	84,000	168.34 ± 16.08	1200
D	3.61 ± 0.32	112,000	110.84 ± 221.84	1600
E	3.61 ± 0.32	140,000	170.00 ± 87.20	2000

ratio of designed gross production (the highest standing crop) of the shrimp to tilapia in each treatment was 1:0.3. Seawater salinity was 30, and there was no artificial aeration and no change of water during the experiment.

After 90 days of experiment, the harvest size of the shrimp in Treatment D was significantly different from those in Treatments A and B (Table 3.10). The highest production (standing crop at harvest) of the shrimp was 1455.5 kg/hm^2 in Treatment D, which was significantly different from those in Treatments C and E. The production of tilapia increased with the increase of stocking density of the fish.

Table 3.11 shows the changes of the average growth rate (%/d) of the shrimp in each treatment during the experiment. The data in the table shows that the growth rate of the shrimp in the early stage (small size) is higher than that in the later stage (large size), and in general, the average growth rate with lower stocking density is greater.

Table 3.12 shows the changes of the major water quality indexes of each treatment in the later period of the experiment. As can be seen from the table, DO (dissolved oxygen) and SD (transparency) tend to decrease with the increase of stocking density and the extension of culture time, while TAN (total ammonia nitrogen) and COD (chemical oxygen demand) are on the contrary. By the end of the experiment, the DO, SD, and COD in Treatment E have obviously exceeded the Water Quality Standard for Fisheries of China.

Table 3.13 shows the economic benefits of each treatment in that year. The net profit and output–input ratio of Treatment D are the highest. The net profit of Treatment is 50,592 yuan /hm^2, much higher than those of other treatment.

The aquaculture benefits can be evaluated by multiple indexes, such as the biological synthesis index (*SI*) and the synthetic efficiency index (*CI*). *SI* is defined as the geometric mean of gross yield or production (*Y*), size at harvest (*S*), and feed efficiency (*K*), namely, $SI = (Y \times S \times K)^{1/3}$. *SI* can also be expressed as a relative value, in which the control group is calculated as 100. *CI* is defined as the geometric mean of the *SI*, net profit (*P*), and output/input ratio (*R*), that is, $CI = (SI \times P \times R)^{1/3}$. The *CI* can also be expressed as relative value. The aquaculture benefits of each treatment are shown in Table 3.14. As can be seen from the table, the *SI* and *CI* of Treatment D are the best among all treatments.

In this study, there are three criteria for judging the carrying capacity: water quality can be kept normal during the culture period; the growth of the shrimp tends

Table 3.10 Yields of shrimp and tilapia in the experiment (from Liu et al. 2000c)

Treatments	Shrimp sizes (cm)	Shrimp survival (%)	Shrimp productions (kg/hm^2)	Shrimp feed coefficiencies	Fish sizes (g)	Fish productions (kg/hm^2)
A	11.5 ± 0.2	94.29 ± 22.99	473.2 ± 123.2	1.46 ± 0.05	500 ± 66	200 ± 27
B	11.3 ± 0.1	85.00 ± 5.01	872.2 ± 21.8	1.63 ± 0.08	375 ± 25	300 ± 100
C	11.2 ± 0.4	83.34 ± 12.09	952.3 ± 291.2	1.79 ± 0.14	468 ± 70	561 ± 84
D	10.6 ± 0.2	85.83 ± 6.51	1455.5 ± 97.0	1.81 ± 0.25	448 ± 110	742 ± 142
E	10.0 ± 0.5	75.58 ± 9.29	1142.8 ± 168.1	2.24 ± 0.51	463 ± 39	925 ± 55

Table 3.11 The growth rate of the shrimp during the experiment (%/d) (from Liu et al. 2000c)

	Date (d/m)					
Treatments	2 Jul.	17 Jul.	1 Aug.	6 Aug.	31 Aug.	14 Sept.
A	8.53	4.40	3.11	2.36	3.01	1.69
B	8.60	4.33	3.77	1.59	2.40	2.07
C	8.16	3.99	3.17	2.47	2.32	1.86
D	7.60	4.49	2.97	2.24	2.94	1.36
E	8.13	3.66	3.23	2.34	2.45	1.33

to stagnate at the later stage of culture; and there are the best aquaculture benefits. It can be seen from the above experimental results that the growth of the shrimp in all treatments slows down in the later stage of culture, especially in Treatments D and E (Table 3.11). Except for Treatment E, the water quality of other treatment is basically normal (Table 3.12). The net profit and output–input ratio of Treatment D are the highest, and its *SI* and *CI* are the best among all treatments. Therefore, the gross yield (standing crop at harvest) of Treatment D, i.e., 455.5 kg/hm^2 for shrimp, 742 kg/hm^2 for tilapia), can be taken as the carrying capacity of the pond under the experimental conditions. Because the carrying capacity have considered economy and water quality, it is actually production carrying capacity.

3.4.2 Carrying Capacity of Cage Aquaculture in Reservoirs

Large inland waters (lakes, reservoirs) usually have multiple functions, such as flood control, irrigation, fisheries, tourism, power generation, etc. With the increase of public awareness of water resources protection, aquaculture in large inland waters has gradually changed from the pursuit of single output to environmentally friendly aquaculture. Therefore, the carrying capacity in the waters should be the maximum aquaculture load that does not exceed the corresponding water quality standards. The following is a brief introduction to a case study of the carrying capacity of a reservoir by field enclosure experiment.

Li et al. (1994) conducted an experimental study on the carrying capacity of Reservoir Dongzhou, Shandong Province, for fed common carp in cage. The functions of the reservoir are irrigation and fish farming. In the experiment, 18 floating enclosures (14.3 m^3 each), common carp (initial weight of 50–60 g/ind.) were stocked. Six stocking densities (treatments) were 0, 0.76, 0.38, 0.25, 0.19, and 0.15 kg/m^2, marked as A, B, C, D, E, and F, respectively. Each treatment had three replicates, and the experiment lasted for 34 days.

During the experiment, there was a significant negative correlation between the dissolved oxygen (DO) in the morning and fish load in each treatment. Treatments B–D successively dropped below the minimum value stipulated in Water Quality Standards for Fisheries of China (Table 3.15), among which fish asphyxia occurred in Treatments B and C. The DO in Treatments E and F was always above 3.5 mg/L,

Table 3.12 Changes of water quality in the later stage of the experiment (from Liu et al. 2000c)

		Date (d/m)										
Treat.	Parameters	2 Sept.	3 Sept.	4 Sept.	5 Sept.	6 Sept.	7 Sept.	8 Sept.	9 Sept.	10 Sept.	11 Sept.	14 Sept.
A	DO	4.38	4.87	4.31	4.56	4.67	4.02	3.25	3.25	2.85	3.30	
	SD	52	50	47	50	37	38	42	47	40	37	
	TAN			0.017					0.002			0.014
	COD								2.96			3.52
B	DO	3.78	4.26	3.91	3.76	4.36	3.82	3.19	3.31	3.47	3.38	
	SD	30	33	31	30	30	32	27	30	30	30	
	TAN			0.017					0.052			0.060
	COD								3.01			3.58
C	DO	3.54	5.19	4.02	4.51	4.07	2.39	2.94	2.77	2.58	2.84	2.84
	SD	32	28	22	25	25	27	17	20	20	20	20
	TAN			0.013					0.047			0.042
	COD								4.71			5.68
D	DO	4.73	4.73	3.88	4.13	4.11	2.67	3.19	3.29	2.98	2.89	2.89
	SD	28	28	18	22	23	28	25	30	23	27	27
	TAN			0.047					0.098			0.077
	COD								4.92			5.78
E	DO	3.44	4.04	4.03	4.21	4.60	3.59	1.31	1.45	1.26	1.23	1.23
	SD	20	15	15	15	17	17	20	17	13	17	17
	TAN			0.045					0.079			0.120
	COD								5.98			6.31

Note: *COD* chemical oxygen demand (mg/L), *DO* dissolve oxygen (mg/L), *SD* transparency (cm), *TAN* total ammonia N (mg/L)

Table 3.13 Economic efficiencies in each treatment (CNY/hm^2) (from Liu et al. 2000c)

Treatments	Costs	Shrimp yield values	Total output values	Net profits	Output/ input
A	14,678	24,746	27,146	12,469	1.75
B	30,399	52,335	55,934	25,535	1.84
C	35,321	57,140	63,882	28,561	1.71
D	45,642	87,330	96,234	50,592	2.11
E	55,964	69,260	79,665	23,701	1.41

Table 3.14 Comparison of aquaculture benefits among different treatments (from Liu et al. 2000c)

Treatments	Absolute *SI*	Relative *SI*	Relative profits (%)	Absolute *CI*	Relative *CI*
A	15.5	100	100	48.0	100
B	18.2	118	205	63.2	132
C	18.2	118	229	67.2	140
D	20.3	131	406	78.6	164
E	17.5	113	190	66.4	139

Note: *CI* is synthetic efficiency index, *SI* is biological synthesis index

Table 3.15 Comparison of the extreme values of the water quality parameters in each treatment and water quality standards (Li et al. 1994)

Parameters	Maximum or minimum						The standards	EFS
	A	B	C	D	E	F		
pH	7.7–8.6	7.0–8.4	7.1–8.6	7.1–8.5	7.3–8.6	7.4–8.6	6.5–8.5	
DO (mg/L)	4.3	0.2	0.8	2.9	3.7	4.1	>3.0	B, C, D
COD (mg/L)	4.15	7.14	5.84	4.22	4.04	3.81	<15	
UIA (μg/ L)	8.7	36.9	28.4	16.6	14.4	17.0	<20	B, C
BOD (mg/L)	3.52	8.86	4.00	3.20	2.40	1.76	<5.0	B

Note: *EFS* means enclosures failing to meet the Water Quality Standard for Fisheries of China

and the time of above 5 mg/L lasted more than 16 h/day, implying that these two treatments is in line with the standards.

There was a positive correlation between the concentration of un-ionic ammonia (UIA) and the fish load. UIA concentration in Treatments B and C exceeds 20 μg/L stipulated in the standard. The biochemical oxygen demand (BOD) varied from 1.76 to 8.86 mg/L, and only treatment B exceeded the standard.

Comparison of the measured extreme values and the values of the standard at the end of the experiment are shown in Table 3.15. As can be seen from the table, Treatments B–D are overload, while Treatments E and F meet the standard. The fish load of Treatment E is higher than that of Treatment F. Therefore, from the perspective of water quality and fish load, Treatment E can represent the physical carrying capacity of fed common carp in the reservoir, i.e., 3096 kg/hm^2.

To evaluate the aquaculture benefits, a biological synthesis index (*SI*) is used and defined as:

$$SI = (Yn \times \Delta W \times K)^{1/3}$$

where Yn is net yield of a treatment (g); ΔW is average weight gain (g/ind.); K is feed conversion efficiency (%). *SI* values of Treatments F and E are 88.7 and 80.3, respectively. From the perspective of *SI*, Treatment F is better than E. Therefore, the fish yield (standing crop at harvest) of Treatment F, i.e., 2594 kg/hm^2, is the production carrying capacity of the reservoir.

3.4.3 Carrying Capacity of Kelp in Bays

Kelp (*Saccharina japonica*) is a large brown alga widely cultivated in China. In general, carrying capacity of aquatic plants is mainly restricted by inorganic nutrient supply and water temperature. Since 1990s, the growth of kelp in Sanggou Bay, Shandong Province, began to slow down because of lack of dissolved inorganic nitrogen (DIN) in the water. Therefore, the carrying capacity or optimal cultivation density of kelp in Sanggou Bay was evaluated based on a multi-species culture ecosystem model by altering the kelp culture density (Shi et al. 2010).

The DIN in Sanggou Bay is derived from the metabolism of various organisms, the mineralization of organic matter, and the supplement from the open sea. When bivalve excretion and DIN release from sediment are invariable, the replenishment of DIN from the open sea become the main factor controlling the growth of kelp. The density of kelp culture is related to the frictions of the aquaculture facilities and kelp body, and will affect the supplement of the nutrients from open sea, thus inhibits the growth of kelp itself.

The hydrodynamic part of the model used to evaluate the carrying capacity of kelp is based on the POM (Princeton Ocean Model) with the addition of the influence of farming activities. The real flow field of Sanggou Bay as a typical aquaculture area was simulated by parameterizing the frictions of aquaculture facilities on sea surface and kelp in water, respectively. The ecological part of the model includes four state variables: kelp, phytoplankton, DIN, and organic particulate matter in water.

Duration of kelp cultivation in Sanggou Bay is from November to next May. The results of the model after 1 year of operation are taken as the initial field of the final model, and the growth and final yield of the kelp under the actual cultivation density are obtained by continuing to run for 1 year. By changing kelp culture density in the model, the growth and yield of kelp under different culture densities are obtained, and then the optimal culture density, namely carrying capacity, is discussed.

Table 3.16 Currents, nutrient from the open sea and kelp production at different kelp culture densities (Shi et al. 2010)

	Current velocity		DIN supply from the open sea		Kelp production (dry weight)	
Densities	cm/s	Variation (%)	t N	Variation (%)	10^4 t	Variation (10^4 t)
1.0-fold	10.80	0	589.2	0	7.01	0
0.8-fold	12.13	+12.3	721.7	+23	6.76	−0.25
0.9-fold	11.42	+5.8	661.1	+12	7.21	+0.20
1.1-fold	10.26	−5.0	555.2	−6	7.08	+0.07
1.2-fold	9.78	−9.5	510.1	−13	6.90	−0.21
1.5-fold	8.61	−20.3	397.9	−32	6.39	−0.62

The current culture density is set as the standard density (1.0 fold), and the friction changes of aquaculture facilities on sea surface and kelp in water are calculated under the current density of 0.8, 0.9, 1.1, 1.2, and 1.5 fold. When kelp culture density increases from 0.8 to 1.5 fold of the standard density, the average current velocity of kelp culture area decreases from 12.13 to 8.61 cm/s, and the DIN supply from the open sea decrease from 721.7 to 397.9 t (Table 3.16). When the culture densities are 0.8, 0.9, 1.1, 1.2, and 1.5 folds of the standard density, the DIN supply from open sea are 1.23, 1.12, 0.94, 0.87, and 0.68 folds of the standard culture density, respectively.

The results of the calculation show that when kelp culture density is 1.5-fold of the current culture density, the production of kelp is only 63,900 t dry weight. When culture density is reduced to 0.8 fold of the current culture density, the production is 67,600 t, although the nutrient supply from the open sea is sufficient. When culture density is 0.9 fold of the current culture density, the production is 72,100 t, the greatest among all treatments. This value can be regarded as the carrying capacity of the kelp in Sanggou Bay.

3.4.4 Carrying Capacity of Bivalve Aquaculture

Filter-feeding bivalve aquaculture is common in both the developing and developed countries. The bivalve can directly filter phytoplankton in water, so it is also called extractive species (Chopin et al. 2001). For managing bivalve aquaculture in the natural environment, tools are needed to estimate the different types of carrying capacity and to identify the optimal production level in relation to management goals of a given area. Farmed bivalve in high density needs to filter large amounts of water each day, resulting in the reduction of phytoplankton and water turbidity, and increment of metabolic waste and biogenic deposit. However, under the condition of limited inorganic nutrients in water, the nutrients (metabolic waste) excreted by the bivalve can stimulate the increments of the productivity and availability of phytoplankton to the bivalve. The indicators and models as tools can clarify the interaction between bivalve aquaculture and the ecosystem, and their relevance for decisions on how to manage carrying capacity.

The indicators of bivalve carrying capacity should address the positive and negative impacts of bivalve aquaculture for the production and ecological carrying capacity. An indicator can be used as a parameter to establish the value of a variable or a set of parameters with a specific meaning, often called an index; an index is a calculation based on a set of variables that can be used for comparative analysis. There are four kinds of indicators for evaluating carrying capacity in bivalve aquaculture, i.e., pelagic, benthic, production performance, and socio-economic indicators (Cranford et al. 2012). Pelagic indicators address the influence of bivalve suspended and bottom culture farms; for the pelagic system, the interaction between the bivalves and their food is the most important determinant of both the production carrying capacity and ecological carrying capacity. Benthic indicators address the impact of suspended culture on the benthic habitat, comprising the effect of organic enrichment of the sediment and the consequences for the benthic community. Benthic indicators predominantly describe impacts at farm scale rather than bay scale, while pelagic indicators tend to be more relevant at bay scale. Production indicators, like bivalve condition indices and yield, address the effectiveness of the culture practice in the given environment and provide a tool to evaluate culture measures. Socio-economic indicators refer to the social acceptability of the bivalve culture, the supply availability to the market, the livelihood security for the local communities, and the economic efficiency of bivalve culture operations. These indices and indicators can be used to address the effects of bivalve aquaculture on the social carrying capacity.

Dame and Prins (1998) define bivalve carrying capacity as the total bivalve biomass supported by a given ecosystem as a function of the water residence time, primary production time, and bivalve clearance time. The carrying capacity for bivalve exploitation depends primarily on the availability of food—through transport and primary production—in relation to filter feeding capacities.

There are two important indicators for bivalve culture, clearance ratio (*CR*), and grazing ratio (*GR*) (Smaal and van Duren 2019). $CR = CT/RT$, where *CT* is the clearance time for the bivalve to filter the water body in a given area; *RT* is water residence time. $GR = CT/PT$, where *PT* is primary production time to renew the phytoplankton stock in a given area. If $CR > 1$, then the water renewal time is shorter than the bivalve clearance time, hence the system is relatively open and the bivalves have little control over the ecosystem. When $CR < 1$, bivalves filter the water column faster than this water is renewed, hence the bivalves potentially control pelagic processes through their grazing activity. When $GR > 1$, primary production exceeds bivalve filtration capacity, hence food is produced faster than consumed. When $GR < 1$ the system will collapse as food is depleted. If the grazing ratio is just above 1, the system will be unstable as depletion due to daily variation in primary production may occur.

Similarly, Gibbs (2007) established three indicators to evaluate the carrying capacity of filter-feeding bivalves, namely, clearance efficiency (*CE*), filtration pressure (*FP*), and regulation ratio (*RR*). *CE* ($= RT/CT$) gives a measure of how effectively the bivalves can process the water in the inlet by comparison to the flushing of the inlet. $FP = BF/PP$, where *BF* is the total carbon extracted from the

Table 3.17 Evaluation results of food limited indicators in Zhangzidao mariculture area (Zhang et al. 2008)

Indicators and indices	Average
Days it takes for the water in the area to be flushed (*RT*, d)	8.45
Days it takes bivalves to process all the water (*CT*, d)	221
Total carbon extracted from the water column by bivalve culture each year (*BF*, t)	87,466
Total carbon fixed by phytoplankton in the area each year (*PP*, t)	279,730
Ratio of daily volume of water cleared by the bivalves to the total volume of water in the area (*TC*)	0.005 5
Phytoplankton turnover rate (*PT*)	0.037
Food limited indicator:Clearance efficiency ($CE = RT/CT$)	0.048
Food limited indicator:Filtration pressure ($FP = BF/PP$)	0.31
Food limited indicator:Regulation ratio ($RR = TC/PT$)	0.16

water column by the bivalve culture every year. *FP* gives an indicator of the resource requirement of the bivalve culture by comparison with the total resources generated within the bay. *PP* is the total carbon fixed by autotrophs (principally phytoplankton) in the bay each year. $RR = TC/TP$, where *TP* is the phytoplankton turnover rate and is calculated from the ratio of the daily mean phytoplankton production (gC/(m^3·d) to the daily mean phytoplankton concentration (gC/m^3). Similarly, *TC* is the ratio of the daily volume of water cleared by the bivalves to the total volume of water in the growing region. This indicator gives a measure of how much control the bivalves have on the algal population within the bay.

Gibbs (2007) suggested that when grazing ratio (*CT/PT*) values are close to 1.0, the culture has reached the production carrying capacity because the pelagic food web has collapsed down into a nutrient–phytoplankton–bivalve loop. Smaal et al. (1998) suggested that the grazing ratio threshold for ecological carrying capacity should be above 3. The clearance efficiency (*RT/CT*) values below 0.05 indicate that the culture will not be able to significantly impact pelagic functioning, thereby meeting the definition of ecological carrying capacity (Gibbs 2007).

Zhang et al. (2008) evaluated the carrying capacity of scallop (*Patinopecten yessoensis*) in Zhangzidao sea area, Liaoning Province, China, using the above indicators. The aquaculture area of Zhangzidao was 33,300 hm^2, and the scallop yield was 49,890 t in 2010. Because the clearance efficiency (*CE*), filtration pressure (*FP*), and regulation ratio (*RR*) were all less than 1.0 (Table 3.17), the standing crop of scallop in the area had not reached its production carrying capacity. The values of *FP* and *RR* were between 0.05 and 1.0, which indicated that the standing crop of scallop in Zhangzidao sea area could control the dynamic changes of phytoplankton.

Smaal and van Duren (2019) analyzed the clearance ratio (*CR*) of bivalves in 20 water bodies around the world and found that the Log*CR* value of 12 water bodies was greater than 0, indicating that the clearance time (*CT*) of these water bodies was longer than the water residence time (*RT*), and the Log*CR* value of the remaining 8 water bodies was less than 0, i.e., the *CT* was shorter than the *RT*. Log*CR* values less than 0 indicate that the bivalves potentially control pelagic processes in these areas. Aad et al. (2019) analyzed the grazing ratio (*GR*) of bivalves in 11 water bodies, in which *CT* were shorter than *RT*, and found that *GR* of these areas range from less than 1 to more than 11, implying that their local primary production was the main factor determining carrying capacity in these areas.

There are many specific and general models for evaluating carrying capacity of aquaculture, and the choice of model depends on the purpose. Some questions do not require very elaborate modelling. To get a first order impression of whether a system is approaching carrying capacity for bivalve, relatively simple models that include data on grazing rates, primary production rates, and retention times will suffice. Other questions regarding optimal locations and optimal spacing of bivalve farms need much more explicit detail on transport of nutrients, algae, and other constituents and therefore at the very least need a well-validated hydrodynamic model as a basis.

3.4.5 Carrying Capacity Evaluation by Nutrient Loading Models

For small aquaculture waters such as ponds, water quality is the main factor restricting the growth and yield of farmed animals, while for large aquaculture waters, people often pay more attention to the environmental effects of aquaculture activity. Phytoplankton densities are negatively correlated with water quality, the growth, and survival of fish stocks in general. Phosphorus (*P*) is the limiting nutrient for phytoplankton in most lakes and reservoirs.

Based on the nutrient loading models, the carrying capacity of fed species in large inland waters can also be evaluated. Taking phosphorus (*P*) as the most important factor limiting fish productivity, the following models were used by Beveridge (1984) and Dillon and Rigler (1974) to calculate the desired or allowable aquaculture production (Q, t/year)

$$Q = P_{\mathrm{mac}} / P_{\mathrm{food}}$$

where P_{mac} is the maximum acceptable P load (t/year) and P_{food} is the P load (kg/kg) lost to water by aquaculture.

P_{mac} can be obtained by the following model

$$P_{\mathrm{mac}} = (P_{\mathrm{max}} - P_0) \times H \times A \times r[1/(1 - R)]$$

where P_{max} is the maximum allowable P concentration in water (mg/L); P_0 is the background P concentration (prior to exploitation) in water (mg/L); H is the mean water depth (m); A is the surface area of aquaculture waters (m^2); r is annual water exchange rate; and R is the retention fraction of P by the sediments.

P_{food} can be obtained by the following models

$$
\begin{aligned}
&Q_{(x)} = k \cdot x = \sum k_i \cdot x_i \ (i = 1,2,3)\\
&k_i = (p_1 + p_2 - p_f)(h \cdot w)\\
&p_1 = p_m / b\\
&p_2 = F \times p_F\\
&k_1 = (p_m / b + F \times p_F - p_f)/(h \cdot w)\\
&P_{\text{food}} = \{\sum [(p_m / b + F \times p_F - p_f)/(h \cdot w)] \cdot x_i\}/x
\end{aligned}
$$

where $Q_{(x)}$ is total P load (kg) of fish farming; k is the P load of fish (kg/kg); x is the total fish production (t); x_i is the production of a certain farming species (t); k_i is the P load of a certain farming species (kg/kg); p_1 is the P content of stocking fingerlings (kg/kg); p_2 is the P content of feeds (kg/kg); p_f is the P content of fish captured (kg/kg); h is the survival rate of farmed fish (%); w is the capture rate (%); p_m is the P content of stocking fingerlings (%); b is the multiple of weight gain; F is the feed coefficient; and p_F is the P content in feeds (%).

Examples for evaluating carrying capacity of fish farming can be found in the book of 'Cage Culture' (Beveridge 2004). Bian et al. (2011) also used this model to calculate the carrying capacity of Baiyangdian Lake, Hebei Province, China. It should be noted that aquaculture of fed fish species is now prohibited in Baiyangdian Lake due to water quality protection. Therefore, the introduction of the above researches is only to provide readers with a method to evaluate the carrying capacity of large waters based on the environmental carrying capacity.

In addition to carrying out aquaculture, some public natural waters also have functions of irrigation, flood control, tourism, fishery, power generation and so on. Therefore, the determination of carrying capacity of the waters should also consider the needs of other stakeholders. In Brazil, for instance, where aquaculture has grown very rapidly over the past decades, environmental permitting of new tilapia farms in reservoirs is determined through the application of the Dillon and Rigler (1974) phosphorus loading model. A maximum limit of 30 mg/L of P has been established for reservoir, 5 mg/L of which is reserved for fish farming, to allow for multiple uses including cattle ranching, sugar cane production, urban discharges, and the natural background. Fish farms are licensed sequentially, based on the contribution to P loading of their declared production (Ferreira et al. 2013).

As mentioned earlier, there are four levels of carrying capacity of aquaculture, and a great deal of research has been done on the first three levels. However, the most important matter to know for practical purposes is the social carrying capacity. A lot of our work is down to the last mile, and the participation of social scientists is very important for us to complete this last mile!

3.4.6 Models of Carrying Capacity Evaluation

Models are especially useful in carrying capacity studies since they can define ecological thresholds and indicators, and run simulations to depict hypothetical scenarios related to different levels of production or environmental conditions. Models are simplified representations of the variables, relationships, and processes in the environment. Carrying capacity models for aquaculture range from simple mathematical expressions to farm-scale models of production, to complex processes involving multiple interactions at the ecosystem scale. While models must be carefully validated through case studies and trials, models are particularly relevant since they allow decision makers to determine thresholds and test the limits of production without needing to manipulate the real environment (Weitzman and Filgueira 2020).

The least complex models are static mathematical expressions that depict simple relationships between cultured organisms and the surrounding environment, such as the MEI (Ryder 1982), the clearance ratio (Dame and Prins 1998), and regulation ratio (Gibbs 2007). Other mathematical models include simple energy budget models that reflect production characteristics and focus on growth in relation to food supplies and consumption patterns at the individual and farm scale (e.g., Cui and Li 2005; Grant and Bacher 1998). This category of models also includes widely used growth functions such as the thermal-unit growth coefficient (TGC) often applied to production of pond aquaculture (Jobling 2003). Despite their wide application, indices and simple growth models have limited relevance since they do not provide information on spatial or temporal variability.

The dynamic nature of the ecosystems in which aquaculture is embedded has driven to the development of dynamic models at both the farm and wider ecosystem scales. Farm-scale models are often concerned with individual growth and production carrying capacity. Bioenergetic models have been well developed to predict individual growth of cultured species based on food supplies, following either the empirical scope for growth approach or more mechanistic dynamic energy budget (DEB) approach (Kooijman 2010).

These farm-scale models often include a hydrodynamic submodel to account for the effects of water circulation on food supplies (Ferreira et al. 2007). While most farm-scale models are concerned with production carrying capacity, several depositional models have been applied to estimate ecological carrying capacity at the local scale. Depositional models have been applied consistently to predict the fate of organic materials from culture sites to the benthos and, consequently, to explore benthic impacts (see Chap. 13 for detail). These include the finfish waste model DEPOMOD and shellfish DEPOMOD (Cromey et al. 2002; Weise et al. 2009).

To manage increasingly complex interactions of cultured species and their aquatic environments, modelling the interrelations of multiple processes over wider regional or ecosystem scale has become increasingly common. For example, the popular EcoPath with Ecosim has been used to calculate the energy transfer between cultured organisms and other trophic levels (Byron et al. 2011). In freshwater environments, phosphorous budget models such as the one proposed by Dillon and Rigler (1974) have been applied to predict the impact of aquaculture on water quality and estimate ecological carrying capacity (Buyukcapar and Alp 2006). EcoPath with Ecosim and budgets lack spatial resolution, neglecting spatial variability within the model domain, which has been criticized. New developments such as Ecospace, a spatial and temporal dynamic module for EcoPath, could overcome these limitations.

In general, ecosystem models can be differentiated based on their spatial resolution into simple box models, which divide the study area into few large homogeneous areas, or fully spatial models, which divide the area into hundreds or thousands of separate areas. Fully spatial models are considered desirable to inform site selection and marine spatial planning since they can more accurately describe complex hydrographic patterns (DFO 2015). The fine-scale resolution of fully spatial models is particularly important since it enables the investigation of both local- and ecosystem-scale effects, and the feedbacks between cultured species and their environment (Guyondet et al. 2010).

In recent years, bioenergetic models such as DEB models have been coupled with biogeochemical and hydrodynamic models to predict the interactions and feedbacks between the cultured species and wider ecosystem-scale dynamics (Dabrowski et al. 2013). Coupling individual growth models to ecosystem functioning and hydrodynamics can help estimate optimum production yield and predict the impacts of aquaculture on the wider ecosystem (Dowd 1997, 2005).

Brief Summary

1. The productivity of aquaculture waters is the ability or performance of aquaculture waters to produce commercial aquatic products and can be expressed as productivity potential, maximum daily gain, and actual productivity. The productivity potential of an aquaculture waters refers to the production under the conditions of optimal stocking density and zero mortality of farmed organisms. In the process of aquaculture, the standing crop or biomass of the farmed organism in the water changes like a S-shaped curve, at the inflection point, the growth rate or daily weight gain of individual or stock reaches the maximum. The actual productivity refers to as the maximum economic net yield.
2. Productivity of aquaculture waters is an attribute of aquaculture ecosystem itself, which is determined by various objective factors such as environmental conditions of the waters, but it is also affected by farmed species and farming models.
3. There are kinds of methods to evaluate the productivity of aquaculture waters: one is based on the reductionism and the other is based on the holism. The reductionism approaches usually calculate the productivity of a specific aquaculture waters based on the natural food quantity, food conversion efficiency, and some influencing factors; while the holism approaches, on the other hand, estimate the productivity according to the growth status of farmed organisms or the statistical correlativity between influencing factors and the productivity. Both the approaches have their own advantages and complementary characteristics, so they are used in combination to better estimate the productivity of aquaculture waters sometimes.
4. Carrying capacity of aquaculture of a given waters is the optimum standing crop or stocking quantity of farming organisms that meets the requirements of all stakeholders, especially environmental protection requirements. Aquaculture

productivity basically describes the natural attribute of the waters, while carrying capacity of aquaculture is the social value of the aquaculture waters.

5. The carrying capacity of aquaculture is not only affected by the ecological characteristics of farmed species, but also by the physical, ecological, economic, and social conditions of the waters. Physical carrying capacity is the maximum stocking density or optimum standing crop of a given species using a given method that can be supported by physical space and conditions; production carrying capacity is the stocking density or optimum standing crop of farmed species at which harvests are maximized; ecological carrying capacity is the stocking or farming density above which unacceptable ecological impacts become apparent; social carrying capacity is the level of farm development above which unacceptable social impacts are manifested.
6. There are two important indicators for bivalve culture, clearance ratio (CR) and grazing ratio (GR). $CR = CT/RT$, where CT is clearance time for the bivalve to filter the water body in a given area; RT is water residence time. $GR = CT/PT$, where PT is primary production time to renew the phytoplankton stock in a given area. If $CR > 1$, then the water renewal time is shorter than the bivalve clearance time, hence the system is relatively open and the bivalves have little control over the ecosystem. When $CR < 1$, bivalves filter the water column faster than this water is renewed, hence the bivalves potentially control pelagic processes through their grazing activity. When $GR > 1$, primary production exceeds bivalve filtration capacity, hence food is produced faster than consumed. When $GR < 1$, the system will collapse as food is depleted. If the grazing ratio is just above 1, the system will be unstable as depletion due to daily variation in primary production may occur.
7. Models are especially useful in carrying capacity studies since they can define ecological thresholds and indicators, and run simulations to depict hypothetical scenarios related to different levels of production or environmental conditions. The least complex models are static mathematical expressions that depict simple relationships between cultured organisms and the surrounding environment, such as the MEI, the clearance ratio, regulation ratio, and energy budget models. Despite their wide application, indices and simple growth models have limited relevance since they do not provide information on spatial or temporal variability. In recent years, bioenergetic models such as DEB models have been coupled with biogeochemical and hydrodynamic models to predict the interactions and feedbacks between cultured species and wider ecosystem-scale dynamics. Coupling individual growth models to ecosystem functioning and hydrodynamics can help estimate optimum production yield and predict the impacts of aquaculture on the wider ecosystem.

4

Interactions Between Aquaculture and Environment

Shuang-Lin Dong and Qin-Feng Gao

Humans have been engaged in aquaculture for 8000 of years. Because of limited scale, aquaculture activities as a whole do not expose significant impacts on surrounding environment in most of the aquaculture history. Since 1970s, the increasing adoption of artificial pelletized feed, modern fish cages, and aerators have promoted the rapid expansion and intensification of aquaculture in the world. Nowadays, the situations that the environmental consequences derived from aquaculture have threatened the sustainable development of aquaculture itself have been widely perceived and accepted by human beings. As such, scientific and technological measures must be taken to reverse such situations.

Interactive relationships exist between aquaculture activities and environment. On the one hand, the impacts of anthropogenic activities on aquatic ecosystems and in turn on aquaculture are increasingly intensified as a result of the economic and social development; on the other hand, aquaculture activities also affect the environment. In other words, aquaculture is not only injurer and also sufferer of environmental deterioration. In addition, the environmental effects due to different aquaculture practices cannot be generalized. Waste discharge from fish farming with feed supply, for example, leads to enhanced eutrophication while seaweed cultivation absorbs nutrients from surrounding water and hence avoid or mitigate eutrophication.

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Table 4.1 Generalized characteristics and trends among fishes characterized according to temperature range and salinity range (from Tidwell 2012)

Ecological type	Dissolved oxygen requirement	Ammonia tolerance	Protein requirement
Coldwater	> 5 mg/L	Low	High
Warmwater	> 2 mg/L	Moderate	Moderate
Tropical	> 1 mg/L	High	Low
Marine	Higher		Higher
Freshwater	Lower		Lower

4.1 Requirements of Water Quality for Aquaculture

Aquaculture is the activities of FOOD production using water as medium for the survival of aquaculture organisms. As such, water quality with guaranteed standard in terms of cleanliness and sanitation is the obligate requirement for aquaculture, and water quality is one of the decisive factors to the aquaculture profit. In order to prevent and control the pollution of fisheries waters, and to ensure the normal growth, reproduction and product quality of cultured fish, shrimp, shellfish, and seaweeds, obligate water quality standards for fisheries have been widely legislated in numerous countries (see Chap. 13).

Requirements of aquatic organisms inhabiting in cold, flowing or salty waters for water quality are generally stricter compared with those living in warm, static or fresh waters (Table 4.1). For aquaculture waters, physiochemical factors such as temperature, transparency, dissolved oxygen, salinity, pH value, un-ionic ammonia, nitrate, nitrite, and hydrogen sulfide are particularly important for the survival and growth of farmed aquatic animals. Introduction on these physiochemical factors is summarized in Chap. 2, and refer to Boyd and Tucker (1998) and Lei (2004) for more details.

4.2 Effects of Exogenous Pollutants on Aquaculture

Aquaculture production requires unpolluted clean water and thus its development is inevitably influenced by agriculture, industry, and urban sewage. Although aquaculture waters possess the self-purification capacity to some extent in terms of biological, chemical, and physical aspects, water is polluted when the pollutant loading exceeds such capacity. Results of investigation on the interaction between mariculture and the environment carried out by the International Council for the Exploration of the Sea (ICES) in the 1980s indicate that dominant pollutants affecting mariculture and nearshore marine environment include domestic sewage, fertilizers, pesticides, oil, heavy metals, and sometimes occurred harmful algal blooming (HAB) (Dong et al. 2000b).

4.2.1 Nutrients Derived from Agriculture and Sewage Discharge

Considerable quantities of the nutrients loaded to coastal areas are from activities of urbanization, industrialization, and agricultural development. In Mexico, the N and P loads in coastal water derived from agriculture are 74% and 68%, respectively (Páez-Osuna et al. 1998). In Sweden, the loads of N and P from agriculture are 40% and 25% (not including atmospheric deposition), respectively (Ackefors and Enell 1990). The nutrients from agriculture source in developing countries may be greater than those from other sources in developed countries.

According to *Bulletin on Marine Ecological and Environment Status of China 2018*, marine ecology and environment of China has shown increasingly steady trends with overall improvement in the quality of marine environment. The marine area conforming to the class I standard of seawater quality accounts for 96.3% of the total areas under jurisdiction. Water quality at 74.6% of the total monitoring stations, or 6.7% year-on-year increase, is superior or good. The polluted sea areas are mainly distributed in Liaodong Bay, Bohai Bay, Laizhou Bay, Jiangsu coast, Yangtze River Estuary, Hangzhou Bay, Zhejiang coast, and other coastal waters with the main overproof parameters of inorganic nitrogen and soluble reactive phosphate.

In marine and estuarine waters, N, and to lesser extent Si, level control phytoplankton growth, however, N/P and N/Si ratios affect species composition. There has been an apparent declining trend in input for P in the counties around the North Sea, which results in a significant change of ecological characteristics from N limitation to present situation of marked P limitation (ICES 1993).

Nutrient accumulation due to anthropogenic activities enhances the process of eutrophication, which is highlighted by increase in productivity and biomass as well as shift in species composition of phytoplankton, frequent occurrence of harmful red tides, changes in benthic algal and faunal communities, and changes in oxygen consumption of water column and sediment.

Nutrient accumulation and eutrophication expose significant influence on mariculture. Elevated nitrogen inputs derived from anthropogenic activities stimulate excessive growth of algae, cause the miniaturization of phytoplankton, and drive the change in food webs toward the systems dominated by microbial food loops. Such kinds of changes are detrimental to aquaculture production such as more frequent disease outbreaks due to the water quality deterioration.

4.2.2 Harmful Algal Blooming

As phytoplanktons are the important food sources of filter-feeding bivalve and other commercial species including larvae of fish, shrimp, and crab, moderate proliferation of phytoplankton is generally beneficial to mariculture and capture fisheries. Excessive blooming of phytoplankton causes economic losses, even threatens human health under some circumstances. Such kind of algal blooming is also known as harmful algal blooming (HAB) or (harmful) red tide. Algae which potentially form HAB include about 300 species, of which about 40 species might generate potent toxins and ultimately affect human health as the result of food chain transfer. The red tide outbreak due to the excessive growth of *Pseudochattonella* and *Karenia* in Chile in 2016, for example, led to the mass mortality of 40,000 tons of salmon, and several salmon, mussel, and abalone farms were closed for avoiding food safety risk resulting in a total of $800 million economic loss (Diaz et al. 2019).

HABs generally affect the mariculture production and human health through three ways, including massive dissolved oxygen consumption, production of toxins, and damage to fish gills. Oxygen consumption by red tide is mainly caused by respiration of algae at night or dark time, but more commonly caused by the respiration of bacteria, which greatly thrive following the collapse of algal blooming.

With the development of mariculture industry, damages to fish gills caused by HAB are increasingly noticed. Some algal species cause direct mechanical damage to fish gills. Wild fish can actively avoid HAB while the fish cultured within cages are unable to escape from HAB waters. HAB of *Chattonella antiqua* which occurred in the Seto Inland Sea of Japan in 1972, for example, resulted in the mass mortality of cage farmed yellowtail with $500 million economic loss (Hallegraeff 1995). The long hollow spines (setae) and smaller barbs of diatoms *Chaetoceros convolutus* and *C. concavicorne* can break off and penetrate the gill membranes of salmons and kill them through capillary hemorrhage, dysfunction of gas exchange at the gills, suffocation from an overproduction of mucus, or even from secondary infection of the damaged tissue. Large-scale HAB which broke out in Europe from May to June 1988 covered a total area of 60,000 km^2 with algal density of 10^7 cells/L. The *heterosigma* HAB which occurred in Big Glory Bay, New Zealand, caused massive death of cage-farmed salmon *Oncorhynchus tshawytscha* (Walbaum 1792), and the total economic loss reached more than $NZ 17 million.

Several methods are developed to ovoid or mitigate harmful algal blooms, such as careful site selection, harmful algal blooms and fish health monitoring, aeration, air-lift pumping of deep water into cadges, submerging cadges, therapeutics, water treatment, and so on. During 1988 *Chrysochromulina* bloom, more than 26,000 ton of fish in 1800 cages thus moved from their permanent site into inland fjords (Hallegraeff 1995).

4.2.3 Oil Pollution

Artificial activities introduce large amount of oil into sea through oil platforms, oil industries and accidents, etc. The oil can affect the ecosystems in several ways, depending on the type of oil and how it occurs in the marine environment, e.g., attached to sediment particles, dissolved or dispersed in the water, or as slicks on the surface.

In the 1980s, serious oil pollution in the North Sea and the Gulf of Mexico led to overproof oil concentration in substantial marine organisms (Páez-Osuna et al. 1998). Oil dissolved in seawater causes odor of farmed animals, and slows the growth and respiration of mussels. Swimming activities of goby are weakened and the mortality rates are increased when oil concentration reaches 0.3–1.2 μg/L.

Abnormalities in metamorphosis of codfish juveniles are observed when oil concentration is less than 50 μg/L (ICES 1993).

4.2.4 Heavy Metals

In the 1980s and 1990s, the mercury concentrations of marine organisms in some countries are too high to be edible (ICES 1993; Rensel 1995). Like some of other heavy metals, mercury is not only a direct hazard to marine life, but can also be biologically magnified along food chains. Fish are exposed in the water with mercury level of 0.0024 mg/L for 23 days, the contents of mercury in fish muscle reach as high as 3.38 mg/L. Mercury accumulation in fish tissue increases with ages and body weights. Effects of mercury on organisms depend not only on its concentration, but also on the chemical forms of mercury and the nature of the organisms themselves. Inorganic mercury such as mercuric chloride can be converted to more toxic methylmercury by microorganisms on the fish surface and such conversion is more rapid under anoxic conditions. The 96-h half-lethal concentration (LC_{50}) of phenylmercury acetate for silver carp, and that of ethylmercury chloride for silver carp, and for red carp are 0.05, 0.04, and 0.05 mg/L, respectively.

Cadmium is predominantly accumulated in the kidney and liver of higher animals. It can damage animals when cadmium levels exceed 13–15 mg/kg in wet biomass. The 96-h LC_{50} of cadmium sulfate for silver carp is 2.77 mg/L and for red carp is 2.27 mg/L; the 42-d LC_{50} concentration for rainbow trout is as low as 0.006 mg/L. Cadmium-poisoned fish appear various symptoms, such as necrosis of gill and epidermal cells, damage in the mucosa of the intestinal wall and renal tubules, alteration in blood composition, decrease in cholinesterase activity, effects on neuromuscular ganglia, and ultimate metamorphosis.

Lead can be highly enriched in the tissues of fish and shellfish and hence results in damage to their predators, including humans. Lead compounds are not readily soluble in natural water, and therefore lead is dissolved in natural water in very low level. Generally, lead concentration in freshwater ranges between 0.06 and 120 μg/L with average of 3 μg/L, while the average level of lead in seawater is about 0.03 μg/L. High concentration of lead induces malformation of loach hemoglobin and oocytes, destroys the normal growth of hemoglobin and oocytes, reduces the survival rate of cells, affects the normal physiological and reproductive functions of loach, and increases estrogenic hormone activity.

The ionic component of dissolved copper of 0.1–0.2 μmol/L in seawater exerts inhibition to the growth of phytoplankton and bacteria. The combination of a part of dissolved copper with dissolved organic carbon which naturally exists in seawater might mitigate its effects on organisms. Copper results in the reduction of erythrocyte and leukocyte even subsequent mortality of fish. For example, exposure in 5 mg/L copper sulfate, the lethal durations for yarrow fish (*Leuciscus*) and for red-eye trout (*Squaliobarbus curriculus*) are 22 h and 36 h, respectively. Most fertilized eggs of Chinese shrimp fail to hatch when the copper ion concentration is as high as 13.2 μg/L. At 8.0 μg/L, activities of nauplius larvae are inhibited and metamorphosis time is prolonged. At 32.2 μg/L, no nauplius larvae metamorphose and most of them die after 2 days.

Zinc is usually present at higher concentration in sea waters with relatively less toxic than other aforementioned heavy metals. Rainbow trout with body weight of 8–12 g exposed in water with 40 mg/L zinc sulfate show typical acute inflammatory reaction such as the production of a large number of granular leukocytes which results in the stagnation of blood circulation in the gill filaments and ultimate mortality due to respiratory failure. When cultured in water with 24.3 mg/L of zinc ions, the hatching rate of Chinese shrimp decreases, nauplius larvae develop abnormally, swimming ability is weakened, and vast majority of larvae cannot finish metamorphosis and die.

4.2.5 Pesticide and TBT

Crustacean and fish are extremely sensitive to organochlorine compounds. Exposure of larval shrimp *Penaeus vannamei* in sublethal concentrations leads to elevated respiration rates and reduced glycogen synthesis (Galindo et al. 1996).

Organic tin, especially in forms of tributyl tin (TBT), is ever widely used for the prevention and removal of fouling organisms in ships or fish-farming cages, resulting in substantial hazards to various organisms. The concentration of TBT over 1 ng/L exerts impacts on zooplankton and phytoplankton. Morphological features of oyster shells appear abnormal under the exposure of TBT over 2 ng/L, and behavior and reproduction of oyster are affected at TBT concentration over 20 ng/L. As for fish, behavior and reproduction are influenced by TBT with the concentration of 1–10 ng/L and 1–100 ng/L, respectively. Contamination of North Sea by TBT was widespread in 1980s; however, the obviously effect was population decline and masculinization of dogwhelks (ICES 1993).

4.3 Negative Effects of Aquaculture on Environment

Aquaculture is not only the sufferer of environmental pollution but also the injurer of environment due to inappropriate aquaculture models or activities. Aquaculture can cause direct or potential hazards to biodiversity, water quality, ecology, health, and resource uses of the aquatic ecosystems (Table 4.2). Brief description regarding environmental threats derived from aquaculture including obstruction of water flow by aquaculture facilities, biodeposition from farmed animals, nutrient and chemical discharges, escape of farmed fish, invasion of exotic species, damage to mangroves, and hazards to biodiversity is presented in this section.

Table 4.2 Environmental threats from aquaculture (from Hai et al. 2018)

Threat	Hazard	Risk
Genetic	Escapes	Fitness issues
	Exotics/GMOs	Genetic contamination; loss of biodiversity
	Wild brood stock	Introgression
	Stock enhancement	Extinction
Water quality	Effluent	Eutrophication; pollution
	Sediments	Habitat loss
Ecology	Land modification	Habitat alteration
	Salinization	Loss of freshwater
	GHG emission	Pollution; climate change
Health	Antibiotics	Resistance
	Chemicals	Pollution; bioaccumulation; toxicity
	Escapes	Disease
Resource use/inputs	Fishmeal	Depletion of wild fish population
	Wild seedstock	
	Water extraction	Water shortage

Note: *GHG* represents greenhouse gas, *GMO* represents genetically modified organism

4.3.1 Obstacle to Water Current and Sedimentation

The obstacle of mariculture facilities to water current and the biodeposition of aquaculture animals impose non-negligible impacts on marine ecosystems. The effects derived from bottom sowing or proliferation of shellfish on water current are not significant, while the impacts of farming rafts for shellfish and seaweeds on water current cannot be ignored. In 2020, 36.0% of the total mariculture productions in China were contributed in form of farming rafts and lantern cages. The scales and densities of mariculture in some sea areas are so high that exert significant influence on the local marine environment. For example, the resistance of scallop-farming rafts in Sanggou Bay (Shandong Province, China) is greater than the stress on the seabed, and the phenomenon of surface seawater rising/setting tide first occurs, which is very different from the general rule of tide. Due to the impact of mariculture facilities, the flow velocity in Sanggou Bay is reduced by 40%, and the average time needed for half of the water exchanged is prolonged by 71% (Shi and Wei 2009).

Mariculture activities also have a significant impact on the flow field of aquaculture waters. For instance, flow rate in mussel-farming areas in New Zealand is reduced by 30% compared with the surrounding areas (Gibbs et al. 1991). Flow rates outside the raft area of shellfish culture in Saldanha Bay, South Africa, are six times higher than those in aquaculture area (Boyd and Heasman 1998).

Large-scale culture of filter-feeding shellfish in semi-enclosed bays generates large amounts of biodeposition and has a marked impact on the substrate. The biodeposition produced by shellfish has an adhesive effect and is able to reduce the erosion of seabed, which can be raised at a speed of 30–50 cm per year (Pillay 1992). In Sanggou Bay (Shandong Province, China), the culture area of scallop

(*Chlamys farreri*) is up to 7500 hm^2, producing about 1.74×10^5 tons of biodeposition each year (Zhou et al. 2003a). Biodeposition in mussel culture areas of Swedish is three times higher than those in nonmussel culture areas (Dahlbäck and Gunnarsson 1981). The biodeposition in the mussel culture areas of Mediterranean is 32.54 mg ash-free dry weight $[g/(m^2{\cdot}d)]$. In Hiroshima Bay (Japan), the culture area of Pacific oyster with a 200 m^2 raft frame produces 19.3 t fecal matter (dry weight) over a 10-month culture period (Arakawa et al. 1971). In shellfish culture area, biodeposition provides nutrients for the benthic community on the bottom of shellfish culture area. However, excessive biodeposition and limited water exchange would lead to hypoxia and increase the concentration of H_2S, which has a negative impact on the benthic community.

The residual feed and feces deposition produced by cage culture can also have an impact on the environment of sediment. The concentrations of organic carbon and sulfide in fish culture areas of Daya Bay (Guangdong Province, China) are 2.82% and 562 mg/kg, respectively, which are significantly higher than those in adjacent sea areas (2.42% and 238 mg/kg, respectively). Moreover, the concentration of dissolved oxygen in the bottom water of culture area is 5.25 mg/L, which is significantly lower than that in the control area (6.48 mg/L) (Huang et al. 2007). The average concentrations of total nitrogen, organic carbon, and organic matter in the sediment of Tangjiawan Bay (Qingdao, Shandong Province, China) are 1.27 mg/L, 1.31%, and 0.76%, respectively, which are also much higher than the concentrations in adjacent sea areas (0.79 mg/L, 0.78%, and 0.45%, respectively) (Jiang et al. 2007b).

Investigation of salmon culture areas in European shows that the fluxes of C, N, and P in sediments are relatively small, with only about 10% of organic matter being decomposed each year. About 79% C, 88% N, and 95% P (equivalent to 23% of the feed input C, 21% of N, and 53% of P) deposited on the bottom sediment are not bio-available, which leads to eutrophication, hypoxia, and lower redox potential, and further causes an increase in reduced compounds (e.g., ammonia, hydrogen sulfide, methane), flourish of sulfur bacteria, and a decrease in macrobenthic biomass and species (Gowen 1992).

The effects of aquaculture activities on environmental organisms are gradually diminished with the increase of distances from culture areas. In the area close to the culture cages, number of macrobenthos decreased and opportunistic species increased, which can be used as a biological indicator for the pollution. There is a transition zone not far from the culture area where benthic growth is stimulated by moderate accumulation of nutrients. When goes further, the benthic biomass, composition, and abundance of benthic fauna drop to the normal levels.

4.3.2 Eutrophication

Both cage and pond culture would discharge wastewater into adjacent water areas when feed or fertilizer is applied, leading to eutrophication and phytoplankton bloom. Feeds cannot be fully consumed by farmed animals in cages or ponds.

Table 4.3 Typical nutrient load from production of selected aquaculture species in ponds and tanks (kg/t; from Hai et al. 2018)

Species	TSS	TN	TP	BOD_5	Carbon
Shrimp	476	15.9	1.46	63.3	730
Trout	289–839	47–87	4.8–18.7	>944	101–565
Salmon	191–606	20.3–39.3	9.1–10	410	226
Tilapia	382	44.95	14.26	10.4	145.6
Pangasius	2050	46–46.8	14.4–26.6	740	305.5
Channel catfish	353	83.6	12.7	25.6	713.5

Table 4.4 The ratios of N and P in total output from different aquaculture systems (%)

Culture patterns		Discharge	Leak	Escape	Harvest	Sediment	References
Semi-intensive	N	7.4	10.6	52.7	24.7	–	Boyd (1985)
	P	6.8	8.3	–	29.7	55.3	
Intensive	N	24.8	–	55.5	19.7	–	Daniels and Body (1989)
	P	4.9	–	–	41.8	53.3	
Semi-intensive	N	17.5	–	1.0	–	65.0	Acosta-Nassar (1994)
Semi-intensive	N	–	5.9–8.9	55.5	–	–	Qi et al. (1998)
	P	–	1.9–3.6	–	–	–	
Intensive	N	8.0–12.0	5.0–7.0	–	19.0	62.0–68.0	Yang et al. (1999)

There is always a portion of feeds that ends up in the substrate or is discharged into adjacent waters. Phosphorus input from feeds usually accounts for 82.6–84.3% of the total phosphorus input to the polyculture systems of grass carp, and phosphorus inputs from runoff, pump water, and stocking organisms are estimated as 4.04–4.12%, 7.81–7.96%, and 3.66–5.55% of the total phosphorus input to the system, respectively (Sun et al. 2015). Phosphorus accumulation in the sediments is the largest proportion of total phosphorus output, ranging from 76.5 to 80.0%. The monoculture system of grass carp has the greatest accumulation of phosphorus in the sediments, and only 6.91% of the phosphorus in feed is yielded in fish. Polyculture of grass carp, silver carp, and common carp is able to utilize 13.5% of the feed phosphorus. Although the phosphorus utilization efficiency is improved in polyculture systems, a significant amount of phosphorus is still remained in the pond system, part of which would be discharged into the adjacent waters during drainage.

N and P loads of aquaculture systems vary among farming species and levels of intensification. The nutrient loads of some aquaculture species are summarized in Table 4.3. As showed, N and P loads are different significantly among species.

In addition, the amount of N and P discharged to the environment varies among aquaculture patterns (Tables 4.4 and 4.5). If feed is provided, cage culture and intensive fish pond system release more N and P into the environment.

Table 4.5 The N and P loading in different culture systems (kg/t) (from Chang 2006)

Culture systems	N	P
Fresh water fish cage	100	23
Sea water fish cage	90	20
Fish pond	68	16
Intensive pond	104	42
Semi-intensive shrimp pond	50	14

N or P loading (kg) in the environment for 1 t aquatic products harvested

As a major aquaculture country, increasing attention is paid to the pollution derived from aquaculture in China. In 2002, 119.8 × 10^8 m^3 wastewater from mariculture was discharged along China's Yellow Sea and Bohai Sea coast, which contained 6010 t N, 924 t P, and 29,016 t COD (Cui et al. 2005). In this area, discharge of N and P from aquaculture accounts for 2.8% and 5.3% of pollutants from land-based source, respectively. The N discharge from mariculture cage and pond in China in 2008 is amounted to 37,000 and 50,000 t/years, respectively, while the total amount of ammonia nitrogen discharged from urban domestic wastewater in China is 900,000 t/years (Cheng 2009). Although the amount of mariculture wastewater remains limited, the significant impact has been detected in some local areas. This is an important reason that China government encourages fish culture to move offshore.

4.3.3 Chemical Discharge

A variety of chemical drugs are used in aquaculture for the purposes of disease treatment, removal of hostile organisms, disinfection, anesthesia, and inhibition of fouling organisms. At the present, 104 types of drugs belonging to seven categories are approved for usage in aquaculture in China, including antimicrobial drugs, herbal medicines, antiparasitic drugs, disinfectants, environmental improvers, vaccines, and reproductive and metabolic regulators. At the end of the twentieth century, major shrimp-farming countries in Southeast Asia are seriously infested by viruses, bacteria, fungi, and other pathogenic microorganisms, and as many as 43 types of drugs are commonly used during farming processes. In 1995, $100 million was spent on the purchase of drugs in the industry of shrimp farming in Thailand, mainly for water treatment, and disease prevention & treatment. (Tonguthai 1996). As food production systems, use of prescribed drugs during the farming process should be prescribed by qualified persons. However, nonstandard use of aquatic drugs exists sometimes and somewhere, which threatens the environment and human health.

4.3.3.1 Antimicrobial Drugs

Antimicrobial drugs are mainly applied for the prevention and treatment of aquatic animal diseases caused by the infection of virus, bacteria, and fungi. As the most widely used and diverse classes of drugs in aquaculture, their impacts on the environment are of great concern.

The chemical property of numerous antibiotics is relatively stable, which have the ability to remain active for a long time even after the excretion by cultured animals. Such drugs can affect the diversity of planktonic communities and increase the resistance of pathogenic microorganisms. Moreover, the use of antibiotics can also exert impacts on surrounding wild lives, which in turn affect the food safety of humans.

A total of 36 types of antibiotics are used in aquaculture in Asia (Rico et al. 2012). The amount of antibiotics used in salmon culture varies greatly among countries. For example, with the production of 3×10^5 t of Atlantic salmon, a total of 385.6 t antibiotics were used in the salmon farming in Chile in 2007, while less than 1 t antibiotics were used for the production of 8.2×10^5 t Atlantic salmon in Norway.

A substantial portion of the drugs used to treat cultured animals would be directly dispersed into the environment. The dispersion rate of antibiotics mixed in fish feed varies from 70 to 80% (Samuelsen 1989). The residues of norfloxacin, ofloxacin, and tetracycline, with an average concentration of 7.63–59.00 ng/L were detected in the water of the typical aquaculture area located in the Pearl River Estuary (Liang et al. 2013). In addition, the concentration of antibiotic residues was gradually increased with increasing farming period.

The accumulation of some drugs in cultured organisms becomes another potential threat. Although discharge of the drug residuals from aquaculture into coastal waters is relatively lower compared with agriculture, local impacts of residual drugs from mariculture on environment cannot be ignored.

4.3.3.2 Pesticides

Antiparasitic drugs are used to kill the parasitic pathogens which infest aquaculture animals in vitro or in vivo and those existing in farming environment. Pesticides are widely applied worldwide in salmon farming, and the cost of treating sea lice accounted for more than 10% of the total expenses in salmon farming. The main drugs available for the treatment of sea lice include avermectin, pyrethroid, hydrogen peroxide, and organophosphate. The dispersion of such drugs exerts hazardous effects on the environment, such as killing indigenous organisms, especially crustaceans, and altering the structure of planktonic communities. Detailed descriptions of the usage and side effects of these pesticides have been reviewed by Burridge et al. (2010).

In Southeast Asia, ammonium fertilizer, calcium hypochlorite, copper compounds, and formalin were widely applied to kill feral fish and pathogenic organisms in shrimp pond. Herbicides, which are commonly used for water quality control in shrimp ponds, are also broadly defined as pesticides that remove water weeds and kill phytoplankton. When killing the target organisms, these pesticides often have some adverse effects on cultured organisms or the environment (Gräslund and Bengtsson 2001).

Bio-fouling is a special problem in mariculture. Fouling organisms are attached on the surface of cultured organisms or farming facilities, resulting in the reduction in the productivity of the culture system and damage to the farming facilities. Fouling organisms, adhering to the shells of cultured shellfish and the cage net, compete food with filter-feeding shellfish, leading to reduced food sources and deterioration of water quality as a result of interference in water exchange. Some fouling organisms, such as some polychaete species, might penetrate shells and attack cultured shellfish while others affect the ability of shell opening and closure, and increase the weight of cultured organisms or facilities. The cost of removing fouling organisms accounts for at least 5–10% expense of shellfish culture (Fitridge et al. 2012).

4.3.3.3 Metals

Some metal elements in aquaculture waters are derived from exogenous pollution, while others are generated from aquaculture activities, such as the application of antifouling compounds and additive ingredients of feeds. Modest doses of additives such as copper, zinc, iron, manganese, and other metal elements in the feed are essential for meeting the nutritional requirements of farmed animals. The metals, however, will be toxic after dissipation into the environment or accumulation to a certain level.

Copper compounds are often used as coatings on the netting of cages to prevent the growth of fouling organisms and maintain the permeability of the netting. The releasing rate of copper compounds from the paint is associated with the nature of the compound, water temperature, and water flow rate. Copper concentrations in sediment under cages with copper coatings are significantly higher than that in other places. For example, the copper in sediments of dry weight around Canadian salmon cages ranged from 100 to 150 mg/kg, which exceeded the concentration of safety standard (Burridge et al. 1999). Copper concentrations of four sediment samples among the 14 investigated farming zones exceeded the safety standard (Brooks and Mahnken 2003). Microalgae, shellfish, and crustaceans are very sensitive to copper. Therefore, copper is often used to prevent fouling organisms such as algae and shellfish. However, it should be noted that copper also have significant impacts on ecosystems of aquaculture waters.

Another important feed additive is zinc which is less toxic relative to copper. Similar with copper, concentration of zinc often exceeds safety standard in the sediment around farming cages. In particular, algae are very sensitive to zinc.

4.3.3.4 Disinfectants

Through splashing or soaking, disinfectants are usually used to kill harmful or pathogenic organisms on the surface of animals, tools, and in the aquaculture waters. It has been reported that at least 18 or more types of disinfectants are applied in the salmon culture in Chile (Bravo et al. 2005). A number of disinfectants show surface activity and some are environmental hormones that can disrupt the endocrine system of cultured fish. At the present, knowledge in this area is still insufficient to thoroughly understand the effects of disinfectants on cultured and environmental organisms. In Thailand, 5×10^4 t chlorine is consumed annually for the disinfection in shrimp-farming industry. Once chlorine enters the farming water, it reacts with different organic substances to produce halogenated hydrocarbons, which can be very toxic or carcinogenic (Gräslund and Bengtsson 2001).

Now, China has established strict standards for wastewater discharge from aquaculture. Farmers should strictly comply with the standards and administrators should be responsible for the mandate authorized by the state so as to improve the product safety, environmental health, and industrial sustainability.

4.3.4 Escape of Farming Fish and Invasion of Exotic Species

4.3.4.1 Escape of Farming Fish

In the last century, the countries around North Atlantic were major producer of Atlantic salmon. Potential impacts of escaped fish on wild populations are of great concerns in these countries.

According to ICES reports (ICES 1997), the proportion of farmed salmon caught in Norwegian coastal fisheries has varied between 34% and 54% of total catch during the period 1989 to 1996, while in fjord the proportion is from 10% to 21%. In Scotland, Northern Ireland, Canada, and USA, the escaped fish have also been detected in wild populations. In 1994, escapes of Atlantic salmon in the Bay of Fundy area (Canada) were estimated at 20,000–40,000 salmon, an amount greater than the total returns of wild and hatchery origin salmon to the entire Bay of Fundy in the same year. In recent years, the number of salmon escapists have been greatly reduced due to the improvement of culture facilities.

The escape of fish from mariculture operation may have adverse effects in ways of disease transfer, genetic composition in relation to wild stocks, etc. Sometimes, diseased shrimps and farming water are together discharged into the sea, resulting in serious hazards to wild populations. Potential impact of escaped fish is to cause exogenous genetic pollution. Selection breeding program may have conducted on the escaped fish for some specific traits, such as high growth rate, low reproductive capacity, and low swimming capacity. It would result in reduced variability of genes and high purity (Nair and Salin 2012; Baskett et al. 2013). If these cultured fish escape to nature and hybridize with indigenous species, it would lead to the reduction in the gene pool of indigenous fish populations, and also decrease the genetic variations and cause homogenization of genetic composition.

In recent years, numerous species have been introduced from abroad into China. Some transgenic fish species may be cultured in large scale in some countries. Worries about the harm caused by invasion of exotic species attract more and more attention. To prevent this effect, the use of sterile fish (by triploid or all-female or all-male stock) or use of native or near native fish is suggested.

4.3.4.2 Invasion of Exotic Species

Exotic species are often introduced with the purposes of breed improvement, and quality and yield enhancement. The introduction of exotic species might bring benefits to people. For instance, successful introduction of bay scallops, tilapia, rainbow trout into China promoted the optimization and adjustment of China's aquaculture structure, and some species have formed new aquaculture industries. It has been reported that a total of 62 exotic species have been directly or indirectly introduced to Shandong Province of China, including channel catfish, rainbow trout, Nile tilapia, bay scallops, whiteleg shrimp, and so on (Liu et al. 2003b). Jiangsu Province (China) also introduced 51 exotic species such as sturgeon, eel, and so on (Wang et al. 2008). On the other hand, however, the introduction of some species can be disastrous, which is so called as invasion of exotic species.

Invasion of exotic species refers to the introduction of species from other regions into local natural or semi-natural ecosystems, either intentionally or unintentionally, through human activities, causing significant damage or impact to local ecosystems or landscapes. Because of strong adaptability and lacking natural enemies, some exotic species can grow, reproduce, and spread very rapidly. They could not only compete with native species for food and space, but also exclude native species, and even replace them. Some exotic species would hybridize with native species to reproduce offspring, resulting in “genetic pollution”.

Invasion of exotic species can disrupt the ecological balance of native ecosystem, threaten native biodiversity, and lead to the decline of many native species, which cause significantly economic losses and even catastrophic consequences. The introduction of the Nile perch (*Lates niloticus*) in 1950s has resulted in the extinction of more than 200 haplochromine cichlid species in Lake Victoria, Africa; the invasion of lamprey into the Great Lakes of North America has led to huge fishery losses; the invasion of Asian carp into the United States has become a public hazard.

In Yunnan Province, China, the introduction of invasive topmouth gudgeon (*Pseudorasbora parva*) and icefish (*Neosalanx taihuensis* Chen) directly or indirectly leads to the extinction of some indigenous fishes, such as *Xenocypris yunnanensis*, *Schizothorax taliensis,* and *Cyprinus megalophthalmus*. Currently, of the original 432 indigenous fishes in Yunnan Province, a total of 130 species have not been collected in the last 5 years, representing about 30% of the total number of fish species. There were about 150 fish species, which were common in the 1960s but were rarely found now. The population of the remaining 152 species are significantly decreased compared with those in the 1960s (Kang et al. 2015).

The introduction of harmful exotic species is often the result of unconscious or weak awareness of laws and regulations. Of the 62 new species introduced into Shandong Province, less than ten species have been approved by the government; however, most of them are introduced arbitrarily (Liu et al. 2003b). Therefore, it is a long-term task to strengthen the management and education on biodiversity conservation.

4.3.5 Destroy of Mangrove

Mangroves are not only important wetland landscapes in tropical and subtropical coastal areas, but also one of the hot spots of international concerns regarding biodiversity conservation.

Attracted by high profit from shrimp farming, large areas of mangrove wetlands have been converted into shrimp or milkfish farms, particularly in the Philippines, Thailand, and Ecuador. Nearly 50% mangroves in Philippines have been transformed into ponds for raising saline fish and shrimp (Pollnac 1992). The areas of mangrove in China used to be recorded as 2.5×10^5 hm^2. As a result of exploitation including polder reclamation and aquaculture, there were 4.2×10^4 hm^2 mangrove in the 1950s, 2.2×10^4 hm^2 in the early 1980s, and only 1.6×10^4 hm^2 in the 1990s. Worldwide, mangrove forests have decreased from 18.8×10^4 hm^2 in 1980 to 15.23×10^4 hm^2 in 2005.

Mangroves are spawning and nursing grounds for numerous fish, crustaceans, and shellfish. In addition, mangrove areas are nutrient sinks where nutrients discharged from the uplands are accumulated, decomposed, and filtered. The nutrients required for primary production of humid tropical Rhizophora mangrove forest are 219 $kgN/(hm^2 \cdot yr)$ and 20 $kgP/(hm^2 \cdot yr)$ (Robertson and Phillips 1995). Loss of mangrove forest will subsequently loss of dependent capture of fisheries, accumulation of pollutants, and development of acid-sulfate soils.

4.3.6 Effects on Biological Community

Biological community is a collection of populations of various species that gather on the same area at the same time with temporal and spatial dynamics. The structure of biological community changes dynamically over time even within the same spatial extent. In addition, the distribution of different species within a given community, which is the result of interactions between the populations within the community and between populations and the environment, is well-organized. The co-existence of multiple species is a common characteristic of communities in ecosystems including aquaculture ponds.

During the processes of aquaculture, facilities, feeds, feces, and farming activities cause changes in aquatic environment, which subsequently affects the structure of biological communities in aquaculture waters and adjacent waters. Therefore, changes in the structure of biological communities in aquaculture waters are considered as an important indicator of the effects of aquaculture activities on the aquatic environment.

4.3.6.1 Direct Effect on the Structure of Biological Community

Physiological activities and physical movements of cultured animals, such as feeding, metabolism, and bioturbation would exert effects on the community structure of plankton and benthos in aquaculture waters. The feces and pseudofeces produced by farmed bivalve and jellyfish are settled and accumulated on the bottom sediment of aquaculture waters. It not only provides food for benthic animals, but also modifies the environmental conditions of substrate, affecting the community structure of benthos.

Previous studies have indicated that the sedimentation rate of particulate organic matter and the total organic matter content of the substrate in jellyfish-farming ponds are significantly higher than those in ponds without jellyfish farming (Feng et al. 2011). Before jellyfish culture, Shannon-Wiener index[1] and Pielou's evenness index[2] of the ponds are calculated as 0.43 and 0.16, respectively. Both of them are lower than the values in control pond (0.55 and 0.21). Nevertheless, Shannon-Wiener index and Pielou's evenness index of the ponds increase to 2.09 and 0.84 after jellyfish culture, indicating that jellyfish culture can improve benthic biodiversity in the cultured ponds.

The activities of filter-feeding animals such as bivalves, silver carp, and bighead carp can directly affect the community structure of plankton in the water (see Chap. 7 for details). Silver carp co-cultured with grass carp and common carp in ponds can inhibit the occurrence of cyanobacterial blooms, reduce the biomass of plankton, miniaturize the particle size of plankton (Yang et al. 2011a).

4.3.6.2 Effect of Aquaculture Facilities on the Structure of Biological Community

Some aquaculture activities require special facilities in water, such as raft frames and ropes for seaweed, artificial reefs for sea cucumber, net cages for scallop, abalone, and fish. The presence of those facilities will change the hydrodynamic characteristics of aquaculture water. Due to the blocking effect of the raft frame on the water flow, the water exchange time in the oyster breeding area of Taiwan, China, is extended from 3–7 days under normal conditions to 5–13 days (Lo et al. 2008). The reduction in water velocity would affect water quality, community structure of plankton as well as the sedimentation rate of particulate matter in water, which in turn alters substrate conditions and community structure of the benthic organisms.

The establishment of aquaculture facilities will increase the areas of bioavailable habitat and improve habitat diversity, thus, alter the biological community structure

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[1] Shannon-Wiener index (H) is derived from information theory and is calculated to describe the uncertainty of a given individual in a given population; diversity rises with increasing uncertainty. Its formula is listed as follows:

$$H = -\sum_{i=1}^{s} P_i \log_2 P_i$$

In the formula, S represents the number of species; P_i is a proportion of the number of i th species to the total number of living individuals in the community.

[2] Pielou's evenness index (J) is specifically used to measure the evenness of species distribution in a given community. In essence, it is the ratio of the actual Shannon-Wiener index in the community relative to the probable maximum of the Shannon-Wiener index in the community. Its formula is listed as follows:

$$J = H/H_{\max} = H/\log_2 S$$

In the formula, $H_{\max}$ represents maximum possible value of the Shannon-Wiener index in the community. It is the Shannon-Wiener index when the number of individuals of S species in the community is equal. At the moment, the value of Shannon-Wiener index is $\log_2 S$.

of aquaculture waters. In the mussel-farming sea areas of South Africa, massive attachment of macrophytes, barnacles, hydroids, sea squirts, and other flora to the culture rafts has not only increased the biodiversity and biomass of the farming sea areas, but also led to a change in the composition ratio of epibenthic species (Heasman 1996). Compared with the composition of communities in nonculture areas, epibenthic organisms in culture areas become the dominant species. In addition, organisms on the surface of the culture facilities can serve as a direct food source for other animals such as fish and echinoderm. Mussel rafts in Washington, USA, provide 11 times more food resources for local economic fish species than nonculture marine areas (Brooks 2000).

4.3.6.3 Effect of Culture Activities on the Structure of Biological Community

Water exchange, feeding, and other operations could affect the water and sediment environment in aquaculture ponds, and thus affect the plankton and benthic communities. For example, water temperature of sea cucumber pond is usually regulated by adjusting the water depth in different seasons to shorten the time of estivation and hibernation of sea cucumber. Seasonal regulation of water depth not only influences the biomass and sedimentation of plankton as well as the benthic community. Organic matters in sediment and some benthos are the food sources of sea cucumber. Therefore, changes in the community structures of plankton and benthos would influence the food sources of sea cucumber. Diversity indices and community structure of benthic organisms have significantly different seasonal changes among the ponds with the water depths of 1.5 m, 2.3 m, and 3.1 m, respectively (Wen et al. 2016). However, the community similarity of benthic organisms in the ponds is spring (48%) > summer (43%) > winter (43%) > autumn (37%) (Sun et al. 2013).

The correlation analysis between community structure and environmental factors shows that water depth is the main factor influencing the macrobenthic community of sea cucumber ponds. Changes in water depth not only affect the amount of particulate organic matter, but also alter the conditions of temperature and light intensity on the pond bottom. The changes would influence the endogenous primary productivity on the pond bottom, which will in turn alter the macrobenthic community and the environmental conditions of sea cucumber ponds. Water depth can be scientifically adjusted based on the seasonal variation of benthic community structure to provide suitable food conditions for farmed sea cucumbers.

Most of residual feed and feces are eventually deposited on the sediment of aquaculture ponds, and will influence the structures of the biological community. The values of Shannon-Wiener index and Pielou's evenness index of benthic community in the culture area of grouper in Kau Sai Bay are significantly lower than that in the adjacent areas. The ratios of benthic abundance to biomass (W) in culture, transition, and control areas are estimated as 0.238, 0.086, and 0.141, respectively. W values are gradually decreased with the increase of distance from culture area, which indicates that stress from aquaculture activities on benthic organisms is positively related with the distance from culture area. The small individuals (*r*-selective strategy species) such as *Capitella* spp. dominate the culture area (Gao 2005).

4.3.7 Conflicts between Aquaculture and Other Industrial Usage

The environmental impact of aquaculture is largely depending on its scale, the technology applied, and the location where it is implemented. Large-scale aquaculture activities can also conflict with some other industrial usage such as water supply, tourism, transport, capture fisheries, and so on. Greenhouse gases are also generated from materials used in the construction of aquaculture facilities and the production of feed stuffs. The emission of greenhouse gases contributes to the global climate changes. Their detailed description has been summarized in next section of this chapter and Chap. 15.

4.4 Effects of Global Climate Changes on Aquaculture

Nowadays, global climate change, caused by the emissions of greenhouse gases, has become a hot topic worldwide. Gases that trap heat in the atmosphere are called greenhouse gases. Greenhouse gases include more than 30 types of gases, such as carbon dioxide, methane, nitrous oxide, fluorinated gases, and so on. CO_2 is the most important greenhouse gas in the atmosphere, accounting for about 70% of the contribution to greenhouse effect and global warming.

Since the second industrial revolution, CO_2 concentration in the atmosphere has increased from 280 ppm at beginning of the nineteenth century to 389 ppm in 2010 due to the burning of fossil fuels and the destruction of earth's ecosystem by humans (Tarasova et al. 2011). About 7 Gt CO_2 ($1\text{Gt} = 10^{15}$ g) are emitted into the atmosphere annually, of which 5.4 Gt CO_2 come from burning of fossil fuel and 1.6 Gt CO_2 from deforestation (Takahashi 2004). Methane (CH_4) is the second largest global greenhouse gas following CO_2, and the concentration of CH_4 in the atmosphere has increased from 0.715 ppm before the second industrial revolution to 1.774 ppm in 2005 (IPCC 2007). Although its concentration is low, the global warming potential (GWP) of CH_4 is 72 times higher than that of CO_2 on a 20-year scale (IPCC 2007). CH_4 contributes about 20% of the greenhouse effect.

In the past 100 years, the global temperature has increased by 0.56–0.96 °C due to the emissions of greenhouse gases (Solomon et al. 2007). Elevated CO_2 concentrations in atmosphere can cause ocean acidification, eventually leading to changes in the structure of ocean ecosystems. At the same time, climate change will also lead to melting of snow and ice, raising of sea level, and altering of hydrological systems. These phenomena certainly affect the structure and function of aquatic ecosystems. Hence, how to control and reduce the emissions of global greenhouse gases have become an issue that governments around the world need to focus on.

4.4.1 Effects of Global Climatic Changes on Aquatic Ecosystems

About 93% of the energy of global warming is stored in the ocean, and the other 7% is used to heat the land and atmosphere, melt polar ice as well as mountain glaciers, and so on. At same time, 25% of anthropogenic CO_2 are absorbed by ocean. Due to the melting of ice in polar regions and mountains, the average of global sea level rises 0.19 m from 1901 to 2010. It is evident that significant changes are occurring and accelerating in aquatic ecosystems that support aquaculture. Among these changes, changes in hydrological systems, rainfall patterns, sea level, water temperature, dissolved oxygen, ocean acidification, and primary productivities of aquatic ecosystems exert more direct and greater impacts on aquaculture (Barange et al. 2018).

4.4.1.1 Changes in Hydrological Cycle and Rainfall Patterns

Climate warming has a significant effect on the hydrological cycle, leading to inevitable changes in aquatic ecosystems. Changes in temperature, rainfall, climate patterns, and melting of snow and ice would influence the seasonal distribution of water resources.

Observed precipitation changes since 1901 vary among different regions. Models indicate that zonal mean precipitation is very likely to increase in high latitudes and near the equator, and decrease in the subtropics (Ren et al. 2013). Changes in precipitation will significantly alter the ecological characteristics of rivers, lakes, and reservoirs. Due to dam construction, irrigation, and watershed management, there is not significant correlation between global river flows and global climatic warming. However, it can be expected that the melting of snow and ice will increase the flow of rivers in the near future (Pervez and Henebry 2015).

4.4.1.2 Sea Level Rise

Changes in sea levels not only directly influence area and volume of sea, but also significantly alter the ecological characteristics and aquaculture activities of some regions. These changes vary among different regions. Sea level rise in the Western Pacific is three times higher than the global average, while the raised levels of Eastern Pacific are zero or negative. There is a high certainty that the sea level will rise in 95% of the ocean area; however, there will be a significant regional heterogeneity in the sea level rise and thus in its consequences (IPCC 2014).

Continuous rises of sea level will influence nearshore habitats and ecosystems at the freshwater-ocean interface in the North Pacific. With sea level rise, the intensity of seawater invasion and the degree of thermal stratification are likely to increase, and estimated 48% and 28% changes in freshwater volume in spring- and neap-tides, respectively in the Yangtze River estuary by 2100 (Qiu and Zhu 2015). If the sea level rises at the speed of 0.59 cm/years, 37% of the mangroves in Guangxi province, China, and 5.8% of the coastal wetlands in Yangtze Estuary will be threatened in 2100 (Li et al. 2014; Cui et al. 2015).

4.4.1.3 Water Temperature Increase

Since the 1960s, warming of upper ocean (above 700 m) has been observed at a rate of 0.7 °C per century (Huang et al. 2015). Although trends of ocean temperature changes vary among regions, temperature of most of regions (especially in the Atlantic Ocean of Northern Hemisphere) increases. The upper ocean accounts for about 64% of the additional anthropogenic energy accumulated in oceans and seas. Warming of upper ocean is likely to continue across the whole twenty-first century, especially in the tropics and subtropics of the Northern Hemisphere, whereas in deep waters the warming is expected to be more pronounced in the Southern Ocean.

The trend in sea surface temperature already exceeds the range in natural seasonal variability in the subtropical areas and in the Arctic. Comparing with the 1986–2005 average, the best estimates of mean ocean warming in the top 100 m by the end of the twenty-first century are about 0.6–2.0 °C, and about 0.3–0.6 °C at a depth of about 1000 m (IPCC 2014).

Freshwater temperatures also increase significantly in most areas but vary among regions. There is a high confidence that rising water temperatures will lead to shifts in freshwater species' distributions and exacerbate existing problems in water quality, especially in those systems experiencing high anthropogenic loading of nutrients (IPCC 2014).

4.4.1.4 Changes in Dissolved Oxygen Contents

The dissolved oxygen (DO) in the oceans varies widely. Ocean warming is estimated to account for more than 50% of the oxygen loss in the upper 1000 m of the ocean. The warming ocean water will have lower DO in the future. A large variety of oxygen minimum zones (OMZs) exist in the open ocean, coastal upwelling zones, deep basins of semi-enclosed seas, deep fjords, and other areas with restricted circulation (IPCC 2014). GHG-driven global warming is the likely ultimate cause of this ongoing deoxygenation in many parts of the open ocean (Breitburg et al. 2018). Modeling simulations show that the global volume of OMZs is expected to increase by 10–30% by 2100, depending on the oxygen content threshold considered.

Changes in DO have significant effects on the global carbon and nitrogen cycles. Oxygen can affect the physiological and biochemical processes of aquatic organisms. However, the effects vary among species or populations. The presence and expansion of OMZs can influence the depth of vertical migration of some animals and compress their habitat space.

4.4.1.5 Ocean Acidification

Ocean acidification refers to a reduction in the pH of the ocean over an extended period (typically decades or longer) caused primarily by the uptake of atmospheric CO_2. Ocean acidification may also be caused by the increase or decrease of other chemicals in the ocean. pH reduction caused by human activities is called anthropogenic ocean acidification. With the increased concentration of CO_2 in atmosphere, the ocean would absorb more CO_2, which leads to lower pH and less saturation of calcium carbonate ions in the surface layer of ocean. Calcium carbonate plays important roles in the shell formation of some aquatic animals.

Since the beginning of the industrial era, oceanic uptake of CO_2 has resulted in increasing acidification of the ocean; the pH of ocean surface water has decreased by an average of 0.1, corresponding to a 26% increase in acidity (IPCC 2014; Jewett and Romanou 2017). The changes of pH, partial pressure of CO_2, and saturation of calcium carbonate ions in coastal waters are higher than those in the open seas. The decreased salinity caused by ice melting or excessive precipitation can exacerbate water acidification due to dilution of acid-base buffering substances in water. The acidification rates of surface water are different among regions: acidification rates in the North Atlantic are 50% higher than that in the subtropical Atlantic; the speed of acidification in Arctic waters is faster than the global average because of more CO_2 absorbed by colder water.

Although the nature of acidification process is well understood and the predictions of acidification rate are well established, the outcome of acidification in the future remains unclear. The effects of ocean acidification on marine organisms vary based on the physiological response of these organisms to acidification.

The studies of ocean acidification are still at an early stage. Most experiments are short-term, single-factor sensitivity under laboratory conditions, while studies of long-term response and coping ability and multifactors (e.g., temperature and acidification, or oxygenation and acidification) are yet to be enhanced.

4.4.1.6 Changes in Primary Production in Water Area

Phytoplankton production is the process underlying the marine food web, controlling the energy and food sources of organisms in higher tropic levels. Predications about the effect of climate changes on global marine primary production are different among studies. Recent studies suggest that global marine primary production will decline by $6 \pm 3\%$ by 2100 (Kwiatkowski et al. 2017). However, the primary production will increase in some Arctic and boreal freshwater lakes (Michelutti et al. 2005).

In addition, because of climate changes, the circulation of global and regional ocean is changing. The upwelling of Gulf Stream and the California Current is weakening, while others such as Canary Current, California Current, and Benguela Current are strengthening. These changes not only have a significant impact on marine fishery resources, but also directly or indirectly influence aquaculture.

4.4.2 Effect of Global Climate Change on Aquaculture

Temperature, pH, salinity of aquaculture waters, as well as the frequency and intensity of extreme weather events are changing due to global climate change. These changes may have direct or indirect and short-term or long-term effects on the production of aquaculture. Short-term effects include loss of production or infrastructure caused by extreme events, disease, toxic algae, and parasites, and yield reduction caused by poor production conditions. Long-term effects include scarcity of wild seedlings, limited freshwater resources for production, restricted feed resources from marine and terrestrial sources, reduced productivity, eutrophication, and other disturbances.

Climate change could have the effects in small- and large-scale. The former can alter the metabolism of aquatic organisms, while the latter has an effect on activities in a global scale. Available information suggests that the negative effects of global climate change on aquaculture may be greater than the positive effects (Barange et al. 2018).

Long-term trends driven by climate change, such as rising temperatures and salinity, are easily coped with than short-term extremes. For long-term changes, there is time to plan and implement responses, while it is more difficult to plan for unexpected and short-term events, such as storm surges.

In terms of sensitivity and adaptive capacity to climate change, the freshwater aquaculture in Asia, especially Vietnam, followed by Bangladesh, Laos, and China, is susceptible to changes. The freshwater aquaculture in Belize, Honduras, Costa Rica, and Ecuador is more easily influenced by climate change in Americas, while Uganda, Nigeria, and Egypt are relatively vulnerable to the changes in Africa. Brackish water aquaculture in Vietnam, Egypt, and Thailand is more easily to be influenced, while mariculture in Norway and Chile is relatively vulnerable to climate change (Barange et al. 2018).

4.5 Aquaculture and Greenhouse Gas Emission

In the world, aquaculture emits 219.5 Mt. CO_2-equivalent ($Mt = 10^6$ t) of greenhouse gases per year. The result assessed by Life Cycle Assessment is 245 Mt. CO_2-equivalent, which is 0.55% of the total greenhouse gas emission (Boyd and McNevin 2015). Although the percentage of CO_2 emission from aquaculture is not great, its trends to increase are not to be ignored (Yuan et al. 2019).

In 2013, the amount of CO_2 emissions in China was 10 billion tons, accounting for 27.7% of the total CO_2 emissions in the world (Friedlingstein et al. 2014), although its CO_2 emissions per capita were far less than some major developed countries. According to the principle of “United Nations Framework Convention on Climate Change”, i.e., common but differentiated responsibility, China has taken measures to reduce the emissions. At the Paris Climate Change Conference in 2015, China government has promised that the amount of CO_2 emissions in China would reach the peak around 2030, and the CO_2 emissions per unit of GDP will be 60–65% lower than that in 2005. Before 2060 China is going to be carbon neutral. Aquaculture industry in China will also perform a duty to fulfill the commitment.

The effects of aquaculture industry on global climate change in long-term include four main aspects: greenhouse gas emissions in aquaculture activity, carbon removal from aquaculture products, carbon sequestration in sediment of aquaculture waters, and greenhouse gas fluxes between water-air interface.

4.5.1 Energy Consumption and Carbon Emission in Aquaculture Activities

Around the year 2008, about 1.754 million standard coal was consumed by aquaculture and fisheries activities in China, of which fishery, aquaculture, and processing industry contributed to 66%, 21%, and 13%, respectively (Xu et al. 2011). Pond farming accounts for 61.3% energy consumption of the aquaculture industry, followed by water flow-through and recirculating aquaculture systems with 21.3%, cage and pen culture with 14.3%.

Average annual energy consumption of different aquaculture production systems in China is listed in Table 4.6. The energy consumed by seawater ponds is 6.7 times higher than that of freshwater ponds due to their different intensification degree and ecological characteristics of farmed animals.

In China, the pond culture of Chinese carps shows a relatively low energy consumption with the values of 0.17 kWh/kg, while the energy consumption of shrimp ponds reaches up to 1.21 kWh/kg (Table 4.7).

Energy consumption of cultured Nile tilapia, carps, and striped catfish in Bangladesh, India, and Vietnam has been studied by Bosma et al. (2011), Henriksson et al. (2014), and Robb et al. (2017). For striped catfish farming in Vietnam, the energy consumptions (kWh/kg) of small, medium, and large farms are 0.183, 0.243, and 0.0675, respectively (Henriksson et al. 2014). The energy consumption of pond culture of carps in India (0.224) is three times higher than that (0.0585) of striped catfish in Vietnam, and less than that of tilapia in China.

Table 4.6 Average annual energy consumption of different aquaculture systems in China (from Che et al. 2010)

Models	Production (kg/hm^2)	Energy consumption (kWh/kg)
Freshwater ponds	12,681 ± 1037	0.62 ± 0.07
Seawater ponds	12,938 ± 1336	4.19 ± 0.35
Water flow-through systems	173,070 ± 15,317	8.66 ± 0.94
Recirculation systems	244,622 ± 77,320	5.07 ± 1.90

Table 4.7 Average annual energy consumption in freshwater pond culture of different species in China (from Che et al. 2010)

Culture species	Production (kg/hm^2)	Energy consumption (kWh/kg)
Chinese carps	15,292 ± 1062	0.17 ± 0.02
Yellow catfish (*Pelteobagrus fulvidraco*)	5906 ± 901	0.19 ± 0.06
Tilapia	18,469 ± 3266	0.36 ± 0.17
Eel	23,160 ± 3947	1.07 ± 0.12
Mitten crab	1044 ± 64	1.11 ± 0.45
Shrimps	6431 ± 207	1.21 ± 0.10

The description mentioned above is the energy consumption of aquaculture activity excluding the energy consumption of feed manufacture. The total emissions of CO_2 from Nile tilapia, carps, and striped catfish are estimated as 1.58, 1.84, and 1.37 kg equivalent CO_2 per kg of fish produced (fresh weight), the majority of which are generated by their feed manufacture (Robb et al. 2017). The emissions of greenhouse gases from facility construction for aquaculture will be introduced in Sect. 15.3 Carbon Footprint of Aquaculture.

4.5.2 Carbon Removal from Aquaculture Products

The harvest of aquaculture products is the removal of organic carbon from the aquatic ecosystems. The carbon content of most freshwater fish exceeds 50% of their dry weights with the maximum of 64.9%. The carbon content of freshwater shrimp is around 43% in dry weight and shellfish is around 40%, which suggests that a large amount of carbon can be effectively removed from aquaculture waters by harvesting aquatic animals (Xie et al. 2013). As shown in Table 4.8, the total amount of carbon removed from 12 major aquaculture species in China was about 1.3 million tons in 2009 (Xie et al. 2013). The production of some fish species, such as silver carp, bighead carp, grass carp, common carp, and crucian carp is very high; therefore, the carbon removal by these species is significant. Because of the high production and rich carbon in the carapace of mitten crab and shrimp, the amount of carbon removed from their products is also relatively great.

The annual production of seaweed in China is ranged from 1.2 to 1.5 million tons, and the carbon content of its dry weight is estimated between 20 and 35%. In 2007, the amount of carbon fixed by seaweed farming in China was about 0.34 million tons (Tang et al. 2011). In 2007, the production of mollusks in China was 9.94 million

Table 4.8 Carbon removal by freshwater aquaculture species in China in 2009 (from Xie et al. 2013)

Species	Carbon content in wet weight (%)	Annual production (t)	Carbon removal (t)
Silver carp	16.19	3,484,442	564,149
Bighead carp	13.40	2,434,555	326,204
Grass carp	12.81	4,081,520	522,990
Crucian carp	14.22	2,055,478	292,356
Common carp	11.36	2,462,346	279,708
Blunt-snout bream	16.87	625,789	105,579
Mandarin fish	12.73	235,514	29,975
Shrimp	11.08	833,242	92,368
Clam	8.90	88,984	7920
Snail	7.93	99,080	7860
Corbicula	11.06	20,125	2226
Mitten crab	11.10	574,235	63,656

tons. The carbon contents in their soft tissues vary between 42.2 and 46.0%, while the carbon contents in their shell range from 11.3 to 12.7%. Therefore, the amount of carbon removal by the farmed mollusks is about 0.88 million tons each year.

From 1999 to 2008, a total of 37.89 and 12.04 million tons of carbon were removed from aquaculture waters by farmed mollusks and seaweed, respectively (Tang et al. 2011). Shellfish can permanently fix carbon by biocalcifying Ca^{2+} and HCO_3^- from seawater and forming aragonite and calcite crystals. The fixed carbon needs a long geological time to re-enter the biogeochemical cycle again.

4.5.3 Carbon Sequestration in Sediment of Aquaculture Waters

The sedimentation of organic particles, such as residual feed and feces, in aquaculture waters would form large amount of sediment with high concentration of organic carbon. If left untreated, the organic carbon can be sequestrated for a long time and have an impact on the global carbon cycle in long-term.

Carbon sequestration in sediments of 233 inland fish and shrimp-farming ponds in nine countries was reported by Boyd et al. (2010). The ages of the investigated ponds were 14.9 ± 10.4 years, the thickness of the sediment was 16.8 ± 11 cm, and the annual sedimentation rates were 1.44 ± 0.79 cm. The concentrations of organic carbon in the sediment were 2.46 ± 1.21%, and the annual decomposition rates of the sediments were 144 m^3/hm^2. The results indicate that the input minus output of organic carbon is the highest in the ponds applied with manure, 2453 $g/(m^2 \cdot year)$ (Table 4.9). The input minus output of organic carbon in ponds applied with chemical fertilizer is only 1426.8 $g/(m^2 \cdot year)$. Their carbon sequestration rates are estimated as 124.6–249.3 $g/(m^2 \cdot year)$ and 71.3–142.7 $g/(m^2 \cdot year)$, respectively. Organic carbon in all these ponds is majorly derived from the photosynthesis of phytoplankton.

There are 0.11 million km^2 of inland aquaculture ponds worldwide, and these ponds could sequestrate or bury16.6 million tons of carbon each year, accounting for

Table 4.9 The organic carbon budget in typical culture ponds for tilapia (from Boyd et al. 2010)

	Organic carbon [$g/(m^2 \cdot year)$]		
Variables	Manure	Chemical fertilizer	Feeds
Input			
Manure	1400	–	–
Feeds	–	–	450
Photosynthesis	1095	1460	1460
Inflow	10	10	10
Output			
Effluent	30	30	40
Fish	22	13.2	66
Input minus output	2453	1426.8	1814
Carbon burial	124.6–249.3	71.3–142.7	90.7–181.4

Table 4.10 Global areas of inland water bodies and annual rates and amounts of organic carbon burial in these systems (from Boyd et al. 2010)

Waters	Global area (km^2)	Carbon burial rate [t/(hm^2·year)]	Global carbon burial (Mt/year)
Large lakes and inland seas	2,180,000	0.05	11
Small lakes	320,000	0.72	23
Large reservoir	400,000	4.0	160
Ponds	110,830	1.5	16.6
Freshwater	87,500	1.5	13.1
Brackish water	23,330	1.5	3.5
Agricultural impoundments	77,000	21.2	163

4.25% annual global carbon sequestration of inland waters (Table 4.10) or 0.21% of annual global carbon emissions (8 billion t). China, which possesses 55.9% of the world's aquaculture ponds, plays the most important role in this regard.

In mariculture, the budget of organic carbon in intensive monoculture ponds (shrimp) with artificial feed and extensive polyculture ponds (shrimp and sea cucumber) without feeding has been investigated by Chen et al. (2016). During the farming periods, the concentrations of dissolved organic carbon (DOC), particulate organic carbon (POC), and total organic carbon (TOC) in the outflow water of the monoculture ponds are significantly higher than the corresponding concentrations in the inflow water. A total of 1013.3 kg/(hm^2·year) organic carbon are introduced into the pond from inflow water, while the output of organic carbon in outflow water is 145.8% of that in inflow water.

The concentration of DOC, POC, and TOC in outflow water of the ponds without feeding is significantly lower than that in inflow water. The amount of organic carbon input to the polyculture ponds is 1678.2 kg/(hm^2·year), while the amount of organic carbon in outflow water is 75% of that in inflow water. In terms of the interface between the pond and the ocean, the carbon output from the pond without feeding to the ocean is less than the input.

In the ponds with feeding, the amount of organic carbon from feed, photosynthesis of phytoplankton, and inflow water are 1155.6, 2308.6, and 1013.3 kg/(hm^2·year), respectively. And 1476.9 and 234.7 kg/(hm^2·year) of organic carbon are discharged and captured in the farmed animals, respectively. A total of 2765.9 kg/(hm^2·year) organic carbon are sedimented on the bottom of the ponds. If 90–95% organic carbon is decomposed annually in the ponds (Boyd et al. 2010), the organic carbon sequestration rates of the ponds with feeding are 138.3–276.5 kg/(hm^2·year).

In the ponds without feeding, the amount of organic carbon input from photosynthesis of phytoplankton and water inflow are 2071.7 and 1678.2 kg/(hm^2·year), respectively. And 1258.7, 42.94, and 890.1 kg/(hm^2·year) of carbon left from the ponds through outflow, product harvest, and alga (*Enteromorpha*) collection, respectively. The accumulation of organic carbon in the sediments is 1558.1 kg/(hm^2·year). The organic carbon sequestration rates of the ponds without feeding are 77.9–155.8 kg/(hm^2·year) (Chen et al. 2016).

Kennedy et al. (2010) have analyzed 207 seagrass sites at 88 locations worldwide and found that the carbon sequestration rates of sea grass are 41–66 C/(m^2·year). Thus, a total of 48–112 Tg carbon can be annually sequestrated by sea grass in the world (Tg = 10^{12} g), showing that seagrass meadows are natural hot spots for carbon sequestration. Similarly, in the mollusk-farming areas, biodeposition (feces and pseudofeces) can make significant contribution to the carbon sequestration. Due to the large-scale culture of mollusks and seaweeds, the average sedimentation rate of particulate organic carbon at Sanggou Bay, Shandong Province, China, is 20.01 g/(m^2·days), which is significantly higher than that at offshore areas nearby (Yang et al. 2014).

4.5.4 Fluxes of Greenhouse Gases between Water-Air Interface

In terms of the water-air interface, different aquatic ecosystems contribute differently to the increase of the atmospheric CO_2 and CH_4 concentrations. In general, the inland freshwater lakes are source of the atmospheric CO_2, and the oceans are sink of the atmospheric CO_2. The CO_2 release from lakes worldwide has been estimated as about 0.14 PgC/year (Pg = 10^{15} g) (Cole et al. 1994). The average release rate of CH_4 from freshwater lakes is 18.1 mgCH_4/(m^2·h) (Ortiz-Llorente and Alvarez-Cobelas 2012). Among them, the release rate of CH_4 in eutrophic lakes is significantly higher than that in oligotrophic lakes. The CH_4 released from freshwater lakes worldwide ranges from 8 to 48 TgC/year (Bastviken et al. 2004).

The ocean system is the largest carbon sink on the Earth, which contains 3.9×10^{13} tons of carbon, accounting for 93% of the total global carbon. On a millennial scale, ocean absorbs 80–95% emissions of anthropogenic CO_2. At present, the ocean can also absorb about 25% emissions of CO_2 (Rödenbeck et al. 2013), 50% of which is absorbed by coastal shelves (Cai et al. 2006). The average release rate of CH_4 from the ocean is 1.45 mgCH_4/(m^2·h), which is much less than the release rate from inland lakes. Due to relatively high contents of organic matter in the water of estuaries and coastal shelves, CH_4 release rate of which is 3.29 mgCH_4/(m^2·h). The release amount of CH_4 from the ocean ranges from 10.9 to 17.8 TgC/year worldwide (Ortiz-Llorente and Alvarez-Cobelas 2012).

In 2014, the areas of freshwater aquaculture ponds in China are 6.08 million hm^2, accounting for 72.5% of its total freshwater aquaculture area. The area of marine aquaculture ponds in China is 4.57 million hm^2, accounting for 20.0% of its total marine aquaculture area. Therefore, the release or dissolution of greenhouse gases from or into the pond is an ineligible factor affecting the global climate change.

The fluxes of CO_2 between water-air interface of grass carp polyculture in freshwater ponds were investigated in Shandong Province, China (Chen et al. 2015). The results showed that CO_2 fluxes had significantly diurnal and seasonal

Table 4.11 Comparisons of CO_2 fluxes in different inland freshwater systems [mg/(m^2·h)]

Site	Time	Mean	Range	References
Aquaculture ponds for grass carp	2013.4	1.7	−5.0–10.3	Chen et al. (2015)
	2013.5	28.3	21.4–33.1	
	2013.6	37.2	31.3–47.6	
	2013.7	212.9	139.7–298.1	
	2013.8	181.9	33.7–311.8	
	2013.9	124.9	15.0–207.7	
Lake Donghu	2003.3–2003.5	−2.5	–	Xing et al. (2005)
	2003.6–2003.8	−5.7	–	
	2003.9–2003.11	5.8	–	
	2003.12–2004.2	58.8	–	
	Average	14.1	−58.6–159.4	
Lake Biandantang, Hubei	2003.3–2003.5	28.8		Xing et al. (2006)
	2003.6–2003.8	−31.7		
	2003.9–2003.11	−30.0		
	2003.12–2004.2	212.1		
	Average	44.8	−152.3–464.5	
Freshwater marshes	2002.6–2002.12	428.8	18.7–965.4	Song et al. (2006)
	2003.1–2003.12	328.5	11.1–779.3	
	2004.1–2004.12	281.1	2.36–873.7	

variations. The mean value of CO_2 flux in the ponds was 97.8 mg/(m^2·h), which is higher than that in lakes, but lower than the average from marshes (Table 4.11).

The CO_2 and CH_4 fluxes at the water-air interface were measured in seawater shrimp (*Marsupenaeus japonicus*) monoculture ponds with feed supply and shrimp-sea cucumber (*Apostichopus japonicus*) polyculture ponds without feed supply (Chen et al. 2016). During farming seasons, cumulated CO_2-C fluxes were −5.69 g/m^2 (feeding) and 11.23 g/m^2 (no-feeding), respectively (Table 4.12). The cumulated CO_2 emissions from feeding ponds and no-feeding did not differ significantly. The values of CO_2 fluxes in the mariculture ponds are greater than those of the ocean and less than those of the freshwater lakes. The cumulated CH_4-C emissions from feeding ponds (0.57 g/m^2) were significantly higher than those from no-feeding ponds (0.068 g/m^2). The flux values of CH_4 in mariculture ponds are between oceans and freshwater lakes (Table 4.12). Feeding ponds absorbed C from the atmosphere with a mean absorption rate of 5.12 g/m^2, whereas nonfeeding ponds emitted C to the atmosphere with a mean emission rate of 11.30 g/m^2 (Chen et al. 2016).

The global warming potential (GWP) is often used to estimate the potential impact of different greenhouse gases on climate. CO_2 is usually used as the reference gas, and the warming effect of a greenhouse gas over a certain time is converted to an equivalent mass of CO_2. The warming potential of a greenhouse gas varies greatly

Table 4.12 Comparison of CO_2 and CH_4 fluxes and the global warming potentials (GWP) and compressive global warming potentials (cGWPs) in different aquatic ecosystems (g/m^2) (from Chen et al. 2016)

Waters	CO_2-C emission	CH_4-C emission	GWP (CO_2) 20-year scale	GWP (CH_4) 20-year scale	cGWPs
Mariculture pond with feeding	−5.69	0.57	−20.87	54.72	33.85
Mariculture pond without feeding	11.23	0.068	41.18	6.53	47.71
Global lakes	107.0	13.3	107	957.6	1064.6
Eutrophic lake	121.6	8.53	121.6	614.2	735.8
Mesotrophic lake	390.0	7.7	390.0	554.4	944.4
Oligotrophic lake	110.0	0.29	110.0	20.88	130.9
Baltic Sea	−35.2	0.05	−35.2	3.6	−31.6
North Sea	−61.6	0.017	−61.6	1.22	−60.4
East China Sea	−64.1	0.016	−64.1	1.15	−62.9

from year to year. On a time scale of 20 years, the corresponding value for CH_4 is 72 when the GWP value of CO_2 is 1. Over 20-year scale, the compressive global warming potentials (cGWPs) were 33.55 (feeding) and 47.71 (no-feeding), respectively, indicating both feeding and no-feeding mariculture ponds could promote global warming.

Previous studies have indicated that ocean can strongly absorb $CO_{2,}$ although they also release some amounts of $CH_{4.}$ Hence, GWP of the ocean is negative, representing its ability of slowing the global warming. Lakes, unlike oceans, release large amounts of CO_2 and $CH_{4,}$ suggesting their large GWP. It is likely that their GWPs are potentially increased with the eutrophication of water. Mariculture ponds are an intermediate type between oceans and lakes in terms of global warming potential. They all release a certain amount of CH_4, but some release CO_2 while others absorb it due to different farming models.

4.5.5 Carbon Sinking Fisheries

Carbon sink is a process or mechanism that removes carbon dioxide from the atmosphere, such as afforestation, vegetation restoration, and other measures. In recent years, the research of blue carbon is gradually rising in the world. Blue carbon refers to the atmospheric carbon captured and stored by the ocean in various ecosystems and organisms. This activity mitigates the effects of climate change by storing carbon for long periods, often thousands of years or more. The tidal marshes, mangrove forests, and seagrasses found in coastal areas hold the most blue carbon, but marine organisms and biological processes in the open ocean also sequester carbon. In coastal ecosystems and the euphotic zone of open oceans, phytoplankton, phytobenthos, and organisms that secrete calcium carbonate ($CaCO_3$) to form their skeletal material, such as mollusks, are part of a marine biological pump that removes CO_2 from circulation (Lerman and Mackenzie, 2005).

The role of mollusk farming as a method for enhancing the removal of carbon from coastal waters is termed as carbon sink fisheries (Tang et al. 2011) and could be a part of carbon trading systems (Alonso et al. 2021; Moore et al. 2022). Carbon sink fisheries refer fishery production activities that can facilitate aquatic organisms to absorb CO_2 from water and have the effect of directly or indirectly reducing atmospheric CO_2 concentration (Tang et al. 2011). Some scholars even classify the aquaculture without feeding or extractive aquaculture into the scopes of carbon sink fisheries (Yang et al. 2012; Xie et al. 2013). During the decade from 1999 to 2008, a total of 0.67 million tons of carbon were fixed by farmed mollusks in China, equivalent to 2.45 million tons of CO_2 or 0.279 hm^2 forest absorption (Tang et al. 2011). Over the years 2010–2017, aquaculture harvested in the world 53.5 million tons of crustaceans and 122.5 million tons of mollusks, roughly 10.6 million tons of carbon or 3.7% of global carbon emissions from fossil fuel used in this period (Moore et al. 2022).

However, Munari et al. (2013) deny the cultivated bivalves to be part of carbon trading systems, because in the process of biogenic calcification, one mole of CO_2 is released for each mole of generated $CaCO_3$, according to the calcification equation:

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O$$

According to their calculation, farmed Mediterranean mussel (*Mytilus galloprovincialis*) sequestered 136.6 mol $CO_2/(m^2 \cdot year)$ for shell formation, but the CO_2 fluxes due to respiration and calcification resulted 187.8 and 86.8 mol $CO_2/(m^2 \cdot year)$, respectively. During the formation of shell calcification, 1 mol $CaCO_3$ is generated with release of 1 mol CO_2 in freshwater and 0.6 mol CO_2 in seawater (Ware et al. 1992). Asian clam (*Potamocorbula amurensis*), the invading species in San Francisco Bay of United States, is a source of CO_2 production (Chauvaud et al. 2003). Asian clam in this region is capable of releasing 18 $gC/(m^2 \cdot year)$ of CO_2 through calcification and 37 $gC/(m^2 \cdot year)$ through respiration. The amount of CO_2 generated by the calcification and respiration of the clams has exceeded the amount of CO_2 fixed by primary production. Many scholars also believe that mollusk mariculture is a source of the atmospheric CO_2 due to calcification and respiration (Chauvaud et al. 2003; Gazeau et al. 2007; Gollĕty et al. 2008; Mistri and Munari 2012).

It is believed that mollusk respiration and calcification lead to a decrease in the pH of seawater, which increases CO_2 saturation and is not conducive to the absorption of atmospheric CO_2 by seawater. However, insufficient attention has been paid to the promoting effect of mollusk metabolites on microalgae photosynthesis (Sterner 1986), which would increase the pH of seawater and facilitate seawater absorb CO_2 from the atmosphere.

Based on mollusk mariculture field investigation, Zhang et al. (2013) found that partial pressure of CO_2 (pCO_2) did not increase in mollusk-farming waters in

Sanggou Bay, Shandong Province, China. However, more investigators found that CO_2 concentration or pCO_2 in mollusk mariculture areas was higher than that of nonmollusk mariculture areas (Jiang et al. 2012b; Zhang 2015; Liu et al. 2017; Han et al. 2021; Yang et al. 2021).

At present, there is still no consensus on carbon sink of mollusk mariculture. Academic circle has carried out researches with different methodology on it. Based on holism method, such as conservation of matter, Tang et al. (2011) and Moore et al. (2022) consider mollusk mariculture as carbon sink. Based on reductionism method, such as calcification equation, Chauvaud et al. (2003), Gollety et al. (2008), and Munari et al. (2013) consider mollusk mariculture as carbon source. You could think the CO_2 flux on air-sea interface of mollusk mariculture field would prove it, but unfortunately, coastal currents and/or reciprocating tidal currents make the boundaries of mollusk mariculture systems unclear. Filter feeding of the bivalves can rapidly reduce the total carbon content in water, especially the particulate organic carbon content. The field observations ignored the duration and extent of the subsequent impact of the water mass with reduced total carbon mass on the carbon source/sink of the marine ecosystem after it flows out of the mariculture areas. At present, we still lack clear boundaries and long-term manipulative experiments (Hurlbert 1984) that integrate the mollusk individuals, culture environment, and air-sea interface to prove the mollusks as CO_2 sink or source of atmosphere!

According to the studies conducted by Zhang (2011), annual carbon release from the respiration and calcification of farmed scallop in Sanggou Bay is 1.22×10^4 t (446 $mgC/m^2 \cdot d$) and 7.57×10^2 t (27 $mgC/m^2 \cdot d$), respectively. Biodeposition and calcification of the scallop can fix 8.71×10^4 t and 1.06×10^3 t carbon annually, respectively, most of which will be buried or fixed for a considerable time. Hence, although the scallops release some carbon through respiration and calcification, more carbon is buried and fixed through biodeposition and calcification.

Mollusks include species with different feeding habits. The impact of mollusk mariculture on global climate change involves not only CO_2 but also greenhouse gas emissions such as CH_4 and N_2O (McCarthy et al. 2019), as well as biodeposition. To reach common consensus on the interaction between mollusk mariculture and climate change, we still have a lot of work to do!

Brief Summary

1. In general, requirements of aquatic organisms inhabiting in cold, flowing or salty waters for water quality are generally stricter compared with those living in warm, static or fresh waters.
2. Interactive relationships exist between aquaculture activities and environment. On the one hand, the impacts of anthropogenic activities on aquatic ecosystems and in turn on aquaculture are increasingly intensified as a result of the economic and social development; on the other hand, aquaculture activities also affect the environment. In other words, aquaculture is not only an injurer but also sufferer of environmental deterioration.

3. There are various aquaculture methods, some of which will accelerate the eutrophication of water, e.g., fish farming with feed supply. However, others will delay the eutrophication of water, e.g., seaweed cultivation. Since 1970s, the increasing adoption of artificial pelletized feed, modern fish cages, and aerators have promoted the rapid expansion and intensification of aquaculture in the world, which posed increased effects on the environment.
4. Major pollutants affecting mariculture and nearshore marine environment include domestic sewage, fertilizers, pesticides, oil, heavy metals, and sometimes occurred harmful algal blooming (HAB).
5. Environmental threats derived from aquaculture activity include mainly obstruction of water flow by aquaculture facilities, biodeposition from farmed animals, nutrient and chemical discharges, escape of farmed fish, invasion of exotic species and damage to mangroves, hazards to biodiversity, and so on.
6. Due to global warming, significant changes are occurring and accelerating in aquatic ecosystems that support aquaculture. Changes in hydrological systems, rainfall patterns, sea level, water temperature, dissolved oxygen, ocean acidification, and primary productivities of aquatic ecosystems exert more direct and greater impacts on aquaculture. Short-term effects of global warming on aquaculture include loss of production or infrastructure caused by extreme events, disease, toxic algae, and parasites, and yield reduction caused by poor production conditions. Long-term effects include scarcity of wild seedlings, limited freshwater resources for production, restricted feed resources from marine and terrestrial sources, reduced productivity, eutrophication, and other disturbances.
7. The effects of aquaculture industry on global climate change in long-term include four main aspects: greenhouse gas emissions in aquaculture activity, carbon removal from aquaculture products, carbon sequestration in sediment of aquaculture waters, greenhouse gas fluxes between water-air interface.
8. In general, the inland freshwater lakes are source of the atmospheric CO_2, and the oceans are sink of the atmospheric CO_2. Mariculture ponds are an intermediate type between oceans and lakes in terms of global warming potential. They all release a certain amount of CH_4, but some release CO_2 while others absorb it due to different farming models.
9. During the decade from 1999 to 2008, a total of 0.67 million t carbon are fixed by shellfish culture in China, the amount of which is equivalent to 2.45 million t CO_2. Therefore, shellfish culture in seawater is called "carbon sink fisheries".
10. Carbon sink fisheries refer fishery production activities that can facilitate aquatic organisms to absorb CO_2 from water and have the effect of directly or indirectly reducing atmospheric CO_2 concentration.
11. At present, we still lack clear boundaries and long-term manipulative experiments that integrate the mollusk individuals, culture environment, and air-sea interface to prove the mollusk as CO_2 sink or source of atmosphere.
12. The impact of mollusk mariculture on global climate change involves not only CO_2 but also other greenhouse gas emissions, such as CH_4 and N_2O, as well as biodeposition.

Growth of Aquaculture Animals

5

Shuang-Lin Dong and Yan-Gen Zhou

The growth of aquatic animals refers to the increment of their body length or weight, subjected to their endogenous and exogenous factors and the interaction between. Endogenous factors mainly refer to genotypes and physiological conditions. Exogenous factors mainly involve food, water temperature, salinity, light, dissolved oxygen (DO), and other water quality-related factors, as well as the interspecies and intraspecies competition. Genotype determines metabolism type and the progress which control the growth of aquatic animals. Environmental factors are indispensable conditions for the growth and development of aquatic animals.

5.1 Growth Pattern of Aquatic Animals

Each farmed aquatic animal has its own specific growth pattern. Its growth rate is one of the key indicators to measure its economic value, to evaluate the water quality and the management level of a specific aquaculture waters. The growth rate of a farmed animal not only reflects its biological characteristics but is also important for farmer to set the length of farming duration.

5.1.1 Growth Characteristics and Sizes of Aquatic Animals

Fish is one of the most important group of aquaculture organisms. Both farmed fish and wild fish follow their specific growth patterns. In general, fish species as a whole show six characteristics in their growth (Yin 1995):

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1. Indetermination: Growth variation in fish size is far greater than in other vertebrates. Its coefficient of variation (CV, standard deviation of growth divided by the mean value) generally ranges from 20% to 30%, far higher than 7%–10% of most domesticated animals (Gjedrem 1997). Most fish species almost never stop growing in its lifetime. Taking an individual for example, it is rather difficult to accurately predict how long or how heavy it is at a given time due to different exogenous factors that affect its growth rate. The growth variation of sea cucumber is much greater than that of fish, due to both endogenous (genetic) and exogenous (environmental) effects (see Sect. 5.5 of this chapter).
2. Flexibility: Fish cultured under different environmental conditions, even if the same species, may grow at different rates and reach sexual maturity at different sizes. Different geographical populations of the same species may have different growth patterns. For example, growth characteristics of silver carp, bighead carp, and grass carp in Yangtze River, Pearl River, and Heilongjiang River are very different (Li 1998). The average body lengths of 5^+ age silver carp are 74.9 cm, 73.3 cm, and 56.5 cm in Yangtze River, Pearl River, and Heilongjiang River, respectively. The silver carp grows faster in Yangtze River than in Pearl River because of the more diet organisms in Yangtze River, although the suitable period for growth in Yangtze River is shorter. In contrast, the silver carp in Heilongjiang River grows far more slowly than those in both Yangtze and Pearl Rivers because of the shorter suitable period for growth in Heilongjiang River although diet organisms are abundant there. Growth may also vary in the same population year to year due to the interannual variation in climate and hydrology.
3. Growth by stages: Normally, fish growth can be divided into three stages: presexual maturity, postsexual maturity, and senescence. The biggest profit in aquaculture production is usually achieved in the presexual maturity stage when fish grows very fast, which is an evolutionary adaptation to avoid predation as soon as possible at its juvenile stage. At sexual maturity stage, fish use much more its accumulated material and energy for gonadal development, so its growth rate slows down significantly. The age of sexual maturity is vital for determining the culture duration. In general, suitable stages for fish farming is its larvae, fry, and juvenile stages before sexual maturity. Some fish such as rainbow trout have been successfully farmed to obtain a larger size product by stocking triploid individuals with no development of sexual glands.

   Molting is typical of crustaceans such as shrimp and crab which outgrow its shell periodically. The interval between two times of molting is called molting cycle. Molting falls into the stages of premolting (preparatory time before molting), midmolting (from the beginning of molting to the shelling), postmolting (from the end of molting to the hardening of soft shell), and molting interval (between the hardening of shell and the next preparatory time). Crustacean grows longer and heavier very fast during the midmolting stage even though its body tissue is of higher water content, and then grows only in weight instead of length during the postmolting and molting interval stages.
4. Seasonality: Growth seasonality of aquatic animals is a short-cycle growth pattern subject to seasonal changes such as water temperature and diet organisms.

Generally, water temperature of aquaculture waters varies with seasons, affecting the food abundance, the feeding behavior, metabolic rate, and growth rate of the farmed animals. In the case of euthermic fish, it stops growing or grows very slowly in winter when it does not feed or feeds less. When water temperature rises in spring, aquatic animal begins to grow fast and the fastest growth rate occurs in summer, followed by slow growth in autumn. Sea cucumber is of echinoderms in cold temperate zone, estivating at water temperatures higher than 20 °C depending on body sizes, and hibernating at water temperatures lower than 3 °C.

5. Difference between male and female: Many aquatic animals grow differently between male and female, especially in the shapes and sizes of the individuals. For example, male sole (*Cynoglossus* semilaevis) is very different from the female in size at sexual maturity. Therefore, farmers always eliminate male individuals or culture all-female stocks in sole farming practice. In the East Lake of Wuhan, the females of both silver carp and bighead carp at all ages are longer in sizes than the males. Meanwhile, their sexual differences increase as they grow up. The specific growth rates of body length of female and male silver carp differ by 0.56%, 2.75%, and 17.61% from age 1 to 4, and those of bighead carp differs by 0.70% and 6.56% from age 1 to 3, respectively (Ruan 1986). It is easier to produce larger-size products by culturing only female rainbow trout which is sexually mature 1 year later than the male.
6. Isometry and allometry: Some parts of fish grow at the same rate (isometry) while others at different rates (allometry). Some tissues of fish like scale, otolith, and backbone are often used to infer the age of a fish and the body length at a given age, because they grow at the same rate as the body grows.

Aquaculture often involves the selection of fast-growing species, operation in the right season, and creating a good environment for growing aquatic organisms. Size is one of the main attributes of fish. The annual absolute growth rates of different fishes are proportional to their body sizes. Given the same conditions, the annual growth rates of fishes generally decrease with decreasing body size. The maximum body weights of some fishes are listed in Table 5.1.

5.1.2 Growth Models of Aquatic Animals

Fish are the most studied of aquatic animals. Fish biologists have developed some models or equations to describe the growth characteristics of fish, such as von Bertalanffy equation and energy budget model.

5.1.2.1 von Bertalanffy Equation in Fish

One of the characteristics that distinguishes fish from most other animals is that they continue to grow throughout their lives, except that the growth rate before sexual maturity is significantly faster than the growth rate after sexual maturity. The growth curve in weight is a shape of asymmetrical “S”, and the point of inflection usually occurs at sexual maturity period. The growth accelerates before the inflection point and slows down after it.

Table 5.1 Maximum body weights (kg/ind.) of farmed fishes (from Liu and Huang 2008)

Types	Species	Weights	Species	Weights	Species	Weights
Giant fish	*Huso dauricus*	1000	*Acipenser sinensis*	550	*Acipenser baerii*	200
	Acipenser schrencki	108	*Acipenser gueldenstaedti*	>100		
Large fish	*Polyodon spathula*	83	*Mylopharyngodon piceus*	70	*Sciaenops ocellatus*	56.8
	Hypophthalmichthys nobilis	50	*Morone saxatilis*	45	*Rachycentron canadum*	43
	Silurus soldatovi meridionalis	40	*Cyprinus carpio*	40	*Silurus soldatovi*	40
	Scophthalmus maximus	40	*Silurus asotus*	35	*Ctenopharyngodon idella*	35
	Hypophthalmichthys molitrix	35	*Oncorhynchus mykiss*	25	*Lateolabrax maculatus*	25
	Seriola dumerili	>20	*Ietalurus Punetaus*	20	*Colossoma brach ypomum*	20
	Oncorhynchus keta	15	*Chanos chanos*	15	*Paralichthys olivaceus*	15
	Leiocassis longirostris	13	*Mugil cephalus*	12	*Clarias lazera*	>10
	Trachinotus ovatus	>10	*Takifugu rubripes*	10	*Anguilla japonica*	10
	Pagrus major	10				
Medium fish	*Micropterus salmoides*	8	*Cirrhinus molitorella*	8	*Verasper moseri*	8
	Epinephelus akaara	6.2	*Lutjanus argentimaculatus*	6	*Lates calcarifer*	>5
	Cynoglossus semilaevis	>5	*Megalobrama terminalis*	5	*Carassius auratus gibelio*	5
	Oreochromis niloticus	5	*Channa argus*	5	*Siniperca chuatsi*	5
	Sebastes schlegelii	>4	*Parabramis pekinensis*	4	*Acanthopagrus schlegelii*	>3
	Kareius bicoloratus	>3	*Hapalogenys nitens*	>3	*Larimichthys crocea*	>3
	Plagiognathops microlepis	3	*Megalobrama amblycephala*	3	*Lepomis macrochirus*	>2
	Takifugu obscurus	>2	*Hexagrammos otakii*	>1	*Larimichthys crocea*	3.8
Small fish	*Plecoglossus altivelis*	0.9	*Bostrychus sinensis*	0.5	*Clarias macrocephalus*	0.4
	Misgurnus anguillicaudatus	0.1	*Hypomesus olidus*	0.02	*Protosalanx hyalocranius*	0.02

von Bertalanffy (1938) viewed the concept of "growth" in the perspective of metabolism, namely the instantaneous weight gain (growth) of a fish is equal to the increase of instantaneous assimilation minus the decrease of dissimilation. Assimilation rate (A) is proportional to physiological absorbing area (S). Dissimilation (D) is proportional to total consumption rate or weight (W). Therefore

$$\mathrm{d}W/\mathrm{d}t = AS - DW$$

Assume the fish is isometrically growing, then $W = ql^3$, $\mathrm{S} = pl^2$ (q and p are constants, l is body length), then

$$\mathrm{d}(ql^3)/\mathrm{d}t = Apl^2 - Dql^3$$
$$\mathrm{d}l/\mathrm{d}t = (Apl^2 - Dql^3)/3ql^2 = (Ap/3q) - (Dl/3)$$

The solution of this linear differential equation is

$$lt = (A_p/D_q) - (A_p/D_q - l_0)e^{-(D/3)t}$$

When t increases infinitely, $l_t \rightarrow A_p/D_q$, therefore, A_p/D_q is average progressive length, $D/3$ is a constant, abbreviated as k. Therefore, $l_t = L_\infty - (L_\infty - l_0)\mathrm{e}^{-kt}$, and its transformation is

$$l_t = L_\infty\left(1 - e^{-k(t-t_0)}\right)$$

Because of isometrical growth, $W_t = al_t^{\,3}$, $W_\infty = aL_\infty^{\,3}$, therefore,

$$W_t = W_\infty\left(1 - e^{-k(t-t_0)}\right)^3$$

The above is von Bertalanffy Equation, together with its deduction, in which t is age, l_t and W_t are average length and weight at t, L_∞ and W_∞ are average progressive length and weight, k is growth coefficient, and t_0 is theoretical age at which fish begins to grow.

Like other fish, silver carp and bighead carp also grow in accordance with von Bertalanffy Equation. Here are the growing models of the silver carp and bighead carp in the East Lake of Wuhan, based on the calculation of Ruan (1986)

$$\text{Silver carp} \quad l_t = 99.8\left(1 - e^{-0.3040(t-0.4821)}\right)$$
$$\text{Bighead} \quad l_t = 117.6\left(1 - e^{-0.3088(t-0.5392)}\right)$$

The maximum lengths (l_∞) of silver carp and bighead carp are 99.8 cm and 117.6 cm, respectively.

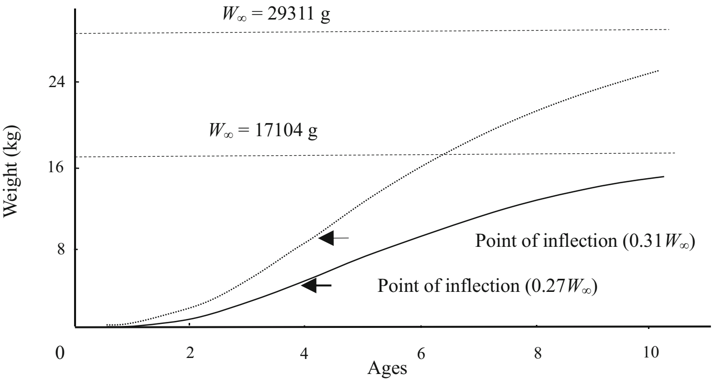


Fig. 5.1 The von Bertalanffy growth curves in body weight of silver carp (solid line) and bighead carp (dotted line) (from Ruan 1986)

As coefficient b is both approximately 3 in the regression equation of the length and weight of silver carp and bighead carp, their maximum weights are calculated to be 17,104 g and 29,311 g, respectively, depending on the value of l_∞. See the following equations and Fig. 5.1 for the relationship between their age and weight.

$$\text{Silver carp} \quad W_t = 17.104\left(1 - e^{-0.3040(t-0.4821)}\right)^3$$

$$\text{Bighead carp} \quad W_t = 29.311\left(1 - e^{-0.3088(t-0.5392)}\right)^3$$

Thus, the weight growth curves of silver carp and bighead carp are asymmetrical S-shaped curves approximating to their maximum weights (W_∞), with the points of inflection occurring at 4615 g and 9099 g, respectively. According to the theoretical growth curve, the growth points of inflection of the silver carp and bighead carp in the East Lake are at the ages of 3.9 and 4.2, respectively, which are the same ages as those of the length growth of the fishes.

Anatomy revealed that the sexual glands of the silver carp and bighead carp in the East Lake were not yet fully developed even if they reach the age of sexual maturity. Bighead carp and silver carp are the migration species between lake and river, only in a flood they can complete sexual maturity, and spawn drifting eggs while against the river current. They cannot complete the sexual maturation process in a still-water environment like the East Lake. It should be noted that the inflection point of fish growth is related to the individual sizes while the sexual maturity is no more than a visible phenomenon, as seen in the case of silver carp and bighead carp of the East Lake whose inflection point of growth will occur in time no matter whether their sexual maturity is completed or not.

Table 5.2 Parameters of von Bertalanffy growth equations of some fish species (from Li 1998)

		Growth parameters				
Species	Sex	L_∞ (cm)	W_∞ (g)	k	t_0	Locations
Hypophthalmichthys molitrix	♂	111.1	31,767	0.1758	−0.1933	Tian'ezhou of the Yangtze River
	♀	125.6	52,962	0.1607	−0.0684	
Hypophthalmichthys nobilis	♂	100.1	18,306	0.2745	0.3219	
	♀	136.0	47,424	0.1521	0.0104	
Ctenopharynodon idellus	♂	102.7	16,361	0.2317	−0.1646	
	♀	113.6	23,916	0.1911	−0.1165	
Mylopharyngodon piceus	♂	198.1	122,466	0.0862	−0.3437	
	♀	220.4	157,384	0.0789	−0.2982	
Megalobrama amblycephala	♂	39.5	1411	0.5109	0.2164	Yunihu, Hubei
	♀	48.5	3132	0.3365	0.1269	
Cyprinus carpio var. *singuonensis*	♂	76.8	13,066	0.1596	−0.1125	Xingguo, Jiangxi
	♀	84.9	28,004	0.0288	−0.6206	

The specific growth rates (G) of silver carp and bighead carp decline as the age increases. For example, the G_s in length of silver carp before the age of 5 decrease by 55.95%, 52.33%, and 30.34%, respectively, and bighead carp are accordingly 60.09%, 45.15%, and 37.98%, respectively.

The growth of fishes is subject to many environmental factors such as food, water temperature, and water chemical factors in addition to genetic factors. The growth variation of different generations of silver carp and bighead carp is attributed to different environmental and food conditions in different years, and also reflects the growth compensation of the fish. During the growth process of fishes, the smaller-size individuals tend to catch up with the larger-size ones, known as the growth compensation.

Some fishes are different in the growth of male and female individuals. The parameters of the growth equations of some species such as silver carp, bighead carp, grass carp, black carp, blunt snout bream, and Xinguo red carp (Table 5.2) (Li 1998) indicate that the biggest male individuals are smaller than the biggest female ones.

5.1.2.2 von Bertalanffy Equation of Shellfish

The growth of mollusks is different from finfish, its shell grows continuously but its soft tissue grows only in certain seasons. For example, the soft tissues of pearl oyster (*Pinctada margaritifera*) grow rapidly in summer but almost stop growing in winter (Fig. 5.2), which can be described by incorporating a sine wave q (Bayne 2017) as follows

$$
\begin{aligned}
l_t &= l_\infty[1 - \exp(-q)] \\
q &= k(t' - t_0) + k/Q[\sin Q(t' - t_s) - \sin Q(t' - t_s)] \\
Q &= 2\pi/(1 - \mathrm{NGT})
\end{aligned}
$$

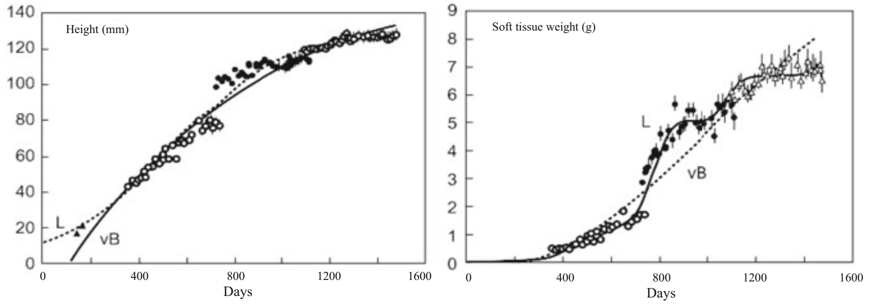


Fig. 5.2 Growth of *Pinctada margaritifera* fitted by logistic (L) and Bertalanffy (vB) growth models for shell height and tissue weight (from Bayne 2017)

where, NGT stands for "no-growth time t_s", and t_0 is obtained by subtracting the total no-growth time occurring up to age t from the real age (t). The seasonality of growth is described by a sine wave with a period of 1 – NGT, and the unit of k becomes $(1 - \mathrm{NGT})^{-1}$ instead of per annum. This modification allows a smooth transition between periods of growth and no-growth.

5.1.2.3 Bioenergetics Models of Aquatic Animals

Bioenergetics models are based on bioenergetics principles to predict the relationship between growth and feeding of aquatic animals, and are widely applied in aquaculture and fishery management. The following is the basic equation of fish bioenergetics model

$$G = C - F - U - R = C - F - U - Rs - Ra - SDA$$

where, G is growth energy; C is feeding energy; F is fecal energy; U is excretion energy; R is respiratory metabolic energy; Rs is standard metabolism; Ra is activity metabolism; SDA is special dynamic action or body heat increment.

Since crustaceans are characterized by molting, their bioenergetics model is then modeled as

$$G = C - F - U - E - R = C - F - U - E - Rs - Ra - SDA$$

where, E is molting energy. In some studies, molting energy is usually viewed as a negligible component in the energy budget of shrimp and crab as it accounts for a very small percentage in their total energy budget.

As for some special aquaculture species, more components are added to their bioenergetics models, such as sexual gland, often seen in some mollusks and echinoderms, either because their sexual glands are more developed or delicious.

The growth of mollusks contains three parts: the growth of soft tissue ($G_{\text{soft tissue}}$), the growth of shell (G_{shell}), and the growth of sexual gland ($G_{\text{sexual gland}}$). Therefore, its bioenergetics model is as follows

Table 5.3 Energy budgets of several aquatic animals

Species	*G*/*C* (%)	*R*/*C* (%)	*F*/*C* (%)	*U*/*C* (%)	*E*/*C* (%)	References
Arca inflata *Scapharca broughtonii*	25.7	29.8	39.5	5.0	0	Chang and Wang (1996)
Abalone *Haliotis midae*	4.5	32.4	63.0	0.1	0	Barkai and Griffiths (1988)
Grass carp *Ctenopharyngodon idellus*	14.34	52.48	29.89	3.30	0	Cui (1998)
Grouper *Epinephelus fuscoguttatus*	20.38	55.54	18.07	6.05	0	Zhou et al. (2012)
Flounder *Paralichthys olivaceus*	45.50	47.49	1.59	5.41	0	Wu et al. (2011)
Shrimp *Fenneropenaeus chinensis*	13.1	67.3	11.9	7.1	0.6	Tian et al. (2006)
Sea cucumber *Apostichopus japonicus*	6.67	39.07	49.98	4.28		Bao (2008)

Notes: *C* ingested food energy, *E* molt energy, *F* feces energy, *G* growth energy, *R* respiratory metabolism energy, *U* excretion energy

$$G = G_{\text{soft tissue}} + G_{\text{shell}} + G_{\text{sexual gland}} = C - F - U - Rs - Ra - SDA$$

The bioenergetics models of some aquatic animals are presented in Table 5.3. The fecal energy of herbivores accounts for a higher percentage of the ingested food energy, such as Arca inflata (*Scapharca bronghtonii*), abalone (*Haliotis midae*), and grass carp. For sea cucumber feeding on organic matter in the sediment, its fecal energy accounts for as much as 50% of the ingested food energy. The proportion of energy used for metabolism is somewhat higher for the more motile fish and shrimp.

The application of bioenergetics models in aquaculture includes estimating the growth of fish according to how much feed consumed or predicting how much feed required according to the expectations about fish growth. Cui and Li (2005) have established the bioenergetics model of grass carp to assess the productivity of a lake and how many grass carp fingerlings can be stocked in it (see Sect. 3.2 for detail). The relationships between the components of energy budget, and between the component and environmental factors are the main research topics of bioenergetics.

5.2 Effects of Temperature on the Growth of Farmed Animals

Compared with mammals, aquatic animals are far more susceptible to the environmental conditions such as temperature, salinity, DO, pH, etc. Nutritional conditions also significantly affect the growth of farmed animals, which is usually secured by adjusting stocking density, culturing natural diet organisms, and delivering pellet feed. It is important to provide good nutritional and environmental condition in aquaculture to ensure the appropriate individual growth rate and high yield of the farmed animals. Water temperature is one of the most important factors that affect the growth of farmed aquatic animals.

5.2.1 Adaptability of Aquatic Animals to Temperature

Farmed fishes and invertebrates are ectotherms that are very sensitive to water temperature. A slight change of temperature will affect their metabolism, development, and growth. Each species of farmed animals has its adapted temperature range, beyond which its metabolism will be affected adversely. Higher temperature within the range usually accelerates the metabolism, development, and growth. But higher temperature above the range will dramatically increase the metabolism rate and decrease the energy reserve, thus impairing the growth. Temperature lower than the range will lead to slow physiological response, low metabolism, and even no growth.

Aquatic animals fall into eurythermal and stenothermal ones. Eurythermal animals can tolerate the temperature change of over 10 °C, such as common carp which can survive both in frozen ponds of Heilongjiang Province in winter and the warm water ponds of Guangdong Province in summer. However, stenothermal animals can only tolerate the temperature change of less than 10 °C, such as the fishes inhabiting Antarctic or tropical coral reefs. Widely farmed animals in aquaculture are usually eurythermal species; hence, they can tolerate greater range of temperature change.

Each species of aquatic animals can tolerate a temperature range between the upper limit and lower limit. Like other animals, the optimum temperature for aquatic animals is also relatively close to the upper limit of the temperature range. Aquatic animals cannot tolerate high temperatures as some bacteria and microalgae do. As a result of evolutionary adaptability to environment, freshwater animals are generally better in tolerating higher temperatures. Some freshwater invertebrates can tolerate water temperature of 41–48 °C, but most marine invertebrates can tolerate no higher than 30 °C. Fish as a whole cannot tolerate high temperatures. Sturgeon eggs stop developing at >20 °C. The upper limit of temperature tolerance is even lower for the development of salmon and cod eggs. The highest sublethal temperature (LT_{50}) for silver carp is 39.4 °C. The optimum temperature range of eel is 25–30 °C and its LT_{50} is 39.2 °C. Mitten crab (*Eriocheir sinensis*) will have abnormal activity at 37 °C and die at 40 °C. The suitable temperature for sea cucumber is 16–20 °C, and dead at 26 °C.

Aquatic animals can adapt to the extreme temperature in behavioral and physiological ways. Migration and schooling are typical of behavioral adaptability, as seen in some fishes that migrate and schooling in deeper areas in winter for higher temperature and lower heat loss. Physiological adaptability can be exemplified by the sea cucumber (*Apostichopus japonicus*), which hibernates in the low temperatures of winter and estivates in the high temperatures of summer.

The adaptability to temperature of aquatic animals can be acclimated and changed. If temperature changes slowly, the upper or lower limit of temperature tolerance of fish will be higher or lower. In a study on mosquito fish, if temperature drops from 25 to 16 °C at the speed of 3 °C/h, the fish is still in normal condition. If temperature drops from 25 to 10 °C, the fish will die within 2–3 days. However, if it is acclimated for 23 days after the temperature drops from 25 to 16 °C, and then from 16 to 10 °C, no fish died within 2–3 days. However, they will die 40 days later.

The tolerance to temperature change of a species varies with the basic temperature of its habitat or acclimating temperature. Relatively high acclimating temperature will raise the upper limit of its temperature range; however, relatively low acclimating temperature will reduce the lower limit of its temperature range. The temperature tolerance of a species also varies significantly with seasons and geographical locations. The animals in summer season (or in low latitudes) can usually tolerate higher temperature, while in winter (or in high latitudes) the same animals usually can tolerate lower temperatures.

The temperature tolerance of animals experiencing different thermal histories will vary. Temperature acclimation can significantly change the heat tolerance of sea cucumber (Ji et al. 2008; Wang et al. 2013). The CT_{max} of the sea cucumbers (*A. japonicus*) acclimated at 16 °C, 21 °C, and 26 °C for 40 days are 33.1 °C, 34.1 °C, and 36.6 °C, respectively. This phenomenon lays the theoretical basis for the sea cucumber in North China to be acclimated and then farmed in South China.

Compared with the population of Chinese shrimp (*Fenneropenaeus chinensis*) in the Yellow Sea and Bohai Sea in China, the population of the shrimp at the Pearl River Estuary is more tolerant of high temperatures, having experienced different thermal histories (Wang et al. 1998c).

Aquatic animals have different adaptabilities to temperatures at different development stages. Generally, the embryonic or larval stage requires more stringent temperature ranges. The reproductive temperature of some aquatic animals is a key environmental factor that restricts the distribution area of their populations.

5.2.2 Effects of Water Temperature on Farmed Animals

Aquatic animals grow faster as temperature increases within certain range. In nature, seasonal variations in temperature can lead to seasonal variations in aquatic animal growth. In practice, extending the growing season through temperature control can lead to an increase in the size of farmed animals. The effects of water temperature on the growth of a few important farmed animals are introduced below.

5.2.2.1 Effects of Temperature on the Growth of Sea Cucumber

Sea cucumber (*A. japonicus*) is a eurythermal species, which grows well at water temperature range of 10–20 °C, and can survive at the range of 2–30 °C. With the increase of temperature, the growth curve of sea cucumber showed a bell-shaped change. Sea cucumber grows the best at about 15 °C, but smaller-sized individuals are better in tolerating high temperature, and their optimal growth temperature would be higher (Dong and Dong 2006). Definitely their tolerance of temperatures is subject to their thermal history and physiological conditions.

The ingested energy and its allocation of 13–32 g sea cucumbers at different temperatures are presented in Table 5.4. There is no significant difference in the ingested energy of the animal when temperatures are at 12, 17, and 22 °C. 12 °C is a relatively optimum temperature at which sea cucumber has good appetite and its energy is best allocated comparing with the animals at other temperatures. The result can be more accurate if the temperature gradients are set with smaller intervals around 12 °C. The results also showed that nearly 50% ingested energy is defecated as feces instead of being absorbed.

The effect of temperature on the growth of the sea cucumber is related to the change of its feed ingestion. The ingestion rate is higher at the suitable temperature range. But both ingestion rate and food conversion ratio will drop significantly at high temperatures. When temperature rises in summer, sea cucumber will stop feeding and reduce its activity, along with intestinal degradation and weight loss. The critical temperature inducing sea cucumber to estivate varies with its geographical distribution and body weight. The higher the latitude, the higher critical temperature for estivation. The heavier body weight, the lower critical temperature for estivation. For sea cucumbers of 25–85, 86–160, and over 160 g, their critical temperatures for estivation are 24.1, 22.9, and 21.8 °C (Li et al. 1996a).

The dry weight of the sea cucumbers increases by 18.5% after 36-d of satiated culture (FD) at 17 °C (Fig. 5.3), while the dry weights in "hibernation" group (HT) at 3 °C, starvation group (ST) at 17 °C, and "estivation" group (AT) at 24 °C all decreases by 19.80%, 38.07%, and 47.42%, respectively, at the same time period (Bao et al. 2010).

The oxygen consumption rates (Vo_2) of the sea cucumbers is the highest at the high temperature (24 °C), followed by the normal temperature (17 °C), and the low temperature (3 °C). The Vo_2 of ST group is higher than that of the FD group only on the first 3 days of the fasting period, while lower than the FD group in all the rest time. The Vo_2 of FD group increases slowly by 26.5% after 36 days. However, the Vo_2 of ST and FD groups keep declining with the fasting time extended. After 36 days, the Vo_2 have decreased by 71.7%, 48.9%, and 44. 9% for the HT, ST, and AT groups, respectively (Bao et al. 2010).

5.2.2.2 Effects of Temperature on the Growth of Shrimp

Chinese shrimp is mainly distributed in the Yellow Sea and Bohai Sea where the water temperature ranges between 4 and 28 °C, but it can adapt to wider temperature ranges in the aquaculture environment. Chinese shrimp (*F. chinensis*) at the range of 28–31 °C grows faster than that at other temperatures, and their specific growth rates reach 3.10%–3.28% (Table 5.5). Based on the polynominal fitting equation, the optimum temperature of growth in Chinese shrimp was 29.7 °C (Tian et al. 2006).

Temperature adaptability of shrimp is related to its development stage and thermal history. The optimum temperatures for the development and growth of nauplius, zoea, schizopod, and postlarvae of Chinese shrimp are 22 °C, 22–25 °C, and 25–28 °C, respectively (Wang et al. 1998c). It is noted that the optimum temperature for Chinese shrimp increases as its size or developmental stage increases.

Table 5.4 Energy allocation of *Apostichopus japonicus* under different temperatures (from Dong and Dong 2006)

Temperatures (°C)	Ingested energy (C, J/(g·d))	*G*/*C* (%)	*F*/*C* (%)	*U*/*C* (%)	*R*/*C* (%)
7	2128.31 ± 68.97^{a}	7.25 ± 0.55^{c}	47.59 ± 1.71^{ab}	4.48 ± 0.10^{b}	40.68 ± 1.60^{a}
12	5308.18 ± 188.81^{b}	10.00 ± 0.19^{d}	56.64 ± 1.84^{c}	3.90 ± 0.15^{a}	25.55 ± 4.26^{b}
17	5564.38 ± 343.06^{b}	6.67 ± 0.31^{c}	49.98 ± 1.54^{b}	4.28 ± 0.51^{b}	39.07 ± 1.61^{a}
22	5281.57 ± 319.11^{b}	4.65 ± 0.21^{b}	43.87 ± 0.84^{a}	4.52 ± 0.07^{b}	42.46 ± 4.58^{a}
27	2622.29 ± 132.41^{a}	1.84 ± 0.10^{a}	43.47 ± 1.71^{a}	4.45 ± 0.12^{b}	45.80 ± 4.74^{a}

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$). *E* excretion energy, *F* feces energy, *G* growth energy, *R*, respiratory metabolism energy, *U* excretion energy

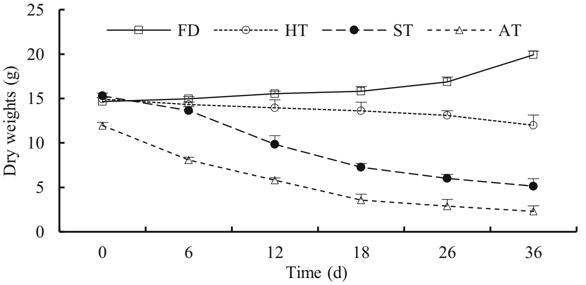


Fig. 5.3 Dry body weight of *Apostichopus japonicus* under conditions of feeding (FD), hibernation (HT), estivation (AT), and starvation (ST) (from Bao et al. 2010)

Table 5.5 Growth (*SGR*), food consumption, and food conversion efficiencies of Chinese shrimp (*Fenneropenaeus chinensis*) at different temperatures (from Tian et al. 2006)

Temperatures (°C)	Initial sizes (g)	Feeding rates (mg/(ind.·d))	*SGR* (%/d)	Energy conversion efficiencies (%)
18	0.35 ± 0.02	10.06 ± 1.11^{e}	1.22 ± 0.29^{c}	15.27 ± 2.12^{a}
22	0.37 ± 0.01	16.50 ± 2.02^{d}	1.83 ± 0.20^{bc}	14.83 ± 1.11^{a}
25	0.35 ± 0.02	27.98 ± 1.84^{c}	2.73 ± 0.22^{ab}	15.70 ± 1.72^{a}
28	0.35 ± 0.02	37.98 ± 3.23^{b}	3.10 ± 0.42^{a}	13.99 ± 1.72^{a}
31	0.36 ± 0.02	50.24 ± 1.90^{a}	3.28 ± 0.20^{a}	13.25 ± 0.59^{a}
34	0.34 ± 0.04	31.40 ± 1.22^{c}	1.96 ± 0.38^{bc}	7.24 ± 1.12^{b}

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$). *SGR* specific growth rate

Whiteleg shrimp (*L. vannamei*) is a more heat-tolerant shrimp species, its upper limit and lower limit temperatures for juveniles are 41 °C and 4 °C, respectively. Its survival water temperature is 6–39 °C, suitable temperature for its growth is 18–35 °C, and the optimal temperature for its growth is 24–33 °C (Wang et al. 1998c). Wang et al. (2004a) reported that 30–33 °C was the optimal water temperature range for the growth and feeding of whiteleg shrimp. Yang et al. (2011b) reported that 31 °C was approximately the optimal water temperature for the juvenile to grow and develop. Wyban et al. (1995) found that the optimum temperature for the growth of the shrimp was subject to its development stages. For small shrimp (<5 g), temperature optima might be greater than 30 °C while for larger shrimp, the optimum temperature was about 27 °C. So, the adaptability of the shrimp to water temperatures is related to its sizes, thermal history, and so on.

There are mainly three patterns in energy allocation of shrimp and crab. First, the energy allocation to growth is the greatest among all components. For example, food conversion efficiency is up to 58% of ingested energy in Australian crayfish (*Cherax tenuimanus*), and even as great as 76% in the dark crab (*Callinectes rathebune*) (Villarreal 1991; Rosas and Vanegas 1993). Second, the energy allocation to respiration is greater than to other components. For example, the energy allocations to respiratory and growth are 40–60% and 30%–40% of its ingested energy in Alaskan crab (*Chionoecetes bairdi*) (Paul and Fuji 1989). Oriental river shrimp (*Macrobrachium nipponense*) has a similar energy budget models to the Alaskan crab (Dong et al. 1994). Third, the energy expenditure for excretion accounts for the biggest one among all components in the larval stage of shrimp and crab.

The energy allocation of Chinese shrimp belongs to the second pattern, in which the proportion of energy spent on respiration is the largest (Table 5.6). Its respiratory energy proportion increases from 61.84 to 71.48% with temperature increasing from 18 to 34 °C. The proportion of growth energy to ingested energy (*G/C*) for the shrimp feeding on pellet feed averages 12.45% and, in general, decreases with increasing temperature. Of course, the above findings are also related to the developmental stage of the experimental animals and the experimental treatment settings.

Fed with polychaete worm, the carbon intake of Chinese shrimp is significantly affected by water temperature and its body weight. With the increase of temperature and the decrease of body weight, the feed intake of Chinese shrimp significantly increases (Table 5.7). At 20 °C, 25 °C, and 30 °C, the average carbon intakes of the shrimp are 12.41, 19.12, and 26.08 mg/(g·d), respectively.

The nitrogen intake rate per unit body weight of Chinese shrimp increases with the increase of temperature, and decreases with the increase of body weight. The regression equation of the nitrogen intake rate (*Cs*, mgN/(g·d)) on polychaete worm versus body weight (*W*, g) and temperature (*T*, °C) is

$$\ln\ Cs = 1.75W^{-0.354}\mathrm{e}^{0.055T}$$

The regression equation for the nitrogen intake rate on pellet (*Cp*, mgN/(g·d)) versus body weight (*W*, g) and temperature (*T*, °C) is

$$\ln\ Cp = -0.704 - 0.364\ln W + 0.076T$$

The nitrogen allocation patterns of Chinese shrimp fed with polychaete worm and pellet are presented in Table 5.8. Their average nitrogen budget models are

$$100Cs = 27.63G + 3.58E + 1.66F + 67.13U$$
$$100Cp = 18.34G + 4.10E + 6.07F + 71.49U$$

where, *U* is the excretion of nitrogen.

5.2.2.3 Effects of Temperature on the Growth of Salmonid Fish

The main Salmonid fish currently farmed in the world are Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*), steelhead trout (*O. mykiss*), and brown trout (*Salmo trutta*). Landlocked rainbow trout and anadromous steelhead trout belong to the same species. Brown trout can adapt to seawater though it is a riverine sedentary type. Salmonids are cold-water fish, mostly found in waters with water temperatures not exceeding 20 °C and clean water.

The temperature tolerance characteristics of salmonids are very important for aquaculture. In terms of heat tolerance, the four widely farmed fishes are, in descending order, rainbow trout > steelhead trout > Atlantic salmon > brown trout. In terms of low temperature tolerance, rainbow trout ≈ steelhead trout >

Table 5.6 Allocation of the consumed energy fed with pellet in Chinese shrimp at different temperatures (from Zhang 1998)

Temperatures (°C)	G/C (%)	F/C (%)	U/C (%)	E/C (%)	R/C (%)
18	14.81 ± 1.24^{a}	16.11 ± 0.89^{a}	6.49 ± 0.24^{a}	0.75 ± 0.09^{a}	61.84 ± 2.22^{a}
22	13.94 ± 1.34^{a}	15.59 ± 1.12^{ab}	6.81 ± 0.15^{a}	0.80 ± 0.09^{a}	62.86 ± 3.12^{a}
25	13.82 ± 0.48^{a}	12.04 ± 0.77^{ab}	7.06 ± 0.26^{a}	0.44 ± 0.15^{a}	66.64 ± 1.52^{ab}
28	12.35 ± 1.56^{a}	11.73 ± 1.04^{b}	7.03 ± 0.27^{a}	0.51 ± 0.11^{a}	68.38 ± 1.44^{ab}
31	12.14 ± 0.57^{a}	8.41 ± 0.45^{c}	7.61 ± 0.06^{a}	0.52 ± 0.01^{a}	71.32 ± 0.41^{b}
34	6.37 ± 0.98^{b}	11.91 ± 1.11^{b}	8.44 ± 0.18^{a}	0.80 ± 0.10^{a}	72.48 ± 2.11^{b}

Note: the values with different letters in the same column are significantly different from each other ($P < 0.05$). C consumed energy, E excretion energy, F feces energy, G growth energy, R, respiratory metabolism energy, U excretion energy

Table 5.7 Chinese shrimp's carbon allocation at different initial body weights fed with polychaete worm at different temperatures (from Dong et al. 2002)

Initial body weight (g)	Temperatures (°C)	*G*/*C* (%)	*F*/*C* (%)	*E*/*C* (%)	*R*/*C* (%)
0.271 ± 0.041	20	31.94 ± 4.90	5.34 ± 0.89	4.64 ± 1.19	58.08 ± 6.12
3.51 ± 0.30	20	31.41 ± 1.72	3.67 ± 0.26	8.78 ± 1.15	56.14 ± 1.89
11.06 ± 1.03	20	30.34 ± 2.71	4.13 ± 1.12	10.39 ± 1.76	55.13 ± 4.74
0.271 ± 0.041	25	26.80 ± 4.81	4.42 ± 0.56	5.25 ± 2.00	63.53 ± 5.58
3.51 ± 0.30	25	29.24 ± 2.41	2.71 ± 0.43	7.15 ± 0.38	60.89 ± 2.42
11.06 ± 1.03	25	24.45 ± 1.99	1.63 ± 0.57	7.67 ± 1.04	66.25 ± 2.32
0.271 ± 0.041	30	17.00 ± 0.57	3.41 ± 0.46	3.88 ± 0.50	75.71 ± 1.17
3.51 ± 0.30	30	19.22 ± 2.77	2.04 ± 0.39	6.55 ± 0.96	72.19 ± 3.97
11.06 ± 1.03	30	14.37 ± 2.71	1.70 ± 0.74	7.55 ± 0.64	76.37 ± 3.21

Note: *C* consumed energy, *E* excretion energy, *F* feces energy, *G* growth energy, *R*, respiratory metabolism energy, *U* excretion energy

Table 5.8 Nitrogen allocation of Chinese shrimp fed with polychaete worm and pellet at different temperatures

	Feeding polychaete worm			Feeding pellet		
Allocation (%)	20 °C	25 °C	30 °C	20 °C	25 °C	30 °C
G/*C*	34.78	29.59	18.53	26.06	20.48	8.47
E/*C*	2.10	1.60	1.27	6.59	6.73	4.88
F/*C*	4.22	3.35	3.18	7.01	4.99	3.58
U/*C*	58.90	65.46	77.02	60.34	67.80	83.47

Note: *C* consumed energy, *E* excretion energy, *F* feces energy, *G* growth energy, *R*, respiratory metabolism energy, *U* excretion energy

Table 5.9 Temperature-tolerant characteristics for four salmonid fishes (°C)

Thresholds	Atlantic salmon	Rainbow trout	Steelhead trout	Brown trout
Temperature range for growth	6.0–22	1.1–22	1.1–22	3.6–19.5
Optimum for growth	17.6	17.2	~17	13.1
Upper lethal threshold	23.9	27.6	24.0	21.5–24.7

brown trout > Atlantic salmon (Table 5.9). Atlantic trout and rainbow trout are among the most heat tolerance of salmonids, and they grow faster and are larger in size, so they are widely farmed.

It should be noted that an individual fish at different stages of development may have different adaptabilities to temperatures, especially the anadromous species. For

Table 5.10 Relationship between feeding and temperature for channel catfish (from Tucker and Hargreaves 2004)

Temperature (°C)	Response
Near 0	Critical thermal minimum
8–10	No feeding
15	Reduced feeding
22	50% optimum
28–30	Optimum
33	50% optimum
35	Reduced feeding
36–38	No feeding
38–42	Critical thermal maximum

example, Atlantic salmon can tolerate 0–16 °C in embryo stage, 0–24 °C at alevin stage, and 0–29 °C at parr stage (Jonsson and Jonsson 2011); however, the upper limit of temperature tolerance becomes lower after molting. The high-temperature tolerance of the three salmonids during the hatching stage is rainbow trout > brown trout > Atlantic salmon. But for the low-temperature tolerance, the order is rainbow trout ≈ brown trout > Atlantic salmon.

5.2.2.4 Effects of Water Temperature on the Growth of Farmed Channel Catfish

Channel catfish is one of the major fishes farmed in the United States, tolerating temperatures of 0–38 °C, 10–35 °C is suitable for its growth, in which the oxygen consumption increases by 35 mgO_2/(kg·h) for each 1 °C increase in temperature. Optimal growth occurs at 28–30 °C in which its metabolism is at the best. Its feeding rate is the highest at 30 °C, but the highest feed conversion rate is between 24 and 26 °C (Table 5.10).

5.3 Effect of Salinity on the Growth of Farmed Animals

Water is a good solution, therefore, natural water dissolves more or less some salts, organic matters, etc. Salinity or salt content as an important indicator for the water quality in aquaculture considerably affects farmed organisms and the ecological processes of aquaculture waters. In natural inland waters, the salt content and ionic composition vary remarkably compared with the relatively stable ionic composition (proportion) of seawater. Therefore, the salt content of seawater is often expressed in terms of salinity and chloride.

Aquatic animals generally inhabit natural waters where salinity changes very little, except some estuarine organisms and sea-river migratory animals that often or periodically inhabit an environment of changing salinity. Farmed animals are sometimes transferred from one waters to another, experiencing different salinities, such as shrimps and Atlantic salmon. If their electrolyte concentrations of the body fluid are different from that of the external environment, their ionic balance may be disrupted as a result of dehydration (swelling), as well as the changes of concentration and the ratio of various ions. Aquatic animals can adjust their bodies to the changing osmotic pressure to a certain extent, which is an energy-consuming process and will affect the growth and development of aquatic animals. Therefore, studying the effect of salinity on the growth of farmed animals can help us to better understand the significance of water quality management.

5.3.1 Adaptability of Aquatic Animals to Salinity

To maintain the stability of the ionic composition in the body, aquatic animals have developed a series of adaptive mechanisms during the evolution process in its body structure, behavior, and physiology. Structural adaptation refers to the formation of impermeable external coverings by aquatic animals to serve as osmotic isolators, represented by rotifer carapaces, crustacean shells, fish skin and scales, mollusk shells, and chitin exoskeleton of aquatic insects, etc. Behavioral adaptation refers to those aquatic animals opt for the favorable osmotic pressure environment in avoidance of adverse salinity environment. Physiological adaptation refers to the adjustment of osmo-adaptability to the environment.

In the perspective of osmotic regulation, aquatic animals can be divided into osmoconformer and osmoregulator. The former's chemical composition of body fluid and osmotic pressure change with the external environment. While in the latter, when the chemical composition of external fluids fluctuates greatly, the chemical composition and osmotic pressure of internal fluids change only slightly, showing a certain regulatory ability. In addition, aquatic animals can also adapt to the unfavorable external osmotic conditions through osmotic isolation.

Aquatic animals can ingest salt from food or absorb from the aquatic medium by osmoregulation of body surface. The salt obtained by osmoregulation fall into passive exchange and active exchange. Passive salt exchange depends on the difference in ionic concentration between body fluid and external medium. The greater the difference, the stronger the exchange. Active exchange refers to the selective absorption or excretion of salt by aquatic animals through certain organs. The active absorption of various ions through lamellar cells is very important in maintaining the mineral nutrition of many animals. For example, shrimp and crabs can absorb calcium and zinc ions from the water.

In terms of the adaptability to salinity, aquatic organisms can be divided into two categories: stenohaline and euryhaline organisms. Stenohaline organisms cannot tolerate a large range of salinity changes, covering most marine and freshwater organisms; euryhaline organisms can tolerate a large range of salinity changes. In general, most of the organisms inhabiting pelagic area of open seas are stenohaline, and most of the organisms inhabiting estuarine areas are euryhaline. Many freshwater species can inhabit a relatively wide saline environment, which is related with their evolutionary history. In addition, the adaptability to salinity in the same species can also vary due to various internal and external factors.

The ability of aquatic animals adapting to the changes in salinity usually increases with age, but some marine invertebrates are more resistant to high salinity in larvae

Table 5.11 Salt-tolerant ranges of some fresh water fishes at different development stages (g/L; from Tucker and Hargreaves 2004)

Species	Reproductive stage	Larval stage	Fingerling stage	Adult stage
Cyprinus carpio	0–3	6	7–10	10
Carassius auratus	0	7	10	10
Ctenopharyngodon idellus	0–2	6–8	9–10	10–12
Hypophthalmichthys molitrix	0–2	5–6		8–10
Hypophthalmichthys nobilis				11–11.5
Bream	0–1.5	0–6.7	0–7.5	10–11
Acipenser	0	0–7.5	0–10	0–36
Huso	0	0–7.5	0–10	0–18
Salmon	0	0–7	15–22	35–36
Trout	0	0–7	15–20	30

stage than adults. The upper limit of salinity tolerance of many freshwater fishes in the larval stage is less than 7 g/L, but higher than 7 g/L in the adult stage. For example, the upper tolerance limit (USTL) for carps, sturgeon, and Salmonidae can reach 10–12 g/L, 18–36 g/L, and 20–36 g/L, respectively (Table 5.11). The USTL for channel catfish's eggs can reach 16 g/L; and decrease to 8 g/L for hatching and reaches 9–10 g/L after the yolk sac is absorbed; the grow-out stage is 11 g/L (Tucker and Hargreaves 2004).

When the salinity of water changes gradually, the aquatic animal will have higher salinity tolerance, and vice versa. A certain period of salinity acclimation can often improve the salinity tolerance of aquatic animals. For example, the USTL of grass carp generally does not exceed 10–12 g/L, but if it is acclimated in 3–7 g/L and 9 g/L brackish water for 15 days, its sublethal salt content can reach 14 g/L and 16 g/L, respectively.

The salinity tolerance of aquatic animals also depends on temperature. For example, the juvenile silver carp tolerates high salinity the best when water is 18–22 °C. The salinity range for aquatic animals to survive is also related to the salt composition in the water. Compared with other anions, carbonate ions (CO_3^{2-}) are more toxic to fish (Lei et al. 1985).

A little salt in water (2–5 g/L) can promote the growth of some freshwater animals. For example, the feeding and growth of silver carp, common carp, and shrimp (*M. nipponense*) will be enhanced in 3 g/L brackish water, which may be the most energy-saving salt content for many freshwater animals in osmotic adjustment. The oxygen consumption rate of juvenile carp in 2 g/L brackish water is 25–30% higher than that in freshwater, and the growth rate is also slightly greater. Juvenile largemouth bass (*Micropterus salmoides*) grows 1.8-fold faster in 1.5–2.0 g/L brackish water than in freshwater. The ingestion rate of grass carp at the salinity of 3–7 g/L is also higher than that in freshwater. The USTL for channel catfish is 11 g/L.

5.3.2 Effects of Salinity on the Growth of Farmed Animals

Since the salinity is frequently affected by tide, rainfall, and land runoff in the coastal aquacultural farms, farmers are very concerned about the salinity changes in the aquaculture waters. In addition, due to harassment of shrimp epidemics, whiteleg shrimp culture has developed rapidly in inland ponds, and massive death of farmed shrimps often occurs due to ionic imbalance in the waters. Therefore, the influence of salt content on the growth of several farmed animals is introduced below.

5.3.2.1 Salinity Effects on the Growth of Sea Cucumber

Sea cucumber (*A. japonicus*) is a stenohaline species, and changes in salinity have a significant effect on its growth. Sea cucumber is mostly cultured in the ponds or cofferdams of intertidal zone in China. The salinity of the ponds or cofferdams varies little; however, it changes greatly during heavy rain. The sudden changes in salinity of the ponds can often cause high mortalities of farmed sea cucumbers. Therefore, it is of vital theoretical and practical significance to understand the salinity effects on the growth of the sea cucumber.

The tolerance to low salinity varies among different sizes of the sea cucumbers. The minimum salinity tolerated by the 0.4 mm larvae is 20–25 ppt; 10–15 ppt for the 5 mm juveniles; and 15–20 ppt for the adults (Sui 1990).

Salinity has a significant effect on the growth of the sea cucumber. With the salinity range of 22–38 ppt, the specific growth rate (*SGR*) of the animal has a bell-shaped curve with salinity. The sea cucumber (initial weight, 2.56 g) has the highest *SGR* at 30 ppt, and then the *SGR* decreases when below or above this salinity (Zhang et al. 2011).

The sea cucumber also has a higher feed intake (*FI*) and food conversion efficiency (*FCE*) at 30 ppt, above or below which *FI* and *FCE* decrease. At the salinity of 30 ppt, the sea cucumber has the highest proportion of energy for growth. The average energy budget formula of the sea cucumber at 30 ppt is: $100C = 6G + 42F + 3\ U + 49R$. The energy deposited to growth is very low (only 6%), and the energy loss in faces and respiration accounts for the majority of ingested energy (91% of C).

5.3.2.2 Effect of Salinity on the Growth of Shrimp

Salinity is one of the most important environmental factors of concern in shrimp farming. Both Chinese shrimp and whiteleg shrimp are euryhaline species with strong osmoregulatory capability. The spawning, embryonic development, and larval metamorphosis of natural Chinese shrimp all take place near the estuaries where the salinity is generally 23–29 ppt. In the case of artificial breeding, Chinese shrimp can keep growing if transferred from brackish water to a salinity of 40 ppt. Natural whiteleg shrimp inhabits a water environment of 1–72 m deep, the water temperature of 25–32 °C, the salinity of 28–34 ppt, and the pH of 8.0 ± 0.3 (Wang 2008a).

Optimal salinity for shrimp growth is a very important technical parameter in water quality management. Chinese shrimp (initial weight, 0.3 g) performs well in feeding and growth when salinity is 5–35 ppt. The fastest growth rate of the animal occurs at a salinity of 20 ppt, though not significantly different from those at salinities of 13 and 28 ppt (Zhang et al. 1999b). It keeps growing slowly at salinity 5 ppt with molting cycle getting longer. The growth of Chinese shrimp is slower at salinity 35 ppt without effect on molting.

Whiteleg shrimp can still grow at a salinity of 0.5 ppt, but the suitable salinities for its growth are 20–30 ppt, at 20 ppt the proportion of growth energy is the largest (Table 5.12).

In the salinity range of 5–35 ppt at temperature of 25 °C, the maximum carbon intake of Chinese shrimp (initial weight 0.3 g) is 61.64 mgC/(g·d) at a salinity of 13 ppt. The regression relationship between the carbon intake (I_C, mgC/(g·d)) and salinity (S) is:

$$I_C = 35.437 + 3.571S - 0.156S^2 + 0.002S^3 \quad R^2 = 0.443$$

At salinity 20 ppt, the carbon allocated to the growth of Chinese shrimp is the highest (25.8%), and the carbon-specific growth rate of Chinese shrimp is 3.89%, also the greatest. The salinity effect on the carbon growth of Chinese shrimp is mainly determined by feed intake and conversion efficiency. The growth of Chinese shrimp fed with polychaete worm is significantly greater than that fed with formulated diet. Their carbon conversion efficiencies are 26.8% and 13.8% of carbon intake, respectively.

About 26.5% of the ingested nitrogen of Chinese shrimp (initial weight 0.3 g) is allocated to the growth at salinity of 20 ppt and 25 °C, which is the highest in the salinity range of 5–35 ppt. Excretion losses are the largest component of N expenditure, amounting to 69.6%–79.9% of ingested nitrogen.

5.3.2.3 Effect of Salinity on the Growth of Salmon and Trout

Some salmonids inhabit fresh water for their entire lives, while others inhabit the ocean and spawn anadromously during the reproductive season. Salmonids are euryhaline, with salinity tolerance varying remarkably at different developmental stages in general. Individuals of anadromous species grow often faster in seawater than in freshwater. Landlocked species can develop normally in inland waters without going down to the sea, and can also grow in seawater after salinity acclimation. However, without entering the sea the sexual gonads of the anadromous species cannot develop to maturity generally living in freshwater all the time.

Although rainbow trout and steelhead trout belong to the same species, the former is landlocked, and the latter is anadromous. Rainbow trout and steelhead trout with an initial weight of about 3.6 g can both adapt well to salinity below 15 ppt, but juvenile steelhead trout are slightly better at salinities of 15–20 ppt (Table 5.13). In terms of growth, there are significant differences between the two types of fish in their response to salinity. The growth rate of rainbow trout is greater than that of steelhead trout at a salinity of 5 ppt, but the latter grows significantly faster at salinity of 10 ppt or above than the former. At a salinity of 5 or 10, the proportion of energy

Table 5.12 Effects of salinities on food consumption, survival, growth, and food energy allocation of *Litopenaeus vannamei* juveniles (from Wang et al. 2006b)

Salinities (ppt)	Consumption (kJ/(g·d))	Survival (%)	*SGR* (%/d)	*G*/*C* (%)	*R*/*C* (%)
0.5	1.78 ± 0.18^{b}	90.00 ± 10.00	3.71 ± 0.16^{c}	16.32 ± 0.26^{e}	69.50 ± 0.35^{a}
5	2.01 ± 0.16^{ab}	96.00 ± 8.94	4.00 ± 0.17^{bc}	16.80 ± 0.28^{e}	69.41 ± 0.60^{a}
10	2.24 ± 0.19^{a}	96.00 ± 5.48	4.09 ± 0.15^{bc}	18.39 ± 0.21^{b}	68.12 ± 0.36^{b}
15	2.22 ± 0.26^{ab}	94.00 ± 8.94	4.24 ± 0.21^{b}	18.03 ± 0.29^{bc}	68.62 ± 0.33^{ab}
20	2.25 ± 0.21^{a}	94.00 ± 5.48	4.66 ± 0.20^{a}	18.93 ± 0.18^{a}	67.73 ± 0.59^{b}
25	2.22 ± 0.11^{ab}	90.00 ± 10.00	4.31 ± 0.07^{ab}	17.68 ± 0.29^{cd}	68.20 ± 0.47^{b}
30	2.23 ± 0.39^{ab}	90.00 ± 17.32	4.38 ± 0.33^{ab}	17.52 ± 0.27^{d}	68.60 ± 0.55^{ab}
35	2.16 ± 0.14^{ab}	98.00 ± 4.47	4.26 ± 0.13^{b}	16.63 ± 0.16^{e}	69.43 ± 0.34^{a}

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$). *C* consumed energy, *G* growth energy, *R*, respiratory metabolism energy

Table 5.13 Energy allocation of rainbow and steelhead trout juveniles (initial weight of 3.2 g) at different salinities after 42 days of culture (from Xiong et al. 2019)

Salinities	Survival rates (%)	*G/C* (%)	*R/C* (%)	*F/C* (%)	*U/C* (%)
Rainbow trout					
0	100.00 ± 0.00^{c}	$27.60 \pm 0.43^{d*}$	$60.44 \pm 0.81^{b*}$	4.57 ± 0.16^{a}	$7.39 \pm 0.15^{ab*}$
5	100.00 ± 0.00^{c}	$34.00 \pm 1.69^{e*}$	$54.90 \pm 1.77^{a*}$	4.22 ± 0.20^{a}	6.89 ± 0.38^{a}
10	100.00 ± 0.00^{c}	$28.28 \pm 0.51^{d*}$	$59.82 \pm 0.87^{b*}$	4.55 ± 0.09^{a}	$7.35 \pm 0.18^{ab*}$
15	100.00 ± 0.00^{c}	$26.35 \pm 0.73^{d*}$	$61.30 \pm 0.80^{b*}$	$4.61 \pm 0.25^{ab*}$	$7.74 \pm 0.13^{b*}$
20	95.83 ± 7.22^{c}	$22.08 \pm 0.51^{c*}$	$64.80 \pm 0.61^{c*}$	$5.07 \pm 0.26^{ab*}$	8.05 ± 0.19^{b}
25	$58.33 \pm 7.23^{b*}$	16.96 ± 0.62^{b}	70.21 ± 0.86^{d}	5.61 ± 0.29^{b}	$7.22 \pm 0.32^{ab*}$
30	37.50 ± 21.65^{a}	$6.66 \pm 0.31^{a*}$	$77.55 \pm 0.37^{e*}$	$8.34 \pm 0.45^{c*}$	$7.44 \pm 0.54^{ab*}$
Steelhead trout					
0	100.00 ± 0.00^{B}	$36.26 \pm 1.08^{E*}$	$53.71 \pm 1.42^{B*}$	4.08 ± 0.21^{A}	$5.94 \pm 0.37^{B*}$
5	100.00 ± 0.00^{B}	$31.37 \pm 0.87^{D*}$	$57.05 \pm 0.94^{C*}$	4.56 ± 0.02^{AB}	7.02 ± 0.21^{C}
10	100.00 ± 0.00^{B}	$43.76 \pm 1.29^{F*}$	$46.73 \pm 0.62^{A*}$	4.65 ± 0.51^{ABC}	$4.85 \pm 0.23^{A*}$
15	100.00 ± 0.00^{B}	$34.99 \pm 0.72^{E*}$	$54.17 \pm 0.76^{BC*}$	$3.92 \pm 0.24^{A*}$	$6.92 \pm 0.28^{C*}$
20	91.67 ± 7.22^{B}	$27.80 \pm 0.52^{C*}$	$60.69 \pm 0.77^{D*}$	$3.95 \pm .028^{A*}$	7.55 ± 0.37^{CD}
25	$87.50 \pm 12.50^{B*}$	18.53 ± 0.80^{B}	68.38 ± 1.41^{E}	5.14 ± 0.34^{BC}	$7.95 \pm 0.40^{D*}$
30	37.50 ± 0.00^{A}	$9.51 \pm 2.00^{A*}$	$75.19 \pm 2.37^{F*}$	$5.63 \pm 0.94^{C*}$	$9.67 \pm 0.17^{E*}$

Note: The values with different letters in the same column are significantly different from each other in the same fish ($P < 0.05$), and the values with asterisk are significantly different from the value of other kind of fish at the same salinity ($P < 0.05$). *C* consumed energy, *E* excretion energy, *F* feces energy, *G* growth energy, *R*, respiratory metabolism energy, *U* excretion energy deposited to growth by rainbow trout or steelhead trout is the highest, and that for respiration is the lowest.

When anadromous salmonid individuals grow to a certain size (also being affected by photoperiod, nutrition, salinity acclimation, etc.), they need to enter the sea, which is called the smolt window. Salinity tolerance, migratory behavior, and several other aspects of development that occur during molting will lost if the individuals remain in freshwater (McCormick 2012). The size of the smolt window for steelhead trout is about 300 g (Xiong 2018).

5.4 Effects of Dissolved Oxygen on the Growth of Farmed Animals

There are significant diurnal and vertical variations of dissolved oxygen content (DO) in open aquaculture waters, which affects on the growth of aquaculture animals significantly. Hypoxia in waters often causes mass death of aquatic animals. At the other extreme, oversaturated DO may also cause "bubble disease" of farmed animals. Therefore, DO is an environmental factor that fish farm operators pay close attention to and often regulate.

5.4.1 Adaptability of Aquatic Animals to Dissolved Oxygen

Aquatic organisms can be divided into aerobic organisms and anaerobic organisms according to whether they require oxygen or not. Most aquatic organisms are aerobic depending on oxygen for survival, and a few microorganisms are anaerobic organisms that can survive in completely oxygen-free conditions. According to the range of adaptation to dissolved oxygen, aquatic organisms can be divided into euryoxybiont and stenooxybiont. The former can tolerate a greater variation in environmental oxygen content, while the latter can only tolerate a smaller variation. Some organisms living in the upper layers of the ocean and some organisms living in clear streams belong to the latter group.

The oxygen consumption of aquatic animal individuals varies greatly, and is related to their body size, developmental stage, activity status, satiation level, gender, etc. In general, the smaller the individual and the higher the water temperature, the higher the respiration intensity. At every 10 °C increase within the appropriate temperature range, the oxygen consumption rates of bacteria, rotifer, and juvenile silver carp increase by about 2.5 times, 2.3 times, and 1.9 times, respectively.

Aquatic organisms are able to adapt to the changes in DO in the water. Fish have two adaptive mechanisms in response to declined dissolved oxygen. When DO drops to a certain level, fish individuals can regulate their respiratory activity such as respiratory rate, and their metabolic rates can still remain relatively stable, which are called oxygen "regulators" or oxygen-regulator fish. Another type of fish, in the process of declining DO, usually show that their respiratory rates slow down, and the

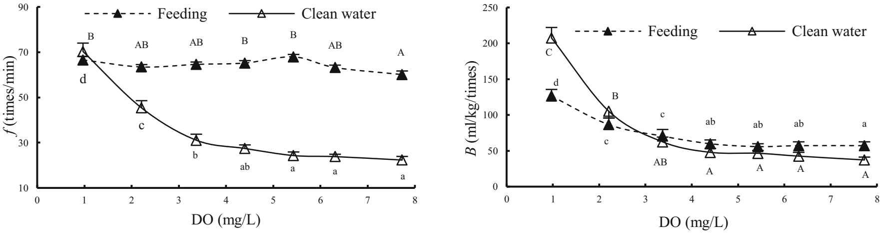


Fig. 5.4 Respiratory frequencies *f* (times/min) and respiratory stroke volumes *B* (mL/(kg·strok)) of silver carp at different DO levels in feeding and nonfeeding conditions (from Zhao et al. 2011b)

oxygen consumption rates decrease, which fish are called oxygen "conformers" or oxygen-conformer fish. The widely cultured silver carp belongs to the oxygen-regulator fish (Fig. 5.4). Within the DO range of 5.43–7.73 mg/L, there is no significant change in respiratory frequency (*f*) and respiratory stroke volumes (*B*) of silver carp. When the DO declines to 4.40 mg/L, the *f* and *B* of silver carp significantly increased (Zhao et al. 2011b). In addition, the response of the silver carp to the DO is retarded in the feeding state.

Increasing the hemoglobin content of the blood is also an adaptation of aquatic animals to changes in oxygen availability. For example, the oxygen consumption rate of salmon fry in rivers is 400 mg/(kg·h), the hypoxia threshold is 1.57 mg/L; however, those are 300 mg/(kg·h) and 1.15 mg/L respectively, in ponds (Dong and Zhao 2004).

Using the skin to uptake oxygen in the air is also an adaptability of many aquatic animals in oxygen-deficient conditions, best exemplified by the catfish and the intestinal epithelium of Asian swamp eel (*Monopterus albus*). The "head floating" phenomenon of fish in hypoxic conditions is also an air-breathing action.

Every kind of aquatic animal has its own range of adaptability to the DO level of the water for its normal respiratory intensity, which would be disrupted considerably if the DO content keeps dropping to a certain limit, namely the hypoxia threshold or suffocation point. The suffocation points (mgO_2/L) of some fish species in freshwater ponds are: crucian crap 0.1, common carp 0.2–0.3, grass carp 0.4–0.6, and silver carp and bighead carp 0.25–0.4.

Oversaturation of the DO in the water also does harm to some aquatic animals. When the dissolved oxygen content reaches 32 mg/L (hyperoxia), the juvenile individuals of freshwater trout (*Trutta iridea* and *T. fario*) become gradually paralyzed and dead, but the adult individuals can well resist high degree of dissolved oxygen. The oversaturation of the DO in water can also lead to the oversaturation with oxygen in the blood of fish. However, when the DO content in the water drops rapidly, the dissolved gas in the blood of fish will turn into bubbles, which may block the blood vessels of the fish and cause "bubble disease" of the fish.

5.4.2 Effect of Dissolved Oxygen on the Growth of Farmed Animals

In general, freshwater and warm-water fishes are more tolerant of hypoxia than marine and cold-water fishes (Table 4.1). Marine fishes and cold-water fishes generally have higher resting metabolism. For example, brown trout has higher resting metabolic rate than crucian carp and common carp (Table 5.14). Therefore, higher intensity of aeration is required in the aquaculture of marine fishes or cold-water fishes.

Decline of the DO content to a certain extent in the water will affect the oxygen utilization efficiency and feeding rate of farmed fish, and then affect the fish growth. The decline of DO in clean water will increase and then decrease the oxygen extraction efficiencies (EO_2) of silver carp (Fig. 5.5). When the DO level decreases to 4.40 mg/L, the EO_2 of silver carp is the highest, reaching 30.1%. But when the dissolved oxygen level decreases further to 0.97 mg/L, the EO_2 of the fish will decrease to 16.9%. With food provided, the EO_2 of the silver carp will continue to increase, indicating that silver carp has a certain regulatory capability to adapt the DO decline.

With the decline of the DO level, filtration rate or feeding rate (*FR*) of silver carp decreases gradually. In the DO range of 4.40–7.73 mg/L, the *FR* of the fish is 1.29–1.40 g/(kg·h). Beyond 4.40 mg/L, the *FR* decreases significantly, reaching the lowest 0.92 g/(kg·h) at DO level of 0.97 mg/L (Zhao et al. 2011b).

Dissolved oxygen content and water temperature interact to affect fish growth. The lower limit for oxygen saturation with maximum feed intake (DO_{maxFI}) of juvenile Atlantic salmon is above 42% DO at 7 °C, and it is 76% at 19 °C (Table 5.15). Similarly, a limiting oxygen saturation (LOS) of 24% DO at 7 °C has been found for juvenile Atlantic salmon, while a LOS of 40% DO is at 19 °C.

Table 5.14 Resting oxygen consumption of three fish species (from Yin 1995)

Species	*Salmo trutta*			*Carassius auratus*			*Cyprinus carpio*		
Temperature (°C)	10	15	20	10	20–22	32–35	10	20	30
Oxygen consumption ($mgO_2/(kg·h)$)	81	128	282	15.7	30–160	127–262	17	48	104

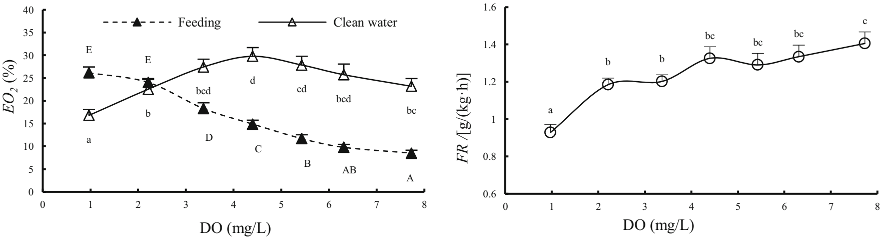


Fig. 5.5 Oxygen extraction efficiencies (EO_2) and filtration rates (*FR*) of silver carp at different DO levels in feeding and nonfeeding conditions (from Zhao et al. 2011b)

Table 5.15 Lower limit for oxygen saturation with maximal feed intake (DO_{maxFI}) and limiting oxygen saturation (LOS) for Atlantic salmon postsmolts of 300–500 g (from Noble et al. 2018)

Temperature (°C)	DO_{maxFI} (%)	LOS (%)
7	42	24
11	53	33
15	66	34
19	76	40

Usually, higher DO level is required at fish embryo stage. No satisfactory results can be achieved in hatching of channel catfish unless the DO level is higher than 8 mg/L. The DO level requirement for the survival of channel catfish embryos is about 1.9 mg/L, and it is hard to over 50% of survival rate unless the oxygen level is higher than 5 mg/L. However, 50% mortality of juvenile channel catfish (mean weight 132 g/ind.) occurs after 72 h at 18 °C, and the DO level of LC_{50} is 0.9 mg/L. The level of 1.5 mg/L is needed for the juvenile survival. Channel catfish (mean weight 60 g/ind.) can maintain a good appetite, higher growth rate, and feed conversion rate when the oxygen level is more than 3.0 mg/L (Tucker and Hargreaves 2004).

5.5 Effect of Light on the Growth of Farmed Animals

Light is the most essential source of energy for survival and reproduction of almost all organisms on the earth, and also one of the most important ecological factors in aquaculture waters. Light not only affects the thermal state of water and the photosynthesis of plants, but also affects the behavior, growth, and gonadal development of farmed animals. Therefore, understanding how light works on aquatic animals is imperative of implementing light-regulating technique in aquaculture operation.

5.5.1 Adaptability of Aquatic Animals to Light

Light is represented by its intensity, photoperiod, and color (spectral composition). In intensive indoor aquaculture systems, the light intensity and photoperiod can be regulated to improve the growth and control gonad development of farmed animals.

The effect of light intensity on the growth of aquatic animals varies with intensity and species. The minimum and optimal light intensity required for the growth of animals is formed during the long-term evolution process, which is the adaptation to the living environment.

Many aquatic animals have the behavior of phototaxis. Some fish have phototropic movements in response to certain light intensity. Sometimes the light may also affect the phototropism of diet organisms of the fish. Therefore, fishmen trap fish by using light. The phototropism of Nile tilapia increases as the light intensity increases, and reaches the maximum at 1000 Lx. On the contrary, for echinoderms like sea cucumbers have the behavior of photophobism, and will move to deep water area or under shaded objects when the light is strong.

The larvae of some fishes are very sensitive to light. For example, the larvae of herrings (<1 Lx), striped bass (1 Lx), and halibuts (1–10 Lx) are attracted to light below 10 Lx, while the minimum threshold values are higher for larvae of Atlantic salmons (200–600 Lx), summer flounders (350 Lx), and *Siganus guttatus* (1000 Lx).

Although echinoderms lack light-sensitive organs, they respond to light intensity, photoperiod, and moonlight by regulating the response to light at the stimulation of light through the cytochromes or photoreceptors of the body wall or nervous system. Typically, they will seek shelter to avoid light exposure. There is a significant diurnal behavioral rhythm of sea cucumbers in natural light (Dong et al. 2010). There is a rapid behavioral shift of the animal into and out of the shelters at dawn about 5:00 and at dusk about18:00 (Fig. 5.6).

The brighter the light, the stronger the daily rhythm of sea cucumber activity. Under 15 Lx of light intensity, the rhythm of sea cucumber activity is already very weak. The "diurnal" behavioral rhythm also exists under total darkness condition. The weaker the daily rhythm of the animals, the longer the duration of feeding activity becomes.

At 5.18 Lx and lower light levels, changes in light intensity have no significant effect on the behavior of sea cucumbers (≥44% of the animals outside the shelters), under which light intensity, the behavioral rhythms of the animals are mainly governed by the biological clock in the animal. In the light range from 5.18 to 278 Lx, the rate of light avoidance behavior gradually increases with increasing light intensity (8.17%–43.96% outside the shelters). Under 278 Lx and higher light intensity, the behavior of the animals is affected mainly by the light, and the effect of increasing light intensity on the animals is no longer significantly enhanced.

The light has uneven vertical distribution in waters. The water absorbs light of different wavelengths in different intensities. In pure water, the absorption rate for long-wavelength light, like red light, is higher than that for short-wavelength light,

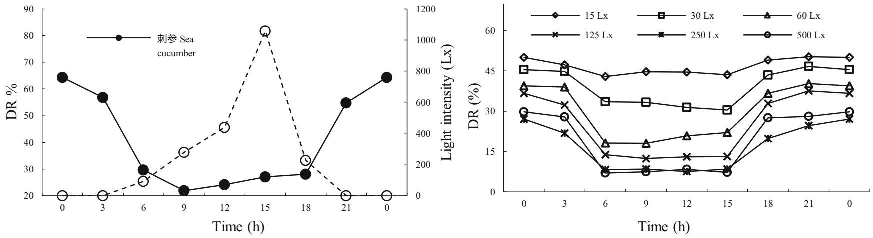


Fig. 5.6 Daily activity rhythm of sea cucumber (*Apostichopus japonicus*) in natural light (from Dong et al. 2010). *DR* stands for distribution rate outside artificial shelters, *DR* = Ni/N × 100% Ni is the number of sea cucumber distributed outside the shelters at a certain observation time, and N is the total amount of the experimental sea cucumber

such as blue light. As a result, not only a decrease in total light intensity but also a rapid attenuation of long wavelength light as the water depth increases. Different parts of light spectrum or color may have different effects on the behavior of aquatic animals. Some aquatic animals have color vision and react differently to different light colors. The effects of light color (spectral components) on the growth of aquatic animals are also species-specific, which is also the evolutionary adaptation to the habitat environment. For example, minnows are more active under red and purple light, and relatively inactive under yellow, green, and blue light. The juvenile pollan (*Coregonus pollan*) is more sensitive to green light but not to red light. In clear water, the juveniles of silver perch (*Bidyanus bidyanus*) and golden perch (*Macquaria ambigua*) are most sensitive to yellow-orange light spectrums as an adaptation to turbid water where wavelengths of yellow and orange light are dominant. Chinese shrimp is more active under blue light, but less active under yellow and green light (Wang et al. 2003).

The response of some aquatic animals to light is related to their developmental stage and environmental conditions. For some fishes, light may act as an environmental signal for activity and defense in the early developmental stage of larvae, and may be a conditioned reflex to food in the later stage. The veligers of the mussel (*Mytilus edulis*) are phototropic at 7–15 °C, but not at 20 °C.

The photoperiod has a remarkable effect on gonad development in many animals. In general, the gonadal maturation of spring and summer spawning animals can be improved by lengthening gradually the photoperiod, while for autumn and winter spawning species it can be done by shortening gradually the photoperiod. In farming practice, extended photoperiod is often used to induce the spawning of spring-spawning trout species, and vice versa.

Light also has a strong influence on the developmental process in aquatic animals. The hatching duration of fertilized eggs of flounder in the dark is 1–2 days slower than in the light. The fertilized eggs of sturgeon (*Acipenser stellatus*) also develop faster in the light than in the dark. However, it is likely to be the opposite for fertilized eggs of salmon developing in natural conditions. For example, the fertilized eggs of *Oncorhynchus keta* develop under gravels develop faster than those exposed to light.

Light intensity, photoperiod, and color all have strong impacts on the feeding rates of aquatic animals. The effect of light intensity on aquatic animal feeding is species-specific. Animal feeding presents two feeding models, i.e., a peak feeding curve and an S-shaped feeding curve (Zhou et al. 2000). The animals with the former type of feeding curve rely on visual feeding and consume more food in the appropriate light conditions. The appropriate illuminance may be different for some animals at different development stages. For example, the appropriate illumination levels are 10–100 Lx for juveniles of red sea bream, 1–100 Lx for larvae. The feeding peaks of mullet juveniles and *Hexagrammos otakii* larvae are both around 100 Lx.

Fish that rely on visual feeding not only have a suitable light intensity range, but also a visual threshold for feeding, below which there is little or no feeding. As vision develops, light sensitivity rises and the visual threshold for feeding can decrease.

5.5.2 Effect of Light on the Growth of Farmed Animals

5.5.2.1 Effect of Light Intensity on the Growth of Farmed Animals

Light intensity has a significant effect on the survival, growth, development, attachment, and metamorphosis of the planktonic larvae of sea cucumbers (Zhang 2013b). The growth rate of sea cucumber (*A. japonicus*) larvae in the second day after feeding tops 99.1 μm/d at 500 Lx. At 2000 Lx, the growth rate of larvae in the sixth day after feeding is the highest (87.9 μm/d) in the range of 0–2000 Lx. The survival rate of the larvae increases significantly with the increase of light intensity, 74.2% at 0 Lx and 86.1% at 2000 Lx. The *SGR* of the juvenile at 2000 Lx reaches 1.50 ± 0.12%/d, which is significantly higher than those at lower light intensities. Currently, the hatching and seedling of the sea cucumbers in China are usually carried out under dim condition; however, light is necessary for the seedling of the sea cucumber.

The light intensity also affects significantly on the growth of Chinese shrimp in the range of 0–5500 Lx, with the fastest growth at 300 Lx (Fig. 5.7), which is significantly faster than that at 5500 Lx (Wang et al. 2004). The light intensity affects significantly the allocation pattern of ingested energy of Chinese shrimp. The highest proportion of energy used for respiration is 72.1% under 5500 Lx light intensity, while the lowest proportion of energy used for growth is only 4.7% under same light condition.

The growth of Arctic Charr (*Salvelinus alpinus*) larvae is the fastest with low mortality at 50 Lx, but is inhibited if light intensity is above or below 50 Lx. Rainbow trout grows faster at 50 Lx than at 700 Lx. The mortality is higher in bright light for both *S. alpinus* and *S. salar* and lower in the dark. However, chinook salmon (*Oncorhynchus tshawytscha*) grows faster in bright light than in dim light. In addition, the light intensity of 8 Lx can inhibit the gonad development of *S. salar* older than 1 year, and the light intensity of 43 Lx can promote their molting.

5.5.2.2 Effect of Photoperiod on the Growth of Farmed Animals

The photoperiod of the aquaculture waters changes with the seasons, significantly affecting the growth, reproduction, and development of the farmed animals. The survival, growth, development, attachment, and metamorphosis of planktonic larvae of sea cucumber (*A. japonicus*) are affected by photoperiod (Zhang 2013b). The attachment and metamorphosis rates of the larvae in descending order are: 10L:14D (67.63%), 14L:10D (63.59%), 24L:0D (55.5%), and 0L:24D (47.69%). The *SGR* of the animals gradually increases with increasing light duration, and reaches the maximum at 14L:10D.

The interactive effects of light intensity and photoperiod on the SGR_w of juvenile sea cucumbers are significant (Table 5.16). The effect of photoperiod on the growth

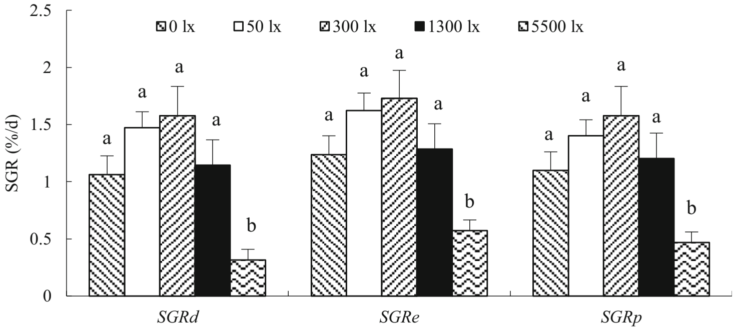


Fig. 5.7 Specific growth rates of *Fenneropenaeus chinensis* under different light intensities (from Wang et al. 2004). The indices *SGR*d, *SGR*p, and *SGR*e indicate specific growth rate in terms of dry matter, protein, and energy, respectively. There is no significant difference among the *SGR* with same letter ($P < 0.05$). Similarly, hereinafter

of the animals is greater than that of light intensity. The SGR_w of the animals is the greatest at 14L:10D and 2000 Lx.

There are no significant differences in the growth, feeding rate, and food conversion efficiency (*FCE*) of Chinese shrimp among the four photoperiods (0L:24D, 10L:14D, 14L:10D, and 24L:0D). However, the molting frequency of the shrimp is significantly different among the four photoperiods, lower under 24L:0D and 0L:24D, and higher under 14L:10D and 14D:10L. The energy allocated to molt is higher under 14L:10D and 14D:10L and differs significantly from that under continuous darkness or continuous illumination (Wang et al. 2005). The photoperiod has little effect on the *FCE*. Compared with light intensity and spectral composition, the degree of effect of photoperiod on the growth of the shrimp is relatively small.

The silver carp, bighead carp, and common carp all grow faster with the longer illumination time, but the common carp grows much faster than the silver carp and bighead carp in the short illumination time. Bighead and silver carp grow fastest and have the highest survival rate at 10–12 h of illumination time (Wang et al. 1994).

Table 5.16 Specific growth rates in wet weight (%/d) of *A. japonicus* in different light intensities (from Zhang 2013b)

	SGR_w			
Photoperiods	0 Lx	1000 Lx	2000 Lx	4000 Lx
0L:24D	0.76 ± 0.02^{a}	0.76 ± 0.02^{1}	0.76 ± 0.02^{1}	0.76 ± 0.02^{2}
10L:14D	0.76 ± 0.02^{a}	$0.88 \pm 0.06^{ab,1,2}$	$1.00 \pm 0.03^{b,2}$	$0.90 \pm 0.06^{ab,3}$
14L:10D	0.76 ± 0.02^{a}	$0.94 \pm 0.03^{b,2}$	$1.17 \pm 0.03^{c,3}$	$0.96 \pm 0.05^{b,3}$
24L:0D	0.76 ± 0.02^{b}	$0.80 \pm 0.05^{b,1,2}$	$0.79 \pm 0.06^{b,1}$	$0.58 \pm 0.03^{a,1}$

Note: The values with different letters in the same line are significantly different from each other ($P < 0.05$), and the values with different figures in the same column are significantly different from each other ($P < 0.05$)

Short-light exposure in autumn and winter can accelerate rainbow trout growth; longer-light exposure from November to July can accelerate Atlantic salmon growth; and providing continuous light exposure from early November to Atlantic salmon that have entered seawater for a year can increase their growth rate and inhibits gonadal maturation. From the perspective of artificial reproduction, most salmon and trout spawn in the fall or winter, so implementing long illumination time followed by shorter illumination time before their gonadal maturity can promote their reproduction.

The growth of animals requires the minimum and optimal photoperiod, which is an adaptation to the living environment developed in evolution. Any artificial lighting conditions that deviate from their natural photoperiod may inhibit their growth rate.

5.5.2.3 Effect of Light Color on the Growth of Farmed Animals

The light color has a significant effect on the *SGR* of sea cucumber (*A. japonicus*) (Bao et al. 2014). The *SGR* rates of the animals cultivated under different color light are: yellow light > white light > blue light > red light > green light. The energy consumption and allocation of the animals under different color light are shown in Table 5.17. The energy consumption is the highest under white light and the lowest under green light, while the highest proportion of growth energy occurs under white light and the lowest under green light.

The *SGR* of Chinese shrimp under different color light is as follows: white > green > yellow > blue light (Wang et al. 2003). The *SGR* of shrimp under blue light is only 73.0% and 85.8% of those under white light and green light, respectively. The maximal and minimal feeding rate of the animal occurs under blue light and yellow light (difference 16.6%), respectively. The lowest *FCE* occurs under blue light, taking up 64.5% and 75.8% of those under white and green light, respectively. Chinese shrimp is relatively sensitive to blue light, under which the animal is active in feeding behavior, and gains a higher feeding rate as well as a lower *FCE*, and therefore, a lower *SGR*. Shrimp may grow faster in the organically rich earthen ponds than in organically poor waters because there is less blue light spectrum in the water of earthen ponds.

Rainbow trout (143 g) grows slightly faster under red light than under white and blue light, but the fish (32 g) under yellow light grows faster than those under red, blue, and white light. Blue LED lights can cause short-term stress on Atlantic salmon, while white LED light do not. The inhibitory effects of different color light on the gonad development of Atlantic salmon are blue light > metal halide spectral color > green light > red light.

5.6 Individual Variation in Growth of Farmed Animals

The growth of animals in nature is very complicated with great individual variation among different species (Table 5.1). However, there is the variation in growth among individuals of the same species, even among offspring of the same parents,

Table 5.17 Energy allocations in *Apostichopus japonicus* under different color light (from Bao et al. 2014)

Color	G/C (%)	F/C (%)	U/C (%)	R/C (%)	C (kJ/(g·d))
Natural light (white)	7.01 ± 0.33^{a}	46.78 ± 0.99^{a}	11.16 ± 0.08^{a}	36.45 ± 1.21^{a}	7342.63 ± 260.42^{a}
Red	6.64 ± 0.29^{a}	50.7 ± 1.05^{ab}	12.06 ± 0.13^{b}	29.76 ± 0.78^{bc}	6282.06 ± 400.08^{b}
Yellow	7.96 ± 0.26^{b}	54.47 ± 2.48^{b}	10.90 ± 0.14^{a}	27.57 ± 0.99^{c}	6437.56 ± 255.43^{b}
Green	4.01 ± 0.30^{c}	47.43 ± 2.35^{a}	11.11 ± 0.2^{a}	35.35 ± 1.05^{ab}	3857.63 ± 191.13^{c}
Blue	5.44 ± 0.30^{d}	48.97 ± 2.25^{ab}	11.01 ± 0.2^{a}	34.14 ± 2.46^{ab}	6230.30 ± 230.71^{b}

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$). C consumed energy, E excretion energy, F feces energy, G growth energy, R, respiratory metabolism energy, U excretion energy and this variation is the individual variation that will be elaborated in this section. The individual variation in growth of fish can affect their survival, reproduction, and yield. In aquaculture practices, farmers often screen individuals of different fish sizes to avoid polyculture different size individuals for better survival rate, better feed utilization, and better growth rate.

The growth variation of individual fish is affected by many factors, including gender, environment, social hierarchy, genetic factors, etc. Researchers have focused on the effects of different feeding strategies, stocking densities, and sizes, regarding them as the reasons for the variation in individual growth of farmed animals.

5.6.1 Factors Influencing Growth Variation

With 7–10% individual coefficient variation (CV, $=100 \times SD/\bar{x}$) in the growth of most terrestrial farmed animals, the CV is much greater for fish (Table 5.18). Most of the direct causes of individual growth variation in animals are differences in feeding rate or food utilization, and indirect causes are genetic and environmental factors, social hierarchical behavior, gender differences, etc.

5.6.1.1 Inherent Growth Variation of Farmed Animals

There is great individual variation in some farmed animals. For example, the range of individual body weight is 7–89 g in Eurasian perch (*Perca fluviatilis*) after 7 months of culture. If these individuals are classified into three size groups with no weight overlap, the size overlap among the groups will reach 60% after another 200 days of culture. This overlap is not only caused by sex-linked growth differences, but mainly caused by individual growth variation (Mélard et al. 1996).

Table 5.18 Individual coefficient variation (CV) in growth for fish and sea cucumber (from Kestemont et al. 2002; Martins 2005; Dong 2015b)

Species	Growth expression	CV (%)
Salmo salar	Body weight (g)	7.5
Oncorhynchus mykiss	*SGR* (%/d)	31.1–166.1
Salvelinus alpinus	*SGR* (%/d)	~16.0
Hippoglossus hippoglossus	*SGR* (%/d)	>100.0
Scophthalmus maximus	*SGR* (%/d)	~30.0
Carassius auratus	Body weight (g)	9
Acipenser sinensis	*SGR* (%/d)	31.7
Anguilla anguilla	*SGR* (%/d)	37.2–46.6
Oreochromis niloticus	Body weight (g)	11
Gadus morhua	*SGR* (%/d)	~100.0
Perca fluviatilis	Body weight (g)	37.7–54.1
Clarias gariepinus	*SGR* (%/d)	18.1–58.2
Apostichopus japonicus	Body weight (g)	40.5–76.3

There are inherent differences in growth potential among animal individuals. In hatching practice, great differences are often found in weight or body length among offspring individuals of the same parents after a period of breeding, which is partially the maternal effect. For example, yellowtail (*Seriola lalandi*) larvae begin to show individual differences at the 12th day after hatching, and aggressive behavior of bigger individuals occurs at 19 days. For another example, when 17 individuals (68.3 ± 1.2 g) of African catfish are housed individually and cultivated (experiencing the same conditions) for 42 days, the individual variation coefficient of body weight still increased from 7.50% to 18.13% (Martins 2005).

The individual variation of farmed animals is related to time and initial size. When 10 sea cucumbers (2–5 g) are randomly selected from the same batch and cultivated separately (experiencing the same conditions) for 100 days, the coefficient of individual growth variation increases from 12.04 to 40.51% gradually (Fig. 5.8). The weight gain rates of small and large individuals were 50% and 175%, and specific growth rates were 0.40% and 1.01%, respectively, during 100 days of culture (Liang et al. 2010).

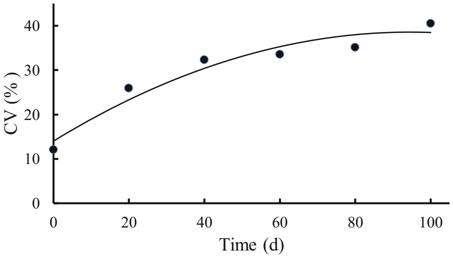
There are great differences in growth, feed intake, and food conversion efficiency among individuals of these sea cucumbers, which are positively correlated with their initial body weight. The final weights (Fig. 5.9a), *SGR* (Fig. 5.9b), feed intake (Fig. 5.9c), and *FCE* (Fig. 5.9d) of the animals are significantly correlated with their initial weights. Slightly different from the sea cucumbers, 80% of the individual variation of African catfish is caused by the differences in feed intake (Martins 2005).

Obvious difference also exists in energy allocation among individuals of the sea cucumbers. Comparing with bigger individuals, the smaller individuals spend more proportion of energy for respiration, and less energy for growth, as exemplified in the significant differences between the average respiration rate of six small individuals [46.13 kJ/(g·d)] and four slightly larger individuals [25.90 kJ/(g·d)].

5.6.1.2 Environmental Factors Affecting Growth Variation of Farmed Animals

The environmental factors affecting individual variation in the growth of aquaculture animals include temperature, light, and perhaps chemical pheromones and so on. The functions of chemical pheromones are the issue of chemical ecology, which remains mostly unknown.

Fig. 5.8 Coefficiencies of variation for body weight of *Apostichopus japonicus* housed individually during 100 days of culture (Liang et al. 2010)



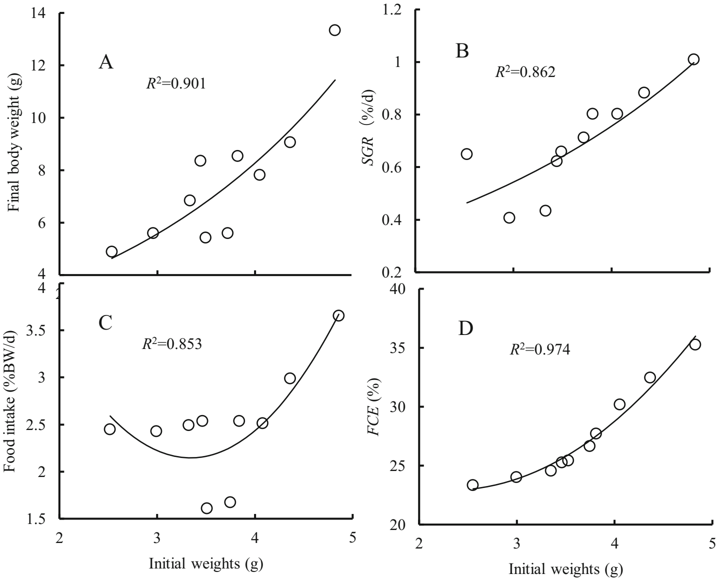


Fig. 5.9 Relationships between initial weight and final weight (**a**), specific growth rate (**b**), feed intake (**c**), and food conversion efficiency (**d**) of *Apostichopus japonicus* housed individually (Liang et al. 2010)

After 44 days of hatching, the weight variation of Eurasian perch larvae is greater at higher water temperature (Fig. 5.10). In addition, the survival rate of the fish decreases with increasing temperature, because the greater the body weight variation the more severe the cannibalism of the fish. There are slight differences in the optimal growth temperatures for pangasius (*Pangasianodon hypophthalmus*) larvae and juveniles of different sizes, and both sizes of the fish have the highest survival rate and least CV in body weight at their optimal growth temperatures.

The light intensity also impacts on the growth of Eurasian perch larvae. The *SGR* of the larvae (with yolk sac) is 20.7%/day at 5 Lx, but reaches 23.7%/day at 400 Lx, whereas the inverse correlation is observed in postlarvae (yolk sac been absorbed), i.e., *SGR* of 10.4%/day at 5 Lx, 7.4%/d at 400 Lx. However, light intensity does not significantly affect the survival, cannibalism, and size heterogeneity of the perch larvae and postlarvae.

Eurasian perch larvae grow slowly with serious cannibalism and large individual growth variation occurs under short illumination time. The survival rates of the perch larvae are positively correlated to illumination time (56.2% under photoperiod 24: 0 vs. 39.6% under photoperiod 8:16) (Kestemont et al. 2002). In contrast, the postlarvae of European seabass (*Dicentrarchus labrax*) survive significantly better under short illumination time (photoperiod 8:16), reaching the maximum 61.2 ± 4.0% (Kestemont et al. 2002). Some studies have shown that when fish

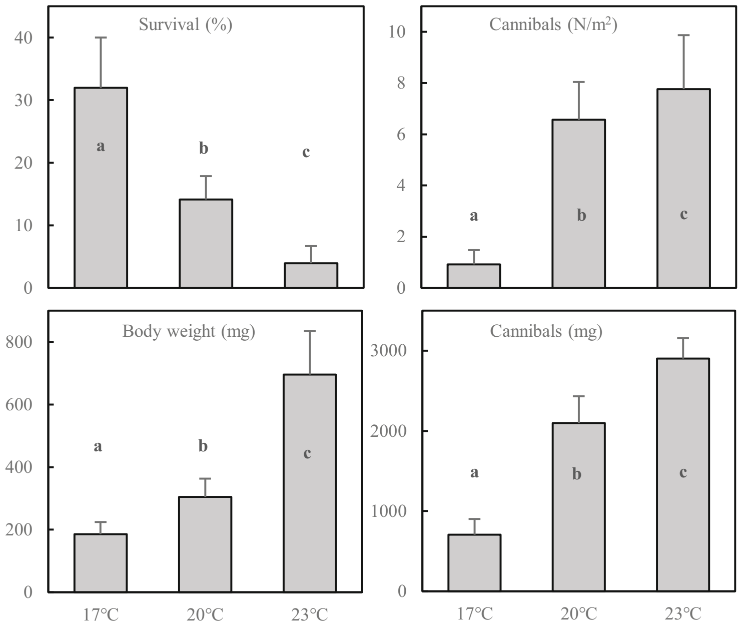


Fig. 5.10 Effect of rearing temperature on survival, growth, and cannibalism among perch larvae reared from egg stage for over 44 days (Kestemont et al. 2002)

expend more energy in overcoming water currents, the frequency of interindividual aggression decreases.

The temperature, light, and water currents mentioned above are all physical factors; however, the influence of water chemical factors on individual growth variation of fish is rarely known. In the case of the sea cucumber (*A. japonicus*) featuring unobvious aggressive behavior, their individuals still interact with each other even in the case of nonphysical contact. Pei et al. (2014) found that unconventional water quality factors such as pheromones may also affect the individual growth variation.

Pheromone refers to a chemical secreted by an animal that influences the behavior or physiology of others of the same species. Pheromone includes sex pheromone, alarm pheromone, aggregation pheromone, trail pheromone, and marking pheromone, transmitted to other individuals mainly by air, water, and other conductive media. The chemical alarm pheromone of fish generally comes from two sources. One is the pheromone released from skin damage, which may be produced by the predator's aggressive behavior toward the prey or the aggressive behavior between individuals of the same species. The other is self-released pheromone, such as interference pheromones. African catfish releases chemical alarm pheromones as a result of mechanical skin damage caused by attacking among individuals, and the alarm pheromone can inhibit physiological functions of other individuals and impair the welfare of farmed fish (van de Nieuweigiessen et al. 2008).

5.6.1.3 Effect of Social Hierarchical Behavior on Farmed Animals

Social hierarchy refers to the hierarchical system in which each animal has its certain status within a group. It has been found that animals like mammals, birds, fish, ants, bees all have social hierarchical behavior which significantly impacts their individual growth.

The social hierarchy is more common in carnivorous fish with aggressive behavior. Large-sized individuals dominate the social hierarchy, thereby gain access to more or better resources, inhibit the feeding, growth, and metabolism of inferior smaller individuals, and aggravate the differentiation of individual sizes within the group. Chasing behavior of yellowtail (*Seriola lalandi*) starts at approximately the 19th day of posthatch. The small individuals who are attacked is about 42% of the fish group, which results in a high mortality. If the large individuals are eliminated, the aggressive behavior will almost disappear, but the growth rate of the smaller individuals is still failing to gain weight until 12 days later (Moran 2007).

Some carnivorous and omnivorous fish are highly aggressive, such as salmon, trout, catfish, and tilapia, and there is significant size differentiation within these fish groups. Typically, individuals with aggressive behavior in the same group of fish grow faster, while less aggressive individuals grow slower. For example, the *SGR* of aggressive African catfish individuals is 7.7 ± 1.8%, while that of less aggressive individuals is 6.2 ± 1.3% (Martins 2005).

The size variation of fish affects the frequency and duration of aggressive behavior within the group. For example, the times and duration of agonistic encounters of signal crayfish (*Pacifastacus leniusculus*) for greater variation group (14.1 ± 5.5 g) were 97.7 ± 34.9 times and 14.1 ± 5.0 s, respectively; however, for smaller variation group (11.6 ± 1.7 g) were 63.4 ± 26.0 times and 19.7 ± 9.7 s, respectively. There was not statistical difference between the mortality of two groups (Ahvenharju and Ruohonen 2007), so they are basically nonlethal attacks, better described as eviction.

When a few dominant large individuals are removed from an Atlantic salmon group, aggression among the remaining small individuals is enhanced by an order of magnitude. The presence of large dominant individuals inhibits aggression among smaller individuals. Growth rates of small individuals range from 4.3%/d to 4.7%/d when large individuals are present, whereas removal of large individuals results in growth rates of 2.8%/d to 2.9%/d (Adams et al. 2000).

5.6.1.4 Effect of Gender on Growth Variation of Farmed Animals

There are great differences in morphology and growth between female and male individuals of many animals, caused by differences in feeding rate, energy allocation to growth and reproductive, and sex steroid hormone levels. Nile tilapia males grow fast and are large in size, while females grow slowly and are small. The digestive tract of male Nile tilapia is significantly longer than that of the female, causing differences in feeding rate and feed utilization efficiency. The different growth rates of female and male bluegill sunfish (*Lepomis macrochirus*) are mainly related to their stomach capacity and feeding rates. The pituitary GH mRNA expression of female European eel (*Anguilla anguilla*) and male Nile tilapia is higher than those of male European eel and female Nile tilapia, which is one of the intrinsic reasons for the different growth rate between female and male.

5.6.2 Effects of Feeding and Stocking Density on Growth Variation

5.6.2.1 Effect of Feeding Strategy on Growth Variation

The food particle size and ration will affect individual growth variation of farmed animals. The growth variation of Nile tilapia juveniles is positively correlated with feed particle size. The optimum feed sizes 3 g and 20 g of Nile tilapia individuals are 1.4 and 2.5 mm, respectively. The feed particles slightly smaller than the optimum size can reduce individual growth variation of farmed tilapia, while delivering feed particles larger than the optimum size will affect the growth rate of the fish (Azaza et al. 2010).

Ration level affects the growth variation of farmed fish significantly. Under restricted food condition (daily ration of 1% body weight), Eurasian perch grows fastest at a feeding frequency of 6 meal/day, but the size heterogeneity of the fish individuals is also the greatest (Mélard et al. 1996). On the contrary, hybrid tilapia (*O. mossambicus* × *O. Niloticus*) fed at daily ration of 3% body weight to satiation shows a higher *SGR* and smaller size heterogeneity, while the individual variation is larger at daily ration of 1.0% body weight (Wang 2003b). The growth rate of snapper (*Pagrus auratus*) larvae and juveniles increases significantly when the feeding frequency increases. Moreover, the coefficient of variation in harvest weight of the fish with 8 meal/d is lower than that with 2 meal/d (38.32% vs. 52.11%–51.24%).

However, some fish are not affected by the ration level on their growth variation. For example, adequate feed can reduce the attack frequency of rainbow trout and Arctic char (*Salvelinus alpinus*), but feeding frequency does not affect the size variation of the fish. Restricted food supply can reduce the feeding rate and growth rate of pollan (*C. pollan*), but also do not increase interindividual differences in feeding rate and growth rate of the fish. The growth rate and feed conversion rate of turbot (*Scophthalmus maximus*) increase with increasing ration levels (Table 5.19), but CV in body weight does not change significantly (van Ham et al. 2003).

The effect of ration levels on individual growth variation of fish may vary depending on the ecological characteristics of the species, developmental stage, environmental conditions, etc. Since the ultimate individual growth variation of cultured fish affects the market price and possibly the total production, feed conversion efficiency, etc., research on this topic needs to be further developed.

5.6.2.2 Stocking Density and Growth Variation

Usually, the growth rate decreases as the density of farmed animals increases, but there are exceptions. When the stocking density of Eurasian perch with an initial weight of 1 g increased from 400 to 10,000/m^3, the average individual growth rate of

Table 5.19 Effects of temperature and ration on specific growth rate (*SGR*), feed conversion efficiencies (*FCE*), and coefficients of variation of body weight (CV_W) after 53 days' rearing of juvenile turbot (from van Ham et al. 2003)

Temperature (°C)	Ration (%W/d)	Feed consumption (% W/d)	*SGR* (%/d)	*FCE* (g/g)	ΔCVw (%)
16	100	0.9	1.16 ± 0.05^a	1.20 ± 0.03^{ab}	1.06 ± 0.3
16	65	0.6	0.85 ± 0.01^b	1.30 ± 0.05^a	1.02 ± 0.3
16	35	0.3	0.46 ± 0.01^c	1.09 ± 0.01^b	1.02 ± 0.5
22	100	1.1	1.15 ± 0.09^a	1.06 ± 0.04^b	1.02 ± 0.8
22	65	0.7	0.87 ± 0.00^b	1.17 ± 0.00^b	1.01 ± 0.7
22	35	0.4	0.36 ± 0.02^c	0.80 ± 0.02^c	1.14 ± 0.5

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$)

the fish increased from 0.12 to 0.2 g/d after 74-days culture, an increase of 67% instead. Meanwhile, the coefficient of growth variation also decreased from 98.4 to 57.9%, which indicates that high-density culture of juvenile Eurasian perch is more effective (Mélard et al. 1996). However, the growth of bigger juvenile (>20 g) at higher density (2080 ind./m^3) is slower than that at low density. Therefore, the effect of stocking density on growth heterogeneity varies from species to species and from size to size.

The great growth heterogeneity of Eurasian perch is related to its territoriality or social hierarchy. For some fishes, large individuals tend to chase (attack) smaller individuals at lower stocking density which, however, will be weakened at higher stocking density. For example, the *SGR* of hybrid tilapia (initial weight of 41.17 g) at a density of 5 ind./tank is significantly lower than that of 10 fish/tank, i.e., 1.72 ± 0.04%/d versus 2.08 ± 0.07%/d. Meanwhile, the *FCE* of the tilapia at 5 ind./tank is also significantly lower than that of 10 ind./tank, i.e., 65.08 ± 3.21% versus 87.97 ± 1.84% (Wang et al. 2002).

Sea cucumbers (*A. japonicus*) do not have obvious aggressive behavior, but their individual growth variation is significantly affected by stocking density (Dong et al. 2009). In the density of 5–50 ind./100L (denoted as D5–D50, respectively), the survival rates of the animals in D5, D10, and D20 are all 100% after 50-days culture. However, the survival rates in D30, D40, and D50 show a descending trend with the increase of stocking density. The maximum *SGR* occurs in D20 and reaches 1.46%/day, which is significantly higher than those in other stoking densities (Fig. 5.11). The relationship between the stocking density and the average growth rate of the animals is accorded with the "Allee effect", namely, survival and growth status of animals with medium density are better.

Figure 5.12 shows the coefficient of variations in weight of *A. japonicus* in different stocking density. The individual growth variation of the animals increases significantly in the first 10 days for all stocking densities, and the coefficient of variation of body weight stabilizes later as the stocking density increased.

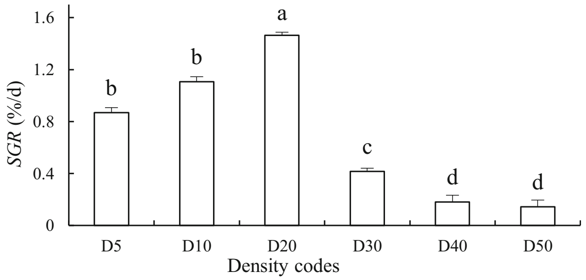


Fig. 5.11 Specific growth rates of *A. japonicus* in different density treatments (from Dong et al. 2009). D5 stands for five sea cucumbers per 100-L fiberglass tank, D10 stands for ten sea cucumbers per 100-L fiberglass tank, and so on

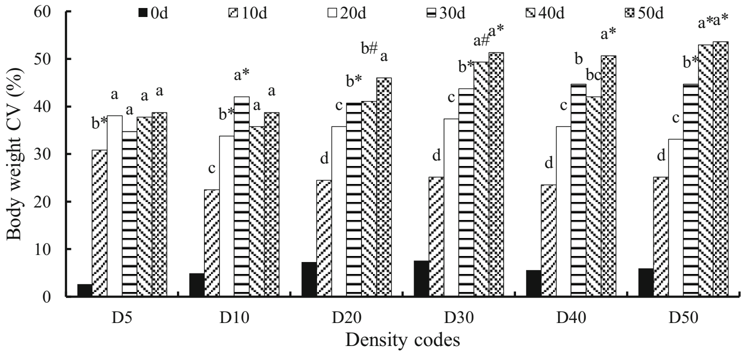


Fig. 5.12 Coefficients of variations in weight of *A. japonicus* in different stocking density treatments (from Dong et al. 2009). Different letters indicate significant difference within a treatment ($P < 0.05$), different symbols indicate significant difference between treatments at the same day ($P < 0.05$)

As mentioned above, several larger size salmon (*S. salar*) will inhibit the aggression among smaller fish and enhance their growth rate (Adams et al. 2000). In addition, hybrid tilapia is weaker in aggressive behavior at 10 ind./tank than that at 5 ind./tank, grows faster at 10 ind./tank (Wang et al. 2002). These phenomena are of interest to us in developing farming programs for these fish.

5.6.3 Individual Size and Growth Variation

Martins (2005) found that size distribution can affect the feeding behavior of African catfish but not the growth rate, feeding rate, feed conversion efficiency, and mortality over 27-days culture. However, Moran (2007) found weight variance of the low-weight, medium-weight, and heterogenous-weight groups of yellow tail significantly increased over 12-days culture, but not for the high-weight group.

The *SGR*s of the sea cucumbers (*A. japonicus*) in deferent weight groups are presented in Fig. 5.13 after a 100-days cultivation (Pei 2012). The sea cucumbers were firstly cultured with similar size for 50 days. Then four weight groups were set according to their individual weight, namely, homogenous heavy-weight (H, 9.36 ± 0.23 g), homogeneous medium-weight (M, 6.40 ± 0.27 g), homogeneous low-weight (L, 3.46 ± 0.36 g), and heterogenous weight (HET, containing different sizes of individuals). Then the groups of the animals were cultured for another 50 days. The *SGR*s in H and M groups were significantly higher than that in L group. In HET, the medium-weight and low-weight animals spent more time on the wall of the tank and ingested little food, hence their *SGR*s showed negative value. The *SGR* of heavy-weight animal in the HET group was slightly heavier than that in the H group (1.67% vs. 1.27%).

The coefficients of variations in weight (CV) of the sea cucumber in different size group change over time are presented in Fig. 5.14. The sea cucumbers in each group also showed significant individual growth variation at the 10d. The CV in H group stabilized after the 10d. The CV in M and HET groups stabilized after the 40d. The CV in L group was always increasing. The CV in HET group reached 76.23% at the 50d.

Effects of size grading on energy budgets of the sea cucumbers are significant. As shown in Table 5.20, 52.7%–64.7% of the energy ingested by the animal was not utilized, but was excreted as feces. The second largest destination of ingested energy was respiration, accounting for 21.5%–37.4% of ingested energy. Growth energy accounted for only 5.9%–11.3% of the ingested energy. The energy deposited as growth in HET-H was the highest among all groups, about 12.4%, and there were no significant differences between those in H (12.4%) and M (10.7%) ($P > 0.05$). The patterns of energy allocation in H and M were different from that in L. The energy lost in faces and energy deposited as growth in L group were significantly lower than those in H, M, and HET-H ($P < 0.05$), and the energy lost in respiration and excretion in L group were significantly higher than those in H, M, and HET-H ($P < 0.05$). In HET group, the medium-weight and low-weight sea cucumbers took

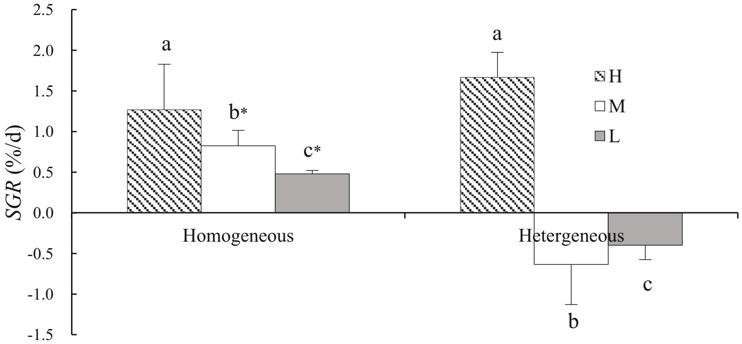


Fig. 5.13 Specific growth rates of low-, medium-, and heavy-weight *Apostichopus japonicus* in different groups (from Pei 2012). Different letters indicate significant different ($P < 0.05$), * indicates significant different in the same size group ($P < 0.05$), and bars represent standard errors of the means

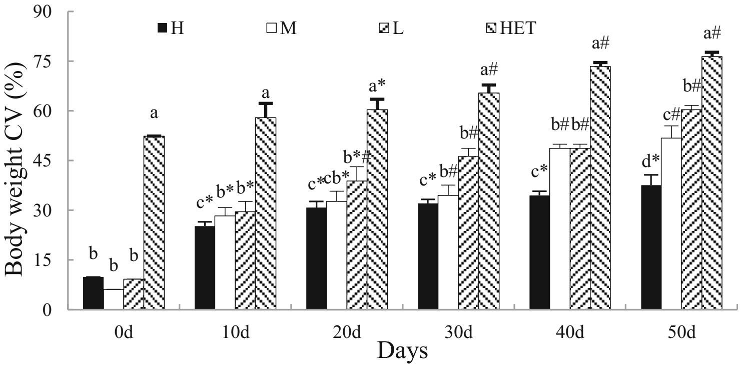


Fig. 5.14 Coefficients of variations of *A. japonicus* body weight in different size groups (from Pei 2012). Different letters indicate significant difference between the groups ($P < 0.05$), different symbols indicate significant difference of the same group at different time ($P < 0.05$), and bars represent standard errors of the means

Table 5.20 Allocations of the consumed energy of *A. japonicus* in different groups (from Pei 2012)

Sizes		*G*/*C* (%)	*F*/*C* (%)	*R*/*C* (%)	*U*/*C* (%)
H		11.30 ± 1.72^{a}	64.60 ± 1.55^{a}	21.48 ± 1.57^{c}	2.62 ± 2.23^{c}
M		10.73 ± 1.29^{a}	63.55 ± 1.61^{a}	24.24 ± 2.81^{c}	2.48 ± 0.52^{c}
L		5.92 ± 1.09^{b}	52.73 ± 1.58^{b}	37.41 ± 1.16^{b}	3.95 ± 1.37^{b}
HET	H	12.39 ± 0.62^{a}	64.76 ± 0.32^{a}	20.28 ± 0.35^{c}	2.57 ± 1.79^{c}
	M	–	0	91.2 ± 1.76^{a}	8.8 ± 1.76^{a}
	L	–	0	82.2 ± 2.67^{a}	17.8 ± 2.67^{a}

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$). The food consumption and faces of sea cucumbers in M and L treatments of HET group were zero, and their growth was negative. So, their excretion and respiration were calculated based on their negative growth values

little feed; therefore, their energy from tissue was consumed by respiration and excretion.

The individual growth variation of the sea cucumber is great, and the variation in HET group is over 70%. The animals have obvious size hierarchy effect, and the dominant heavy-weight individuals can inhibit the growth of the smaller ones, even leading to a negative growth of the smaller ones. After removing the large-size animals from the stock, the medium-sized individuals will show growth compensation, while the smaller individuals may show growth regression (negative growth) due to some reasons.

In practice, the sea cucumbers are normally cultured extensively in ponds without feeding, their food resources are limited in the ponds. Therefore, higher stocking density of the animal in the ponds will reduce the average *SGR*, increase individual growth variation, prolong the duration for reaching the commercial size, and even reduce the yield per unit area (Pei et al. 2013). Therefore, stocking the appropriate density of the sea cucumbers is imperative in production practice.

5.7 Compensatory Growth of Aquatic Animals after Periodic Starvation

Compensatory growth is a phase of accelerated growth when favorable conditions are restored after a period of growth depression. So far, extensive researches have been conducted on the compensatory growth of livestock and poultry animals, and economic benefits have been achieved by changing feeding strategies in some species. Since the 1970s, more attention has been paid to compensatory growth of aquatic animals which has become a hot spot in aquatic animal physio-ecology (Wu and Dong 2000; Ali et al. 2003; Hector and Nakagawa 2012).

5.7.1 Compensatory Growth Phenomena and Characteristics of Aquatic Animals

Compensatory growth in the bay scallop (*Argopecten irradians*) exists in smaller individuals of the same age. Juvenile abalone (*Haliotis fulgens*) nutritionally deficient for a short period is able to compensate by growing rapidly as soon as they are switched to the nutritional diet. The compensatory growth of Chinese shrimp occurs following starvation (Wu et al. 2001a, b). Compensatory growth has been studied in such fish species as Salmonidae, Cyprinidae, Pleuronetidae, Gadidae, Latidae, Acipenseridae, Siluridae, Ictaluridae, Clupeidae, Cichidae, etc.

In the perspective of the extent or degree of compensation, the compensatory growth varies considerably in terms of compensation patterns and extents of food restriction which can be generally divided into four patterns: partial, full, overcompensation, and no compensation growth (Fig. 5.15).

1. Over compensatory growth occurs when the animals that experienced a restricted ration (restriction + re-alimentation period) achieve a greater size at the same age than nonrestricted animals (Ali et al. 2003). For example, the yellowfin sole (*Pleuronectes asper*) starved for 2 weeks and then resumed feeding shows over compensatory growth by 12 weeks (Paul et al. 1995). Over compensatory growth occurs also in the Chinese sturgeon (*Acipenser sinensis*) which is on a 60-day cyclic feeding regime of starvation for 1 day and satiation feed for 3 days (Lu et al. 2009). Similarly, this phenomenon also occurs in rainbow trout, juvenile channel catfish, and Starry flounder (*Platichthys stellatus*) (Chen et al. 2013).
2. Full compensation means that the deprived animals eventually achieve the same size at the same age as continuously fed contemporaries. The full compensation growth of the flounder (*Paralichthys olivaceus*) was reported in a cyclic feeding regime of 3-day starvation and a 6-day normal diet for four times (Jiang and Jiang 2007). The weight growth of the deprived group is similar to that of the continuous feeding group.

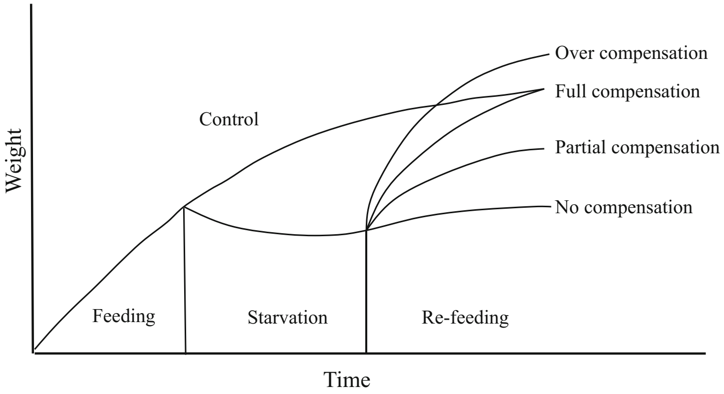


Fig. 5.15 Idealized patterns of growth compensation (From Ali et al. 2003)

3. Partially compensatory growth refers to the growth rate of animals that resumed growth after feeding restriction, but their final weight does not catch up with those in the nonrestricted group. The partially compensatory growth is shown in an 18-week study of hybrid striped bass (*Morone chrysops* × *M. saxatilis*) on evaluating the impacts of cyclic feeding regimes for a 1-week, 2-week, and 4-week period of deprivation, respectively (Turano et al. 2008).
4. No compensatory growth means the body weight and growth rate of the animals resuming growth after a period of starvation or food restriction fails to reach the level of the continuous feeding ones during the same period. For example, the southern catfish (*Silurus meridionalis*), after 60 d of starvation and resumption of feeding, has a lower level of feeding than the individuals fed continuously during the same period, showing no compensatory growth (Deng et al. 1999).

The growth rates of some aquatic animals are higher than those of continuously fed individuals when compensating for growth. However, the high growth rates do not persist, but gradually declines and returns to normal levels after a period of time. In Arctic sockeye salmon (*Salivelinus alpinus*), growth rates increase rapidly and exceed those of the continuously fed group when satiation is resumed after 8 weeks of restriction, reaching a maximum at Week 10 (5 times higher than at the end of restriction and 60% higher than in the continuously fed group) and then declining after 12 weeks. Although growth rates are still above normal at Week 16, the overall trend is that it is only a matter of time before growth rates return to normal levels (Miglavs and Jobling 1989).

The growth rate at the compensatory growth stage varies with species and degree of restriction. The growth rates of *Chalcalburnus chalcoides* and *Scardinius erythrophthalmus* increase rapidly after 2 weeks of starvation, while in *Leuciscus cephalus* physiological responses are generally lower than in the other two cyprinids species and the compensatory growth response is relatively delayed (Wieser et al. 1992).

5.7.2 Compensatory Growth of Aquatic Animals Following Periodic Starvation

5.7.2.1 Compensatory Growth after Treatment with Starvation-Feeding Cycles

Wu et al. (2002) studied the effect of repetitive "starvation-feeding" cycles on compensation growth response in Chinese shrimp at 25.0 ± 0.5 °C. By the end of the experiment, the shrimp fed continuously (the control C40) was significantly heavier than those fed according to the other regimes (Table 5.21). It is important to note that treatment C40 was fed for 40 d while the other treatments were fed for only 32 d. The shrimp in the continuously fed C32 weighed significantly less than shrimp in the other four intermittently fed treatments. This study indicates that the treatment group shrimp exhibited partial compensation for growth.

The shrimp in S1F4 showed significantly higher feeding rate than those in other groups over the whole experimental period. The shrimp in S1F4 showed significantly lower *FCE* than the control group, while no significant differences in *FCE*s were observed between the control and the other periodically starved groups.

The weight of sole (*Cynoglossus semilaevis*) individuals in the S2F4 treated group (starving for 2 days, feeding for 4 days, and repeating 12 times) is less than that in the control group (continuously feeding for 72 days), but the difference is not statistically significant (Fang et al. 2011), indicating that the sole exhibits a full growth compensation in the S2F4 treated group.

A 30-day comparative study (Yang et al. 2005) shows that there is full compensatory growth in the catfish (*Leiocassis longirostris*) and gibel carp (*Carassius auratus gibeli*) in both S1/F4 and S1/F2 groups, but for grass carp, the full compensatory growth exists only in the S1/F4 group, and partially compensatory growth in the S1/F2 group. It can be seen that the compensatory growth phenomenon of aquatic animals is species-specific and the causes are very complex.

Table 5.21 Growth and survival of *F. chinensis* under different starvation-and-refeeding cycles (from Wu et al. 2002)

Treatments	Body wet weight (g)		Weight gain (%)	Survival (%)
	Initial	Final		
S1F4	2.258 ± 0.105	7.542 ± 0.214^b	234.6 ± 6.0^b	100.0 ± 0.0
S2F8	2.217 ± 0.059	7.297 ± 0.130^b	229.4 ± 3.9^b	100.0 ± 0.0
S4F16	2.153 ± 0.017	7.410 ± 0.139^b	244.2 ± 3.8^b	93.8 ± 6.3
S8F32	2.152 ± 0.010	7.302 ± 0.102^b	239.3 ± 3.4^b	93.8 ± 6.3
C40	2.190 ± 0.016	8.400 ± 0.309^c	283.4 ± 11.4^c	93.8 ± 6.3
C32	2.190 ± 0.016	6.735 ± 0.153^a	207.5 ± 4.9^a	93.8 ± 6.3

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$). C40 fed ad libitum throughout the experiment (the control); C32 fed ad libitum continuously for 32 days; S1F4 repetitively starved 1 day and refeed 4 days for eight cycles; S2F8 repetitively starved 2 days and refeed 8 days for four cycles; S4F16 repetitively starved 4 days and refeed 16 days for two cycles; S8F32 starved 8 days and refeed 32 days for one cycle

5.7.2.2 Changes in Body Biochemical Composition during Compensatory Growth Period

When starving or undernourished, the animal consumes its own stored energy to sustain life activities. The main energy stores of most aquatic animals are lipid and glycogen, which are mainly consumed by the animals during starvation or nutritional deficiency. In general, protein is used as a metabolic energy source only after lipid is consumed in large quantities. The relative content of water and ash in body tissues increases gradually with the continuous consumption of energy substances.

In general, after relieving nutrition restriction and resuming normal feeding, the relative water content of the animal body gradually decreases along with the increase of the lipid and carbohydrates. The final biochemical composition (including protein, lipid, water, and ash) returns to normal. The body biochemical composition of Chinese shrimp before and after starvation-feeding cycle treatment is shown in Table 5.22. It can be seen that the intermittent starvation treatment affects significantly the body lipid content of the shrimps. The lipid content in S4F16 and S8F32 is significantly higher than that of the control group, but other components are not affected significantly.

5.7.3 Factors Affecting on Compensatory Growth

Animal growth is influenced by numerous factors, but the factors currently involved in studies of compensatory growth in aquatic animals are mainly the extent of food restriction, duration of starvation and recovery, nutritional properties of food, and sexual maturity.

5.7.3.1 Food Restriction Extent

The degree of food restriction covers both the level and duration of restriction. Food restriction level can be divided into complete restriction (completely stopping

Table 5.22 Body biochemical composition and energy content of *F. chinensis* during the 40-day culture (from Wu et al. 2002)

Time	Treatments	Water (% wet weight)	Protein (% wet weight)	Lipid (% wet weight)	Energy (kJ/g wet weight)
Initial	–	76.92 ± 0.41	16.79 ± 0.34	1.46 ± 0.03	4.39 ± 0.06
Final	S1F4	73.18 ± 0.65	19.54 ± 0.48	1.79 ± 0.06^{a}	5.26 ± 0.12
	S2F8	74.29 ± 0.73	18.22 ± 0.58	1.94 ± 0.07^{ab}	5.01 ± 0.14
	S4F16	73.68 ± 0.48	19.69 ± 0.37	2.14 ± 0.05^{b}	5.31 ± 0.11
	S8F32	73.15 ± 0.87	20.04 ± 0.62	2.53 ± 0.08^{c}	5.40 ± 0.14
	C40	74.16 ± 0.66	18.49 ± 0.47	1.81 ± 0.05^{a}	5.14 ± 0.13

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$). C40 fed ad libitum throughout the experiment (the control); S1F4 repetitively starved 1 day and refeed 4 days for eight cycles; S2F8 repetitively starved 2 days and refeed 8 days for four cycles; S4F16 repetitively starved 4 days and refeed 16 days for two cycles; S8F32 starved 8 days and refeed 32 days for one cycle feeding) and partial restriction (reducing ration level to a certain extent). It is suggested by Wilson and Osbourn (1960) that the nature of the periods of restriction in growing animals may be simply classified into three categories: (a) severe restriction (including starvation), resulting in a loss of body weight, (b) restriction, resulting in maintenance of constant body weight, and (c) mild restriction, allowing small but subnormal increases in body weight.

The effect of food restriction on aquatic animals is species-specific. As for the European minnow (*Phoxinus phoxinus*), mild restriction and maintenance ration have no significant effects on the feeding level, growth rate, and food conversion efficiency of individuals in the recovery satiation phase (Russell and Wootton 1992). For tilapia (*Oreochomis mossambicus* ♀ × *O. niloticus* ♂), after ration restriction at 1.5 and 0.5% body weight, the growth rate and feeding rate of the individuals in the recovery satiation phase are significantly higher than those of the control group. There is no significant difference in the growth rate and feeding rate between the control group and the individuals with a ration of 3.0% body weight in the recovery satiation phase (Wang 1999b).

Chinese shrimps will lose their weight during the starvation period, and the weight lost is proportional to the ration levels. At the end of 10-day starvation, the growth rates of the shrimp tend to decrease with the increase of ration levels. At the tenth day of following 30-day refeeding period, no significant differences occur in body weight between the food restricted group previously fed at 12% body weight/d (R12) and the control group fed ad libitum continuously (C). However, the weights for the other two groups previously held on 4 and 8% body weight/d ration level (R4 and R8) are significantly less than those of R12 and C. The weight of the shrimp in R12 catches up with that in C, while those in R4 and R8 are less than that of the C (Wu et al. 2001a).

The feeding rate and growth rate of the shrimp in the restricted groups are significantly higher than those in the control group after satiety feeding, but the compensatory growth only lasts about 10 days. After a period of restricted feeding, Chinese shrimp shows full and partial compensatory growth when they resumed growth. This compensatory growth effect is mainly achieved through increased food ingestion (Table 5.23).

The compensatory growth is also related to the duration of restriction. The periods of food deprivation of short duration (less than 3 weeks) are insufficient to induce any marked compensatory growth response of Atlantic cod (*G. morhua*), and the cod has the ability for complete compensatory growth during the resumption stage following 8 weeks of food deprivation (Jobling et al. 1994). Similarly, there is no compensatory growth for European minnow with 4 days' restriction, while individuals will not have complete compensatory growth until 16 days' food restriction.

Chinese shrimps will lose their weight during starvation period, and the weight lost is proportional to the duration of the starvation. After starvation for 4 days (S4), 8 days (S8), and 12 days (S12), there is no significant difference in body weight of the shrimp between the shrimp in S4 and S8 at the end of 44-day culture, but the weight of S12 is significantly less than that of continuously fed shrimp (C). After

Table 5.23 Specific growth rates (*SGR*), feed intakes (*FI*), and food conversion efficiencies (*FCE*) of *F. chinensis* during the period of restricted feeding in terms of dry weight and energy content (from Wu et al. 2001a)

Time	Parameters	R4	R8	R12	C
Restriction	SGR_d	-0.08 ± 0.16^a	1.79 ± 0.17^b	3.34 ± 0.33^c	5.07 ± 0.36^d
	SGR_e	-0.80 ± 0.25^a	1.34 ± 0.18^b	3.16 ± 0.28^c	5.46 ± 0.26^d
	FI_d	4.31 ± 0.07^a	7.88 ± 0.15^b	10.15 ± 0.34^c	16.99 ± 1.11^d
	FI_e	5.04 ± 0.08^a	9.11 ± 0.18^b	11.56 ± 0.39^c	18.61 ± 1.22^d
	FCE_d	-4.95 ± 0.85^a	20.81 ± 0.67^b	33.65 ± 2.62^d	28.38 ± 2.48^c
	FCE_e	-18.51 ± 0.53^a	13.16 ± 0.51^b	28.07 ± 2.25^c	28.22 ± 2.13^c
Refeeding	SGR_d	4.12 ± 0.21^b	4.22 ± 0.09^b	3.86 ± 0.34^{ab}	3.29 ± 0.20^a
	SGR_e	4.46 ± 0.13^b	4.11 ± 0.19^b	4.06 ± 0.27^b	3.17 ± 0.24^a
	FI_d	13.25 ± 1.27^a	13.32 ± 0.48^a	12.09 ± 0.49^a	11.87 ± 1.39^a
	FI_e	14.89 ± 1.78^a	14.88 ± 0.07^a	13.19 ± 0.84^a	13.10 ± 1.31^a
	FCE_d	27.79 ± 2.06^a	25.52 ± 4.09^a	28.66 ± 3.32^a	25.96 ± 2.37^a
	FCE_e	26.39 ± 3.18^a	24.00 ± 1.91^a	27.55 ± 3.40^a	22.79 ± 0.99^a

Note: The values with different letters in the same line are significantly different from each other ($P < 0.05$. Treatment C had ad libitum access to polychaete worms throughout the 40 days as the control; Treatments R4, R8, R12 were fed at 4%, 8%, and 12% of body weight per day (% B.W/d), respectively in the 10 days' ration restriction period, and were then fed ad libitum during the recovery feeding period refeeding, all the shrimps having experienced starvation show extraordinary appetite. The FI_W of the shrimps in the starvation treatment is significantly higher than that of the nonstarvation shrimp during the first 8-day after refeeding, and the FI_W is positively correlated to the length of the starvation period. However, the appetite of all the shrimps having experienced starvation drops rapidly to a level similar to that of the nonstarvation shrimp during the second 8-day period after refeeding (Wu et al. 2000).

The growth rates, expressed in terms of dry weight, protein, and energy are related to the duration of previous starvation. The growth rates are not significantly different between S4 and C during the refeeding period, but the shrimps in S8 and S12 grow significantly faster than the control C.

5.7.3.2 Starvation Duration and Recovery Duration

The ratio of starvation to recovery time has a great influence on the degree of compensatory growth of shrimp and fish (Tables 5.21 and 5.22; Fang et al. 2014). A study has shown that the longer the food restriction duration of Nile tilapia, the greater the feeding and growth rate, and the greater the growth compensation ability during the refeeding period (Wang 1999b). But it does not mean the longer the starvation time is, the stronger the compensatory growth ability is in any cases. There is a limit for the duration of starvation, beyond which normal growth cannot be restored and growth stagnation is likely to occur. For example, channel catfish juveniles are not able to increase their growth rates sufficiently to overcome weight loss imposed by the 4-week feed restriction (Gaylord and Gatlin 2000). Also, when feeding is resumed after 10- or 15-day starvation, the content and activity of digestive enzyme of red drum (*Sciaenops ocellatus*) remain low and cannot return to the same level of those fed continuously during the 30-day refeeding period (Jiang et al. 2002). The compensatory growth effect needs to be stimulated by moderate food restriction, exceeding the certain level of restriction will cause irreversible damage to the physiological functions of the animals.

A great number of studies have shown that the growth rates of aquatic animals in refeeding period always rise for a period of time before returning to a normal level. Obviously, if the refeeding time is too short and the growth rate has not yet returned to normal levels, the compensatory growth effect cannot be fully exploited; conversely, if the recovery time is too long, the compensatory growth effect will disappear to some extent, as shown in southern catfish (Deng et al. 1999).

The dry-to-wet ratio (dry weight/wet weight) of the Chinese shrimp body (initial weight 1.454 ± 0.150 g) decreases significantly with the extension of the starvation, from 23.20 ± 0.31% initially to 20.81 ± 0.24%, 18.28 ± 0.29%, and 16.90 ± 0.22%, respectively, after 4, 8, and 12 days of starvation, while returns to 26.23 ± 0.18%, 26.13 ± 0.36%, and 25.86 ± 0.34%, respectively, after 28, 24, and 20 days of refeeding (Wu et al. 2001b). Therefore, the starvation duration also affects the compensation pattern in the biochemical composition of animals.

5.7.3.3 Nutritional Properties of Food

The growth rate of the juvenile abalone (*Haliotis fulgens*) fed abalone viscera continuously is significantly less than those switching from nutritionally unbalanced giant kelp meal to abalone viscera (Viana et al. 1996).

There is also a compensatory growth of Chinese shrimp after certain dietary protein restriction. After 2 weeks of the protein restriction, there are significant differences in growth rates of Chinese shrimp fed low protein feeds (Fig. 5.16). During the first 2 weeks of realimentation, the previously protein-restricted shrimps, i.e., fed 15.0% protein diet (T_{15}) and 29.3% protein diet (T_{30}), display significantly higher *SGR*e than the control (fed 44.6% protein diet), and there seems to be a tendency for these values to decrease with increase in severity of protein restriction. During the last 2 weeks of realimentation, *SGR*e of the shrimp in T_{15} is significantly higher than those of shrimps in other two groups (Wu and Dong 2002b).

Complete compensatory growth occurs in the T_{30} group at the end of 4 weeks of realimentation, while the weight of shrimps in T_{15} group is still significantly less than that in the control group. As the growth rate of dry weight, protein, and energy of the T_{15} group in the late growth stage (fifth to sixth week) is still significantly higher than that of the control group, it is not yet possible to tell whether it has the capability of complete compensatory growth.

As the protein level of feed decreases, the *FCE* or protein digestibility decreases significantly, while the food intake rate and protein efficiency increase significantly. At the end of the restriction period, compared with the control group, the water and ash contents of the shrimp tissue in the protein restriction groups are significantly higher. However, the body composition and energy difference gradually disappear between the protein restriction groups and the control group during the recovery period, showing that the compensatory growth of Chinese shrimp following protein

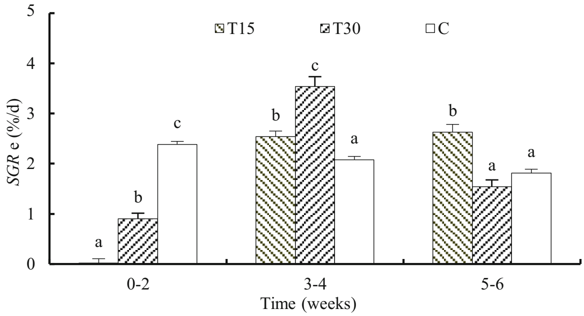


Fig. 5.16 Specific growth rates in term of energy for juvenile Chinese shrimp kept on the three feeding regimes in the course of experiment (Wu and Dong 2002b). Means with different letters within each period are significantly different ($P < 0.05$). Shrimps in Treatment C (control) were given a standardized diet with 44.6% crude protein in ad libitum throughout the trial period. In Treatment T_{15} and T_{30}, the crude protein supply was reduced to 15.0% and 29.3%, respectively during the restriction period. In the realimentation phase, shrimps previously receiving protein restriction were given the same feed as the controls

restriction is accompanied by the recovery of biochemical composition and reserved energy.

The compensatory growth of the T_{30} group is achieved by improving the *FCE*, while the compensatory growth of the T_{15} group is achieved by improving both feed intake and *FCE*. However, Schwarz et al. (1985) reported that carp showed no obvious compensatory growth after protein restriction (30% below normal level) or energy restriction (37% below normal level). Therefore, the compensation effect of nutrient restriction is species-specific and may be related to some environment factors.

5.7.3.4 Sexual Maturity and Temperature

The *SGR* and feeding rate are significantly higher in male Nile tilapia than in females in the refeeding phase after 10-days starvation, thus male Nile tilapia can compensate for a fasting period more efficiently than the female (Barreto et al. 2003). By comparing the compensatory growth characteristics of sexually mature and immature Atlantic salmon, Jobling et al. (1993) found that they are both capable of partial compensatory growth after refeeding, but the final weight of mature individuals is less than that of the immature ones.

The compensatory growth of Chinese shrimp is affected by water temperature to some extent (Wu and Dong 2002a). After 6 days of starvation, the SGR_w of the shrimps are all greater than the control (fed continuously) during the period of resumption (Fig. 5.17). However only at 30 °C does the final weight of the shrimps is significantly less than the control after 30 days of resumption of feeding. So, high temperature is not conducive to the compensatory growth of the shrimp.

The shrimps at each temperature show stronger appetite and faster growth after refeeding. Then, the feeding rate decreases gradually to the level same as that of the control group. The *FCE*s of the shrimps in starvation treated groups at each temperature are significantly lower than that of the control groups in the first 6 days after refeeding, but then the differences begin to disappear. So, the compensatory growth of Chinese shrimp at various temperatures is achieved by increasing feed ingestion rate during the refeeding stage.

5.7.4 Physio-Ecological Mechanism of Compensatory Growth

Le Magnen (1985) proposed the “set-point” theory of weight regulation in mammals, believing that adult mammals “remember” their nutritional history and compensate for it with modifications in appetites. Given fact that fish growth is usually indeterminate and subjected to the environmental factors, Russell and Wootton (1992) believe that the compensatory growth of fish is related to its “set-point” of growth rate regulation. There is still no uniform understanding of the physio-ecological mechanisms underlying compensatory growth in aquatic animals, and there are three main views:

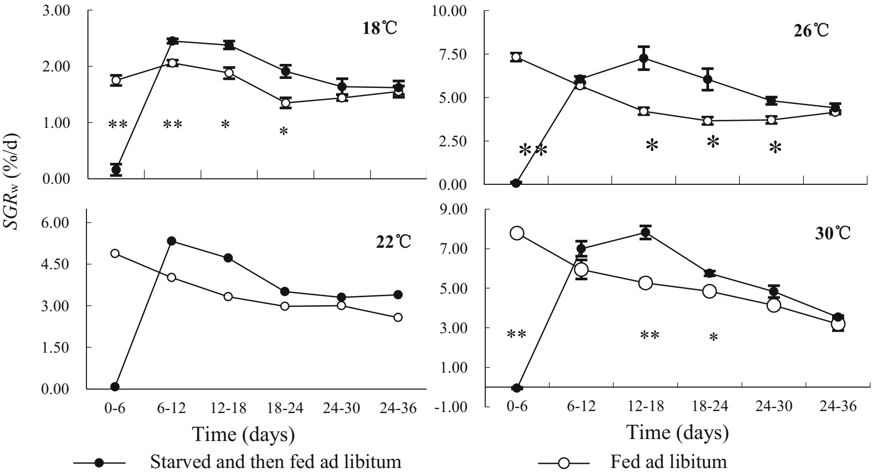


Fig. 5.17 Changes in specific growth rate in terms of wet weight for juvenile *F. chinensis* kept on either fed ad libitum or starved–fed ad libitum at four temperatures in the course of experiment (from Wu and Dong 2002a)

1. Food restriction reduces the metabolic level of aquatic animals. Even if feeding resumes, the lower metabolic level persists for some time. This reduction in metabolic expenditure allows the animal to deposit a greater proportion of ingested energy for growth during the resumed growth phase, thereby increasing the rate of food conversion.
2. When feeding is resumed after restriction, the animal's body immediately undergoes high rates of synthesis and metabolic levels rise rapidly. So, it is impossible to significantly improve food conversion by lowering metabolic levels. Therefore, compensatory growth is achieved by increasing the feed intake during a period of time when the animal resumes the growth phase.
3. Animals not only increase their appetite and improve their feeding rates during the resumption of feeding phase, but also improve their food conversion rate. Thus, compensatory growth is the result of the combined effect of above two physio-ecological mechanisms.

The mechanisms of compensatory growth may vary from species to species, and are affected by other factors.

5.7.5 Application of Compensatory Growth Theory

There have been many studies on compensatory growth in aquatic animals, and the results have shown good promise for application. Some scholars have patented technologies based on compensatory growth mechanisms in farmed aquatic animals for this purpose. But reports on practical applications are few, which may be due to the fact that over compensatory growth in aquatic animals is not very common, or more likely because that statistically "insignificant" difference in weight between the individuals fed continuously and intermittently may be decisive for the astute operator. What is needed in a commercial sense is a significantly over compensation effect, which should be the focus of applied basic research in future.

In addition, the insufficient feed will increase the individual growth variation of some farmed animals, which will affect aquaculture efficiency. However, it is still unclear how intermittent feeding affects the individual growth variation of farmed animals.

Still, the research done in the past is of great importance. When workers and automatic feeding machine are unavailable for feeding on weekends or holidays, you can use the compensatory growth theory to "compensate" or "over-compensate" for the weekend or holiday losses.

Caution should be exercised when applying the compensatory growth theory to crustacean farming, as crustaceans are cannibalism, soft-shell molting individuals are more threatened by hungry individuals. An experiment shows that the intermittent feeding cannot be simply applied to Vannamei shrimp farming in ponds (Jie 2006). Compared with Chinese shrimp, Vannamei shrimp are less cannibalistic, which could be worse if Chinese shrimp were cultured in their experiment!

Brief Summary

1. Fish growth features the following eight characteristics: indetermination, flexibility, growth by stages, seasonality, difference between male and female, isometry, and allometry. The annual absolute growth rates of different fishes are positively proportional to their body sizes. Aquaculture often involves the selection of fast-growing species, operation in the right season, and creating a good environment for growing aquatic organisms.
2. The growth curve of fish is a shape of asymmetrical "S", and the point of inflection usually occurs at sexual maturity period. The growth accelerates before the inflection point and slows down after it. The growth of mollusks is different from finfish, its shell grows continuously but its soft tissue grows only in certain seasons.
3. The model of animal bioenergetics is $G = C–F–U–E–R = C–F–U–E–R_s–R_a–SDA$, where, G is growth energy; C is feeding energy; F is fecal energy; U is excretion energy; R is respiratory metabolic energy; Rs is standard metabolism; Ra is activity metabolism; SDA is special dynamic action or body heat increment. The growth of mollusk falls into three parts: soft tissue growth ($G_{\text{soft tissue}}$), shell growth (G_{shell}), and gonadal growth (G_{gonad}). Therefore, its bioenergetics model is as follows: $G = G_{\text{soft tissue}} + G_{\text{xhell}} + G_{\text{sexual gland}} = C–F–U–Rs–Ra–SDA$.
4. Each species of aquatic animals can tolerate a temperature range between the upper limit and lower limit, and the optimum temperature for them is relatively close to the upper limit of the temperature range. The adaptability to temperature of aquatic animals can be acclimated and changed. If temperature changes

slowly, the upper or lower limit of temperature tolerance of aquatic animals will be higher or lower. The temperature tolerance of aquatic animals can be changed by experiencing different thermal history.

5. In general, most of the organisms inhabiting pelagic area of open seas are stenohaline, and most of the organisms inhabiting estuarine areas are euryhaline. The ability of aquatic animals adapting to the changes in salinity usually increases with age, but some marine invertebrates are more resistant to high salinity in larvae stage than adults, which is related with their evolutionary history. When the salinity changes gradually, the aquatic animal will have higher salinity tolerance, and vice versa. A certain period of salinity acclimation can improve the salinity tolerance of aquatic animals.
6. Hypoxia in waters often causes mass death of aquatic animals. At the other extreme, oversaturated DO may also cause “bubble disease” of farmed animals. In general, freshwater and warm-water fishes are more tolerant of hypoxia than marine and cold-water fishes. Usually, higher DO level is required at fish embryo stage. Most of farmed aquatic animals are oxygen-regulator animals, which can change their respiratory activity such as respiratory frequency when DO of the water declines in order to keep metabolic rates relatively stable. Dissolved oxygen content and water temperature interact to affect fish growth.
7. The effect of light on the growth of aquatic animals varies from species to species, from season to season, and from development stage to stage. The optimum light required for an animal’s growth is an adaptation to the environment it inhabits and is the result of a long period of evolution. Any artificial lighting conditions that deviate from their natural photoperiod may inhibit their growth rate. Shrimp may grow faster in the organically rich earthen ponds than in organically poor waters because there is less blue light spectrum in the “green water”.
8. The coefficient variation in individual growth of aquatic animals is much greater than that of terrestrial farmed animals. The direct causes of the variation are differences in feeding rate or food utilization, and indirect causes are genetic and environmental factors, social hierarchical behavior, gender differences, etc.
9. The food particle size and ration level can affect individual growth variation of many farmed animals. The difference of stocking density and size heterogeneity also affect the growth variation. Some farmed animals, such as tilapia and sea cucumber, exhibit the Alee effect, namely, survival and growth status of animals with medium density are better.
10. Compensatory growth is a phase of accelerated growth when favorable conditions are restored after a period of growth depression. In the perspective of the extent or degree of compensation, the compensatory growth can be generally divided into four patterns: partial compensation, full compensation, overcompensation, and no compensation of growth.
11. Compensatory growth of farmed animal is influenced by numerous factors, such as the ration level, duration of starvation and recovery, nutritional properties of food, sexual maturity, and environmental factors. The degree of the influence varies greatly and is species-specific.

12. The compensatory growth of fish is related to its “set-point” of growth rate regulation. There are three main views on physio-ecological mechanism of compensatory growth: (1) Food restriction reduces the metabolic level of animals. This reduction in metabolic expenditure allows the animal to deposit a greater proportion of ingested energy for growth during the resumed growth phase, thereby increasing the rate of food conversion. (2) Compensatory growth is achieved by increasing the feed intake during a period of time when the animal resumes the growth phase. (3) Animals not only increase their appetite and improve their feeding rates during the resumption of the feeding phase, but also improve their food conversion rate. Thus, compensatory growth is the result of the combined effect of above two physio-ecological mechanisms. The mechanisms of compensatory growth may vary from species to species, and may also be affected by other factors.
13. Studies on compensatory growth in aquatic animals have shown good promise for application. However, caution should be exercised when applying the compensatory growth theory to crustacean farming, as crustaceans are cannibalism, soft-shell molting individuals are more threatened by hungry individuals.

6 Effects of Environmental Factor Fluctuation on Aquatic Organisms

Shuang-Lin Dong and Xiang-Li Tian

An important research direction in aquaculture ecology is the individual ecology of farmed organisms. The main purpose of this direction is to determine the optimum environmental conditions for farmed animals and plants in order to lay a theoretical foundation for building the best environmental conditions for faster growth and development of farmed organisms in aquaculture.

There are many factors that affect the growth of aquatic organism individuals, and the main exogenous factors are water temperature, salinity, light, dissolved oxygen, nutritional factors, etc. Shelford's law of tolerance states that there is an optimum value for animals to adapt to various environmental factors, where they can obtain the maximum survival and growth rate. Based on this idea, people usually try to find the certain optimal value of an environmental factor for the farmed aquatic animals through experiments (trials) and try to control the environment under this optimal condition to farm the animals in order to obtain the highest yield.

In fact, the various environmental factors in natural waters mostly have certain periodic variations, such as daily changes, seasonal changes, and tidal changes. Numerous studies have showed that there is not a so-called optimal 'value' for the growth of some aquatic organisms, but rather an optimal amplitude of variation. Understanding such patterns can help us to innovate farming techniques that accelerate the growth of farmed organisms.

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6.1 Effects of Fluctuation in Temperature on Aquatic Organisms

It was discovered that tomato growth has thermoperiodicity of growth, i.e., there are diurnal differences in its growth and physiological processes, in the 1940s. In recent years, it has also been found that circadian rhythms of fluctuating temperature have beneficial effects on intertidal seaweeds (Wang 2008b).

In nature, the life activities of organisms are periodical; i.e., they follow a certain time sequence that corresponds to the changes of day and night, tides, moon phases, and seasons, which are called circadian rhythm, tidal rhythm, moon rhythm, and annual rhythm, respectively. Biological rhythms are the adaptations of organisms to predictable changes in environmental conditions, with circadian rhythms being the most closely related to the life activities of organisms (Brown 1970). It is the result of the alternating diurnal changes in light and temperature produced by the Earth's rotation and is an intrinsic physiological mechanism formed by organisms living on the Earth after long-term evolution, which enables the process of life activity of organisms to coordinate with diurnal changes and thus adapt to the diurnal light and temperature changes produced by the Earth's rotation. The physiological rhythm formed by this diurnal adjustment is also known as biological clock.

Water temperature changes in aquaculture waters also have a certain periodicity, such as diurnal variations and seasonal changes. Most of the experimental studies on aquatic organisms are currently conducted at constant laboratory temperatures, and thus, it has been questioned whether the experimental results obtained at constant laboratory temperatures correspond to the real situation under natural conditions.

6.1.1 Effects of Diurnal Rhythmic Fluctuations in Temperature on Seaweeds

Some seaweeds living in the intertidal zone can be used as feed for farmed aquatic animals. Some seaweeds are also instrument species for water quality regulation in aquaculture because they can control the growth of microalgae by nutrient competition or allelopathic effect (Jin et al. 2003).

Seaweeds (macroalgae) living in the intertidal zone undergo rhythmic short- and long-term environmental changes and have evolved over time to be adaptive to these dynamic environmental changes. Correspondingly, their growth also demonstrates a thermocyclic phenomenon; i.e., within a certain range of fluctuations, temperature variations can promote the growth of some seaweeds such as *Ulva pertusa*. For example, the growth rates of *U. pertusa* at 20 ± 2, 20 ± 4, and 20 ± 6 °C are significantly higher than those at constant 20 °C. The optimal daily temperature range for *U. pertusa* growth is ±3.69 °C when the average temperature is 20 °C (Wang et al. 2007a).

Daily fluctuations in temperature also promote the growth of the intertidal seaweed *Gracilaria asiatica*. The diurnal high temperature not only promotes the nutrients uptake rate of *G. asiatica*, but also enhances its photosynthesis rate, while

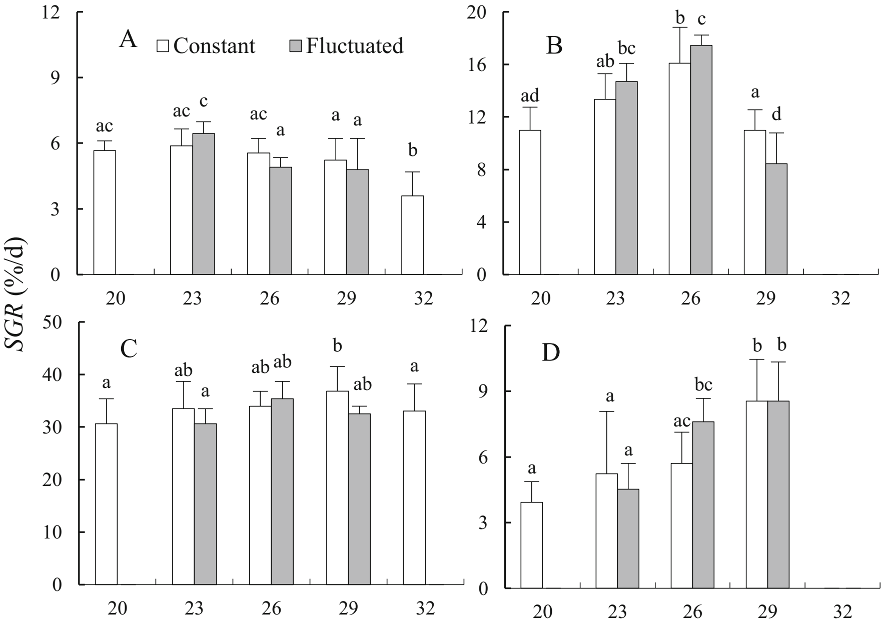

Fig. 6.1 Specific growth rates (*SGR*) of *Ahnfeltiopsis flabelliformis* (**a**), *Ulva pertusa* (**b**), *Enteromorpha linza* (**c**), and *Gracilaria textorii* (**d**) at constant and diel fluctuating temperatures (±0 °C and ± 3 °C) (from Wang 2008b)

the nocturnal low temperature decreases the respiration of the seaweed (Wang 2008b).

Furthermore, the daily rhythm fluctuations of temperature have a significant influence on the spore germination rate of some seaweeds as well. The spore germination rate of *Grateloupia turuturu* is promoted in daily temperature fluctuations of 15 ± 3 and 20 ± 3 °C. However, when the average temperature reaches 25 °C, the daily temperature fluctuations do not demonstrate the promotion on the spore germination rate compared with the corresponding constant temperature regimes, and even significantly reduce the spore germination rate as compared to the constant temperature of 25 °C (Wang 2008b).

The responses of seaweeds to daily cyclic fluctuations in temperature vary among species at different locations in the intertidal zone (Fig. 6.1). The specific growth rate (*SGR*) of the mesotidal seaweed *U. pertusa* at 26 ± 3 °C (mean 17.52%/d) is significantly greater than that of the constant temperature of 26 °C (mean 16.21%/d), and the *SGR* of high-tide seaweed *Ahnfeltiopsis flabelliformis* at 23 ± 3 °C is only slightly higher than that at the corresponding constant temperature (23 °C). Comparatively, for the mid-tidal seaweed *Enteromorpha linza* and the low-tidal seaweed *G. textorii*, no any growth promotional effect resulted from daily rhythm fluctuations of temperature is found (Wang 2008b).

6.1.2 Effects of Periodic Temperature Fluctuations on Aquatic Animals

In the 1970s, it was discovered that periodic fluctuations in water temperature could promote fish growth compared to constant temperature. Most aquaculture animals are ectotherms, whose body temperature varies with water temperature, and it is of great theoretical importance and practical application to understand their adaptability to periodic temperature changes.

6.1.2.1 Effects of Periodic Fluctuations in Temperature on the Growth of Aquatic Animals

In numerous previous experimental studies, fluctuating temperatures within the limit of the ecological norms for an aquatic animal can enhance the growth of aquatic ectotherms (Tian and Dong 2005). For example, the growth rate of sea cucumber (*Apostichopus japonicus*) under the thermal regimes of 15 ± 2 and 18 ± 2 °C is significantly greater than the constant temperatures of 15 and 18 °C (Dong and Dong 2006). The growth rate of Chinese shrimp (*Fenneropenaeus chinensis*) at constant thermal regimes increases from 18 to 31 °C, while decreases significantly at higher temperature of 34 °C. The specific growth rates of *F. chinensis* at 22 ± 2, 25 ± 2, and 28 ± 2 °C increase significantly compared to those at the constant temperatures of 22, 25, and 28 °C, respectively, with the highest growth rate appearing at 28 ± 2 °C (Tian et al. 2004c, 2006; Fig. 6.2).

When *SGR* is plotted against mean temperature, the growth curve of response for some fishes to fluctuating temperatures is shifted horizontally toward colder temperatures than the curve of response to constant temperature regimes. A fluctuating temperature with a mean temperature lower than the constant optimum temperature has a growth-promoting effect on aquatic animals; however, a fluctuating temperature with a mean value higher than the constant optimum

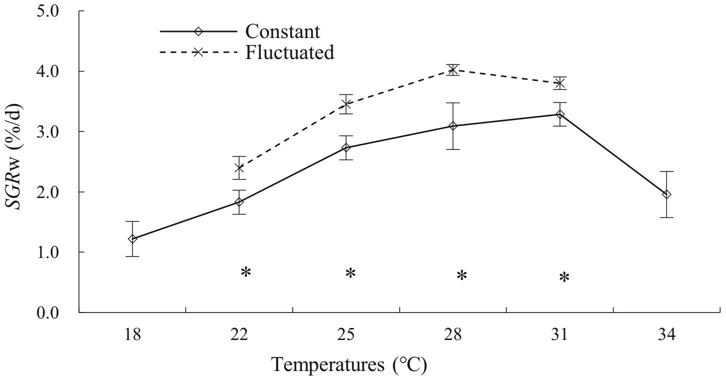

Fig. 6.2 *SGR*$_w$ of *Fenneropenaeus chinensis* at different thermal regimes (from Tian et al. 2006). * Stands for a significant difference between *SGR*$_w$ at constant temperature and corresponding fluctuated temperature

temperature has an inhibitory effect on growth. When compared with the constant temperatures, the mean temperature at which maximum growth rate of *F. chinensis* occurs drifted to lower temperature at fluctuating thermal regimes. The highest growth rate of the shrimp at constant temperature is 31 °C, while the average temperature for highest growth rate under fluctuating temperature is 28 °C (28 ± 2 °C) (Tian et al. 2004b, 2004c, 2006; Fig. 6.2). The curve of response in growth of trout (*Salmo gairdneri*) to fluctuating temperatures with fluctuation amplitude of 3.8 °C was shifted horizontally an average 1.5 °C toward colder temperatures than that to constant temperatures (Hokanson et al. 1977). And the maximum temperature for growth of Arctic charr (*Salvelinus alpinus*) at fluctuating temperatures was estimated to be 0.4 °C lower than at constant temperature (Lyytikäinen and Jobling 1999).

Within a moderate fluctuating thermal regime, the growth rate of some fishes under fluctuating temperatures can be not only greater than that at the corresponding mean temperature, but even higher than the upper limit of the variable temperature. For example, the growth rate of juvenile carp (*Cyprinus carpio*) at fluctuating temperatures of 18–30 °C is not only greater than that at constant temperatures of 18 and 24 °C, but even greater than that of carp at constant temperatures of 30 °C (Zdanovich 1999); similarly, largemouth bass (*Micropterus salmoides*) also grow significantly greater at fluctuating temperatures of 15–29 °C than those at constant temperatures of 15 and 29 °C (Diana 1984). However, thermal fluctuations at the mean temperatures above the thermoregulation range might have an inhibitory effect on the growth of aquatic animals.

6.1.2.2 Effects of Different Change Rates of Temperature on Aquatic Animals

The change rate of temperature affects the growth of aquatic animals at a suitable range of temperature fluctuations, and too great or too small a rate of temperature change can impact negatively on the growth of aquatic animals. In general, the rate of temperature change that positively promotes the growth of eurythermic species is higher than that of stenothermic ones. Common carp (*C. carpio*) grows fastest at a rate of 1.3 °C/h in the range of 2–6 °C and 2–12 h (switching time from high temperature and low one). However, no accelerated growth is found at a rate lower than 0.6 °C/h. When the rate was higher than 4.0–5.3 °C/h, the growth rate is significantly reduced (Konstantinov et al. 1990). The optimal rate of temperature change for common carp is 1.3–2.0 °C/h, and no growth-promoting effect occurred at less than 0.7–0.8 °C/h.

Compared to thermal regimes of rapid-changing and gradual-changing temperature with ±2 °C variation at mean temperatures of 22, 25, 28, and 31 °C, the specific growth rates of Chinese shrimp under gradual-changing temperature (FT-a) are significantly higher than those of the corresponding thermostatic ones (Tian 2001; Fig. 6.3). In the rapid-changing temperature (FT-b), the growth rates of shrimp are significantly higher under than the thermostatic temperatures of 25 °C and 28 °C, while they are not significantly different from the corresponding thermostatic ones under 22 ± 2 and 31 ± 2 °C.

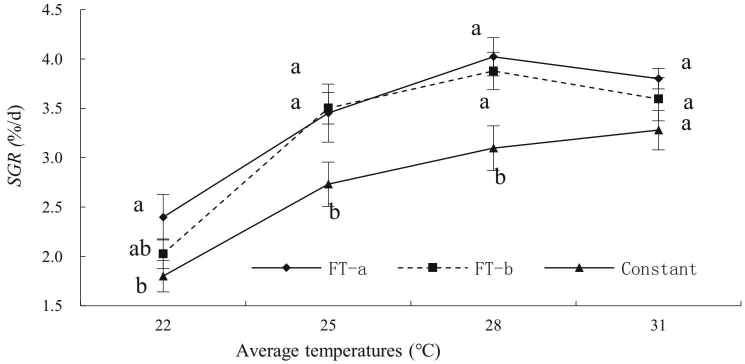

Fig. 6.3 Specific growth rate of *Fenneropenaeus chinensis* at constant and fluctuating thermal regimes (from Tian 2001). ◆ Gradual-changing temperature regimes; ■ rapid-changing temperature regimes; ▲ constant temperature regimes

The energy budget pattern of the shrimp is altered at fluctuating temperatures compared to the corresponding constant temperatures. The equations for the allocation of food energy to shrimp at constant, gradual, and rapid temperature changes are as follows

$$\text{Constant thermal regime}: 100C = 13.1G + 11.9F + 7.1U + 0.6E + 67.3R$$

$$\text{Gradual temperature changes}: 100C = 16.1G + 11.4F + 6.7U + 0.5E + 65.4R$$

$$\text{Rapid temperature change}: 100C = 14.6G + 12.1F + 6.7U + 0.6E + 65.9R$$

The proportion of growth energy to ingest energy (*G/C*) is significantly higher for shrimp under gradual variation than for the shrimp under constant thermal regime. In contrast, no significant difference is found in energy budgets between the shrimp under the corresponding constant and rapid-changing temperature, except for the mean temperature of 22 °C. There are no significant differences in the ratio of respiratory energy to ingest energy (*R/C*) in shrimp at any of the different thermal regimes.

The mechanisms responsible for the differences in shrimp growth at fluctuating and constant temperatures differ depending on the thermal regimes. Variations in the ratio of growth energy to ingest energy and assimilation energy and the ratio of respiratory energy to assimilation energy due to temperature fluctuations are the main reasons for the promotion in growth of shrimp at gradual temperature change. At the rapid-changing thermal regime, the accelerated growth at the mean temperature of 22 °C is attributed to the increase in the proportion of growth energy. Comparatively, the variation in food consumption at the fluctuating thermal regimes of mean temperature of 25 and 28 °C is responsible for the difference in growth from the corresponding constant thermal regime (Tian 2001).

The growth rate of trout (*Salmo trutta*) is significantly greater at continuous gradient temperature fluctuation (12.5 ± 4.6 °C) than at natural diel temperature fluctuations (7.7 ± 1.3 °C) and constant temperature (12 °C), while no significant difference is found between natural diel temperature fluctuations and constant temperature regime (Spigarelli et al. 1982).

6.1.2.3 Effects of the Amplitude of Thermal Fluctuation on Growth of Aquatic Animals

The amplitude of thermal fluctuation is an ecological factor that has a great impact on the growth of aquatic animals. The amplitude of temperature fluctuations within the ecological limits of a species has a positive effect on the growth of fishes, whereas fluctuations with very small amplitude, even with a high frequency, are not sufficient to have a significant positive effect on the growth of aquatic animals (Konstantinov et al. 1989). In general, the optimal fluctuating amplitude for eurythermic species is greater than those for stenothermic ones. The range is ±4 to ±6 °C for the eurythermic fishes, such as channel catfish (*Ictalurus punctatus*), gudgeon (*Gobio gobio*), goloveshka (*Percottus glehni*), tilapia (*Oreochromis niloticus, O. mossambicus, O. aureus*), common carp (*C. carpio*), and goldfish (*Carassius auratus*). (Konstantinov et al. 1989, 1996; Gui et al. 1989; Sierra et al. 1999; Baras et al. 2000). In comparison, the range is much narrower, ±1.5 to ±2 °C for the stenothermic fishes, such as hemigramis (*Hemigrammus caudovittatus*) (Konstantinov et al. 1989).

In comparison with fishes, the range of temperature fluctuations favoring growth in crab and penaeid shrimp is much smaller, which is similar to stenothermic fishes. Juvenile river crab (*Eriocheir sinensis*) grows fastest at an average temperature of 22 ± 3 °C, while a ±4.5 °C variation in temperature inhibits their growth (Wang 1999c). The optimum amplitude of thermal fluctuation that can promote the growth of sea cucumber (*A. japonicus*) is ±1.38 and ± 1.67 °C at an average temperature of 15 and 18 °C, respectively (Dong et al. 2006). The growth rates of Chinese shrimp (*F. chinensis*) at diel temperature fluctuations of 25 ± 2, 25 ± 3, 28 ± 2, and 31 ± 1 °C are significantly greater than those at constant temperatures of 25, 28, and 31 °C, respectively. However, the growth of shrimp at 35 ± 4 °C significantly decreases as compared to that at constant temperature of 31 °C. It is estimated that the optimal amplitude of temperature fluctuations for Chinese shrimp is ±2.0, ±2.2, and ±1.4 °C at mean temperature of 25, 28, and 31 °C, respectively (Fig. 6.4; Tian and Dong 2006).

6.1.2.4 Effect of Temperature Fluctuations and Ration on Growth of Aquatic Animals

The specific growth rates of Chinese shrimp with overfeeding are not significantly different at temperature fluctuations compared to the corresponding constant temperature. The growth rate of the shrimp under fluctuating temperature of 28 ± 2 °C is significantly higher than those under the other fluctuating temperature and constant temperature with 100%, 70%, and 40% satiation (Tian 2001).

Diel fluctuating temperature does not exacerbate the response of the shrimp under starvation, and the degree of weight loss in shrimp at fluctuating temperature is similar to that at constant temperature. It seems that excessive temperature

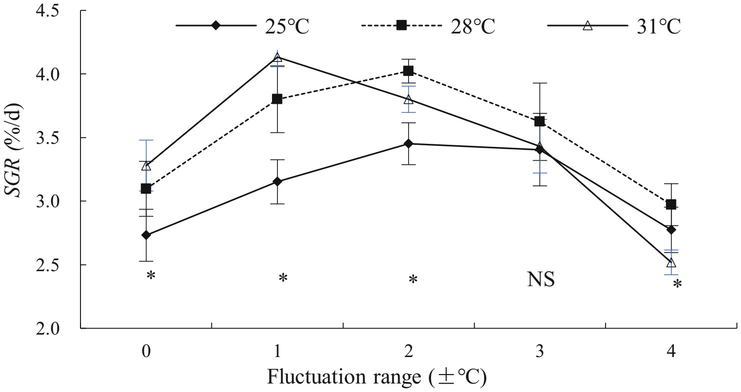

Fig. 6.4 Specific growth rate (*SGR*) of *Fenneropenaeus chinensis* at different fluctuating temperature (from Tian and Dong 2006). NS means no significant difference among the same fluctuation range; * stands for significant difference among the same fluctuation range

Table 6.1 Effects of different temperature fluctuations on the growth performance of *Fenneropenaeus chinensis* (from Tian 2001)

Treatments (°C)	Specific growth rate (%/d)	Food intake/(% body weight/d)	Food conversion efficiency (%)
25 ± 0	0.567 ± 0.045^{ab}	2.461 ± 0.063^{a}	4.089 ± 0.348^{a}
25 ± 1	0.502 ± 0.051^{ad}	2.327 ± 0.066^{ab}	3.687 ± 0.540^{ab}
25 ± 2	0.695 ± 0.030^{c}	2.395 ± 0.092^{ab}	5.457 ± 0.118^{c}
25 ± 3	0.672 ± 0.017^{bc}	2.301 ± 0.020^{ab}	5.455 ± 0.141^{c}
25 ± 4	0.410 ± 0.013^{d}	2.198 ± 0.030^{b}	2.900 ± 0.113^{b}

Means with different letters in the same column were significantly different ($P < 0.05$)

fluctuation (±4 °C) reduces shrimp growth rate at all rations although no significant difference is observed (Table 6.1). The trend for food conversion efficiency at each ration level is similar to that for specific growth rate under different fluctuating temperature. Based on the regression equations, the maintenance ration for shrimp calculated as weight and energy are 0.72%, 0.66%, 0.39%, 0.83% and 4.98%, 4.61%, 4.35%, 5.12% at 28, 28 ± 1, 28 ± 2, and 28 ± 4 °C, respectively (Fig. 6.4). The lowest maintenance ration for Chinese shrimp at the fluctuating temperature of 28 ± 2 °C indicates that the reduction in metabolic rate may be contributed to growth promotion of the shrimp under fluctuating thermal regimes (Fig. 6.5).

6.1.2.5 Mechanisms of Growth Enhancement under Fluctuating Thermal Regimes

There is no unified conclusion about the mechanism by which fluctuating temperatures promote the growth of aquatic animals until now. The energy bonus

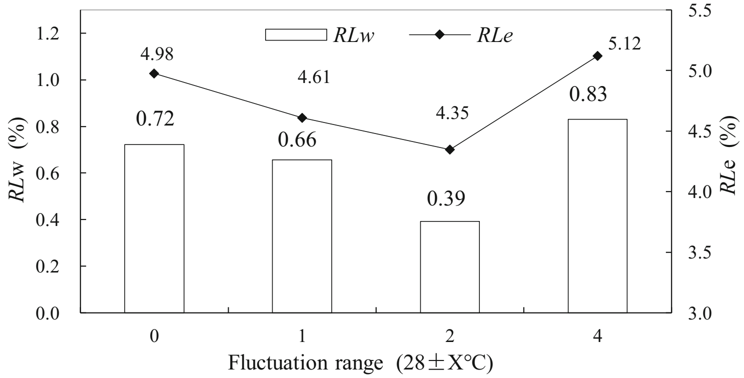

Fig. 6.5 Maintenance ration in weight (*RL*w) and in energy (*RL*e) of *Fenneropenaeus chinensis* at different thermal regimes (from Tian 2001). *RL*e, ration in energy, *RL*w ration in weight

hypothesis was first proposed by Mclaren (1963) to explain the diurnal vertical migration of zooplankton and was further elaborated by Brett (1971). This hypothesis was mainly used to explain the vertical migration of fish and zooplankton. It is believed that higher temperature makes aquatic animals have higher feeding rate, while lower temperature reduces the basal metabolism of the organism, thus facilitating the assimilation and conversion of energy in food so that more energy can be used for growth and reproduction of the organism. Afterward, some researchers have conducted more extensive and in-depth studies on the mechanism by which temperature fluctuations can promote growth of aquatic animals and found that the main mechanism may be species-specific and different under different conditions.

6.1.2.5.1 Increased Food Intake under Fluctuating Temperature Regimes

The food consumption of some aquatic animals increases significantly under fluctuating temperature conditions, which may be one of the reasons for the enhancement in growth of those species. For example, largemouth bass (*M. salmoides*) have significantly higher food intake and grow significantly faster than the constant temperature at fluctuating temperature regime of 15–19 °C (Diana 1984).

Food intakes of Chinese shrimp under fluctuating temperature of 22 ± 2, 25 ± 2, 28 ± 2, and 31 ± 2 °C increase more or less comparing with those at constant temperatures of 22, 25, 28, and 31 °C, and most of them are significant (Table 6.2). This suggests that the significant increase in food consumption may contribute to the faster growth of Chinese shrimp under fluctuating temperature conditions (Tian et al. 2006).

Table 6.2 Growth and food consumption of *Fenneropenaeus chinensis* at different thermal regimes (from Tian et al. 2006)

Treatments (°C)	Initial weight (g)	Specific growth rate (%/d)	Food consumption (mgdw/ind.)
22 ± 2	0.35 ± 0.03	2.40 ± 0.20^a	17.86 ± 1.54^a
22	0.37 ± 0.07	1.83 ± 0.20^b	16.50 ± 2.52^a
25 ± 2	0.35 ± 0.06	3.45 ± 0.16^a	34.70 ± 2.52^a
25	0.35 ± 0.03	2.73 ± 0.20^b	27.98 ± 1.84^b
28 ± 2	0.34 ± 0.02	4.02 ± 0.09^a	49.46 ± 2.82^a
28	0.35 ± 0.03	3.10 ± 0.42^b	37.98 ± 3.23^b
31 ± 2	0.35 ± 0.01	3.80 ± 0.10^a	56.91 ± 2.02^a
31	0.36 ± 0.03	3.28 ± 0.20^a	50.24 ± 1.90^b

Means with different letters in the same column were significantly different ($P < 0.05$)

6.1.2.5.2 Bioenergetic Mechanisms of Growth Enhancement under Fluctuating Thermal Regimes

The bioenergetic properties of aquatic animals are somewhat altered under suitable fluctuating thermal regimes, thus facilitating the efficient use of ingested energy by the organism.

The reduced metabolic rate of individual animals is an important mechanism for the enhancement in growth under fluctuating temperature conditions. Within the range of suitable temperature for aquatic animal growth, the growth rate and metabolic rate generally have a positive correlation; i.e., the higher the metabolic rate, the greater the growth. Some studies have shown that under fluctuating temperature conditions, the metabolism of animals will undergo certain changes. The metabolic rates (e. g., oxygen consumption rate) of many species are significantly lower at suitable fluctuating temperatures that promote the growth of animal individuals, such as crucian carp (*Carassius auratus*), common carp, tilapia (*O. niloticus*, *O. mossambicus*, *O. aureus*), and bay scallop (*Argopecten irradians*) (Tian and Dong 2005). However, no significant differences in both growth and metabolic rate of *Catostomus tahoensis* are found between fluctuating temperature and the corresponding constant temperature (Vondracek et al. 1982).

The metabolic compensation of Chinese shrimp responded to high temperature is partial compensation, and it is not significant at low temperature. For example, when the temperature suddenly increases to 31 °C, the oxygen consumption of 19 °C-adapted shrimp overshoot. After 8 h of adaption, a sudden drop by 12 °C results in an undershoot in oxygen consumption in the shrimp. For the 31 °C-adapted shrimp, the oxygen consumption undershoots when temperature suddenly drops by 12 °C. However, overshoot in oxygen consumption does not appear when the temperature is returned to 31 °C. The fluctuating amplitude of oxygen consumption in shrimp reduces during the process of acclimation to diel fluctuating temperature. When acclimated to temperature fluctuation from 24 to 30 °C, the daily mean oxygen consumption of shrimp significantly decreases as compared to those acclimated to constant temperature of 27 °C (Tian et al. 2004a). Thus, the reduction in metabolic

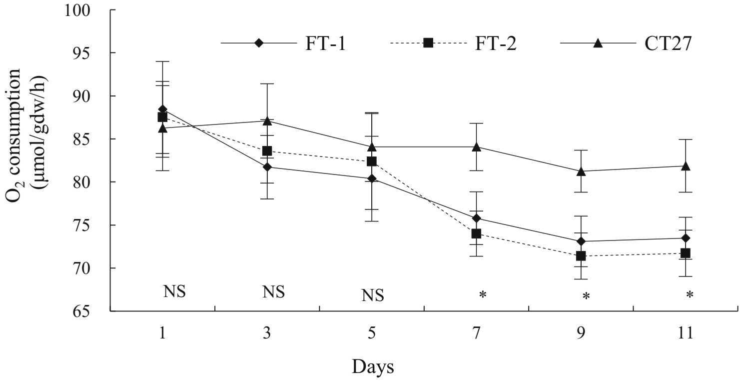

Fig. 6.6 Mean value of oxygen consumption rate of *Fenneropenaeus chinensis* in fluctuating temperature and constant temperature (from Tian et al. 2004a)

rate may contribute to the enhancement in the growth of Chinese shrimp at a diel temperature fluctuation.

Under fluctuating thermal conditions that can have a positive effect on growth, some animal individuals do not have a significant increase in food intake, but have significantly higher rates of food conversion. At the same time, the maintenance ration of aquatic animal individuals generally reduces under fluctuating temperature conditions that have a growth-promoting effect. For example, the maintenance ration of Chinese shrimp under diel fluctuating temperature of 28 ± 2 °C is lowest among four diel fluctuating thermal regime with fluctuation amplitude of ±0, ±1, ±2, and ± 4 °C. Comparatively, the maintenance ration of shrimp is high at both constant temperatures and high fluctuation amplitudes (Tian 2001).

During the domestication period, Chinese shrimp gradually adapts to the diurnal temperature change by reducing the fluctuation range of oxygen consumption rate. After adapting to diel fluctuating thermal regime, the oxygen consumption rate of the shrimp at 24–30 °C (average 27 °C) significantly decreases compared with that at the corresponding constant temperature of 27 °C (Fig. 6.6) (Tian et al. 2004a).

The bioenergetic properties of individual animals alter in a growth-oriented direction under suitable fluctuating temperature conditions. The proportion of ingested energy used for respiration reduces and in turn the proportion allocated for growth significantly increases in Chinese shrimp at diel fluctuating thermal regime favorable for growth (Table 6.3). This is also supported by the examples mentioned above.

6.1.2.6 Potential Applications to Aquaculture Practices

Many researches have shown that an appropriate fluctuating temperature can promote the growth of some aquatic animals, and these findings have important implication for aquaculture. A moderate fluctuating thermal regime could be potentially applied to induce better growth and higher yield of aquatic animals in practices. Firstly, a suitable fluctuating temperature can be used in some recirculation

Table 6.3 Energy budgets in *Fenneropenaeus chinensis* at different thermal regimes (%) (from Tian et al. 2006)

Thermal regimes (°C)	Energy allocated for growth	Energy spent for molt	Energy in feces	Energy from excretion	Energy used for respiration
22 ± 2	18.16 ± 1.12^a	14.81 ± 1.23^a	6.05 ± 1.02^a	0.63 ± 0.04^a	60.35 ± 2.41^a
22	13.94 ± 1.34^b	15.59 ± 1.15^a	6.81 ± 1.15^a	0.80 ± 0.09^a	62.86 ± 3.12^a
25 ± 2	15.62 ± 0.26^a	13.56 ± 1.02^a	6.47 ± 0.28^a	0.28 ± 0.03^a	64.06 ± 1.91^a
25	13.82 ± 0.48^a	12.04 ± 0.77^a	7.06 ± 0.26^a	0.44 ± 0.15^a	66.64 ± 1.52^a
28 ± 2	17.97 ± 1.58^a	10.43 ± 0.96^a	6.41 ± 0.20^a	0.46 ± 0.11^a	64.72 ± 0.55^a
28	12.35 ± 1.56^b	11.73 ± 1.04^a	7.03 ± 0.27^a	0.51 ± 0.11^a	68.38 ± 1.44^a
31 ± 2	12.66 ± 0.21^a	6.75 ± 1.54^a	7.8 ± 0.12^a	0.41 ± 0.01^a	72.38 ± 1.31^a
31	12.14 ± 0.57^a	8.41 ± 0.45^a	7.61 ± 0.06^a	0.52 ± 0.01^a	71.32 ± 0.41^a

Means with different letters in the same column were significantly different ($P < 0.05$)

aquaculture system where water temperature control is implemented. Secondly, a suitable fluctuating temperature also can be implemented in some farms facilitated with two or more water sources with different temperatures, such as power plant warm drainage, underground water, and surface water, etc.

In addition, pond water depth can also be regulated to achieve favorable daily fluctuation of water temperature for the enhancement in growth. For example, the optimum fluctuating amplitudes for the growth of Chinese shrimp at average temperature of 25, 28, and 31 °C are ±2.0, ±2.2, and ±1.4 °C, respectively. In late spring, pond water should be shallow when average water temperature is up to about 25 °C. Thus, the amplitude of water temperature fluctuations will be relatively wider; and pond water can be deeper in the summer when water temperature is up to about 31 °C; thus, the amplitude of water temperature fluctuations will be narrower. Unfortunately, too little is known about the interaction among air temperature, water temperature water depth, and shrimp growth. Therefore, more work is still needed to applicate these findings in aquaculture practices.

6.2 Effects of Fluctuations in Salinity on Aquatic Organisms

Water salinity in estuaries often fluctuates periodically influencing by tides and seasons. Organisms in the intertidal zone experience rhythmic short- or long-term changes in salinity due to rainfall and surface runoff. Some organisms living in the intertidal zone, which are immovable or move slowly, are experiencing daily changes in salinity caused periodic tidal and water evaporation.

Crustaceans may also have different salinity requirements at different periods of development and growth. In order to meet their growth and development demands, salinity is sometimes adjusted artificially during the culture process. Some people believe that low-salinity water can promote molting and growth of farmed shrimp; thus, in the nursery and culture somewhere, freshwater is frequently added to accelerate the growth of the shrimp. Therefore, it is necessary to understand the influence of periodic fluctuations in salinity on aquatic organisms.

6.2.1 Effects of Periodic Fluctuations in Salinity on Seaweeds

U. pertusa is highly tolerant to salinity changes. The growth rate of this species is consistently maintained above 12%/d even under treatments with daily salinity changes of ±15.0 ppt. However, the growth rates of *U. pertusa* under daily periodic changes in salinity are significantly lower than those under constant salinity, and became lower as the magnitude of salinity change increases (Wang et al. 2007a, b). Thus, more work is still needed to study more aquatic plants, especially estuarine plants that experience rhythmic salinity changes, to understand the response patterns of macroalgae to salinity changes.

6.2.2 Effects of Cyclical Fluctuations in Salinity on Shrimp

Although many farmed shrimps are euryhaline, great and sudden drop in salinity can lead to high mortality. The growth of certain aquatic animals at constant salinity is currently understood, but not much is known about the effects of changing salinity on the growth of them. The following is an introduction to the effects of periodic fluctuations in salinity on aquatic animals, mainly with Chinese shrimp as examples.

A large number of molted carapaces of farmed shrimp are often found floating on the water surface of ponds after heavy rain, so many people believe that a sudden drop in salinity will accelerate the molting of shrimp. It has been speculated that a moderate reduction in salinity may promote shrimp growth, and research by Mu et al. (2005a) has confirmed this hypothesis. Their results showed that small-sized shrimp (0.55 g/ind.) were more sensitive to changes in salinity than the large ones (1.45 g/ind.). The salinity fluctuations had a significant effect on the molting cycle of juvenile Chinese shrimp, where a decrease in salinity by 10 ppt (S10) significantly inhibited the molting of shrimp, while S2 promoted the molting of shrimp, with the former extending the molting cycle by 4.97 d compared to the latter (Table 6.4). This indicates that changing salinity within a certain amplitude of fluctuation can promote molting of small-sized Chinese shrimp, but if the fluctuation amplitude is too great, it will inhibit molting of the shrimp. Comparatively, the influence of salinity fluctuation on molting of a larger-sized shrimp is not significant.

Appropriate periodic reduction in salinity followed by a return of salinity can promote growth of Chinese shrimp. The growth rates of the shrimp in S4 and S7 were greater than other treatments. The relative weight gain rate of small size shrimp in S7 and large size shrimp in S4 were 38.5 and 57.8% higher than that of corresponding constant group (S0), respectively. Food intakes are 16.0 and 11.5% higher in S4 and S7 than that in S0, respectively. The salinity fluctuations do not influence the food conversion efficiency of the shrimp significantly, indicating that

Table 6.4 Weight gain, survival, and intermolt period of juvenile *Fenneropenaeus chinensis* in different treatments (from Mu et al. 2005a)

Treatments	Initial weight (g)	Weight gain (%)	Survival (%)	intermolt period (d)
S0	0.55 ± 0.01	94.55 ± 4.96^{a}	100.0 ± 0.0	11.83 ± 0.94^{ab}
S2	0.55 ± 0.05	105.45 ± 5.40^{ab}	95.0 ± 5.0	8.41 ± 0.05^{a}
S4	0.55 ± 0.01	121.82 ± 7.67^{bc}	95.0 ± 5.0	10.32 ± 0.76^{ab}
S7	0.55 ± 0.01	130.91 ± 7.00^{c}	100.0 ± 0.0	11.33 ± 1.03^{ab}
S10	0.55 ± 0.01	109.09 ± 2.21^{ab}	95.0 ± 5.0	13.38 ± 1.67^{b}
S0	1.45 ± 0.01	52.28 ± 7.31^{a}	81.25 ± 11.97	10.18 ± 0.20
S2	1.45 ± 0.01	66.02 ± 9.28a^{b}	87.50 ± 7.21	9.64 ± 0.73
S4	1.45 ± 0.01	82.51 ± 5.40^{b}	87.50 ± 7.21	9.54 ± 0.44
S7	1.45 ± 0.01	69.30 ± 6.26^{ab}	93.75 ± 6.25	9.09 ± 0.55
S10	1.45 ± 0.00	57.63 ± 10.14^{ab}	81.22 ± 11.97	9.17 ± 0.38

Note: S0 is the control; its salinity was kept 30 ppt for 30 days. Other treatments' salinities were 30 ppt for 4 days and dropped to 28 (S2), 26 (S4), 23 (S7), or 20 ppt (S10) within 1 day and were kept for 4 days; then, their salinities were returned to 30 ppt and kept for 4 days; these regimes were repeated in the 30 days' experiment

Means with different letters in the same column were significantly different ($P < 0.05$)

the variance in shrimp growth rate was mainly attributed to the difference in food intake.

Shrimp grow intermittently by molt, i.e., a rapid increase in body length at the time of molting, and little body length increase after molt until the next molt. Either high or low molt frequency is detrimental to growth, as shown for Chinese shrimp in Table 6.4. These results suggest the addition of freshwater to reduce salinity periodically to promote shrimp molting is feasible. Of course, the freshwater should be added in appropriate frequency.

The patterns of energy allocation are different in Chinese shrimp among various amplitude of fluctuations in salinity (Table 6.5). The proportion of energy used for respiration is significantly higher in S0 and S10 than in S4, and the proportion for growth is significantly lower than in S4. The proportion for excretion of shrimp in the S10 and S0 groups was significantly greater than those in S4 and S7. The proportion for feces is significantly higher in S7 than in S10 (Mu et al. 2005b).

This research demonstrates that appropriate periodic reduction in salinity followed by return of salinity can promote the growth of Chinese shrimp, particularly in S4. However, excessive fluctuations will inhibit the growth of the shrimp. As the food intake of Chinese shrimp is not affected by salinity fluctuations, differences in food conversion efficiencies and proportion of energy allocated to growth attribute to the differences in growth among various salinity fluctuations.

The molting of juvenile *Litopenaeus vannamei* at mean salinity of 18 ppt and fluctuating amplitude of ±0, ±2, ±4, ±6, and ±8 ppt is similar to the performance of Chinese shrimp; however, total number of molts in shrimp at salinity fluctuations of ±4 ppt is the highest, while molt synchronization of shrimp at salinity fluctuations of ±8 ppt is the best (Li 2010).

Table 6.5 Allocation of the consumed energy in juvenile *Fenneropenaeus chinensis* at various salinity fluctuation (%) (from Mu et al. 2005b)

Treatments	*R/C*	*G/C*	*E/C*	*U/C*	*F/C*
S0	72.44 ± 0.70^{a}	10.11 ± 0.98^{a}	1.59 ± 0.31	6.91 ± 0.11^{a}	8.96 ± 0.16^{ab}
S2	70.61 ± 1.80^{ab}	12.85 ± 1.67^{ab}	1.46 ± 0.06	6.56 ± 0.27^{ab}	8.52 ± 0.81^{ab}
S4	68.04 ± 0.25^{b}	15.04 ± 0.58^{b}	1.48 ± 0.09	6.15 ± 0.04^{b}	9.28 ± 0.56^{ab}
S7	68.38 ± 0.74^{ab}	13.44 ± 0.80^{ab}	1.94 ± 0.26	6.41 ± 0.08^{b}	9.82 ± 0.31^{b}
S10	72.46 ± 1.47^{a}	10.95 ± 1.21^{a}	1.95 ± 0.32	6.89 ± 0.09^{a}	7.74 ± 0.34^{a}

Note: *C* energy consumed in food, *E* energy spent for molt, *F* energy in feces, *G* energy allocated for growth, *R* energy used for respiration, *U* energy from excretion

Means with different letters in the same column were significantly different ($P < 0.05$)

6.3 Effects of Periodic Exposure to the Air on Seaweeds

Due to periodic tides, some seaweeds in intertidal zone experience submergence and exposure to the air periodically and have evolved and adapted to the periodic exposure environment. In nori (*Porphyra*) cultivation in practice, people also often use periodic exposure to improve the yield and quality of the nori.

The periodic exposure time has a significant effect on the growth of *U. pertusa*. Compared with continuous submersion in sea water, the exposure time of 0.5/12 h significantly promotes the growth of *U. pertusa*; however, the exposure of 5/12 h significantly inhibits the growth of this species (Wang 2008b).

The exposure time has various influence on the growth of seaweeds distributed in different vertical positions in the intertidal zone (Fig. 6.7). The specific growth rates of *Ahnfeltiopsis flabelliformis* (high-tidal species) decrease gradually with increasing exposure time. The specific growth rate of this species is 16% of that submerged in water when exposure time up to 6.0/12 h. The specific growth rates of *U. pertusa* (mid-tidal species) exposed for 0.5 h are significantly higher than those submerged ones. However, its growth rate gradually decreases with increasing exposure time. It is significantly less than that submerged control at exposure time of 6.0 h. No significant difference is observed in specific growth rates of *Enteromorpha linza*

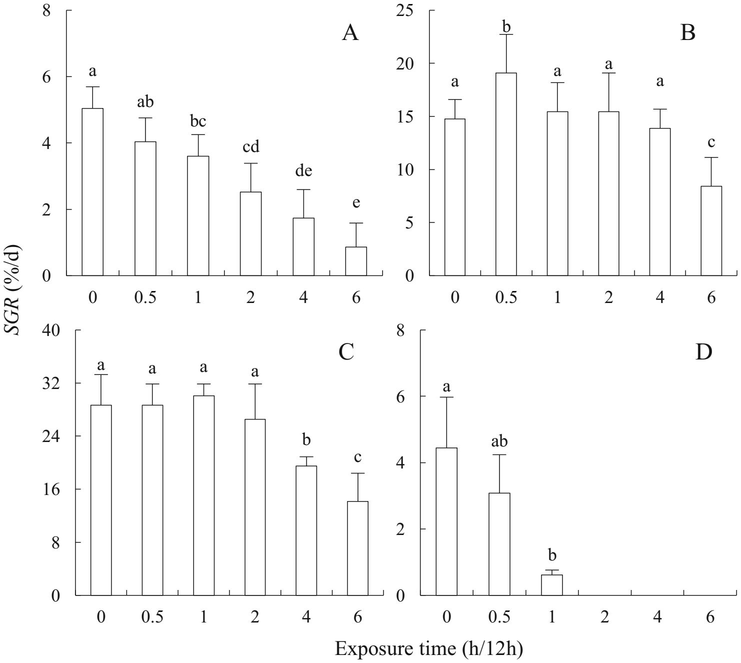

Fig. 6.7 Specific growth rates (*SGR*) of *Ahnfeltiopsis flabelliformis* (**a**), *Ulva pertusa* (**b**), *Enteromorpha linza* (**c**), and *Gracilaria textorii* (**d**) after different time exposed to the air (from Guo and Dong 2008)

(mid-tidal species) within the exposure time of 2.0 h. However, its growth rate is significantly lower than that submerged control with exposure time of 4.0–6.0 h. Comparatively, as a seaweed living in low-tidal zone, *G. textorii* survives and grows only when the exposure time is less than 1.0/12 h (Guo and Dong 2008).

The exposure time has significant impact on the dehydration rate and photosynthesis of seaweeds. Among four species distributed in different vertical positions in the intertidal zone, the exposure tolerance of *G. textorii* is the lowest, and the dewatering rate of *E. linza* is the lowest. Under the same exposure conditions, the dewatering rates of the four species are, in descending order, as follows: *G. textorii* > *U. pertusa* > *A. flabelliformis* > *E. linza*.

The photosynthesis rates of *A. flabelliformis* decrease with increasing exposure time comparing with the continuously submerged control, while no significant change in respiration rate is observed. The photosynthetic rates of *U. pertusa* gradually increase with increasing exposure time and reach a maximum at 2.0 h, which means that exposure promotes the photosynthesis of *U. pertusa* to some extent. However, with further increase of dehydration rate, its photosynthesis rates decrease significantly. The respiration rate of *U. pertusa* is significantly higher from 0.5 to 4.0 h exposure time, while there is no significant difference at 6.0 h comparing with the continuously submerged control. No significant difference is found in photosynthetic rates of *E. linza* subjected to exposure comparing with the continuously submerged control, while their respiration rates are higher than those of control ones.

Periodic exposure has a significant impact on the chlorophyll *a*, chlorophyll *b*, protein, soluble sugars, and free proline contents of *U. pertusa*. The absolute contents of soluble sugars are significantly higher in the seaweeds exposed for 0.5, 1.0, and 2.0/12 h than the continuously submerged control. However, too long exposure time (3.0, 4.0, and 5.0 h) not only reduces the content of the materials in *U. pertusa*, but also increases its osmotic solutes. The free proline contents also increase with the increase in exposure time.

In conclusion, the growth, photosynthetic capacity, and biochemical composition of intertidal seaweeds in the exposure state vary in relation to their morphology and vertical distribution in the intertidal zone.

6.4 Effects of Rhythmic Fluctuations in Light on Aquatic Organisms

The solar radiation received at certain area of the Earth has a diurnal rhythm. Aquatic organisms experience seasonal variations in light intensity due to changes of seasons. At the same time, the sun height (incidence angle of light to water) varies from morning to evening, and the path length of light travels from water surface to bottom differs, so light intensity and light spectrum (light color) at certain water layer will also be different (see Sect. 2.2). Various aquatic organisms have also adapted to this variation over evolution. The results of experiments under constant light conditions hardly reflect the real situation of aquatic organisms subjected in their natural state. Therefore, the study of aquatic organisms under periodically varying light intensity and light color conditions is of great interest to our understanding of the real nature and to build aquaculture systems.

6.4.1 Effects of Rhythmic Fluctuations in Light on *U. Pertusa*

The effects of photoperiod on the growth, development, flowering, and fruiting of crops have long been noted, and photoperiod has been used to improve crop quality and select superior cultivars. Photoperiod is also one of the important ecological factors experienced by aquatic plants; therefore, the understanding of effects of photoperiod on aquatic plants can provide a theoretical basis for the improvement of farming techniques.

6.4.1.1 Effects of Photoperiod on *U. Pertusa*

The growth rates of *U. pertusa* are higher under long photoperiods than those under short ones; however, both continuous light and darkness are detrimental to the growth of the seaweed (Wang 2008b). Under continuous light conditions, the growth rate of *U. pertusa* is high in the first 2 or 4 d. However, the photoinhibition phenomenon occurs in *U. pertusa* shortly afterward, ulcerated spots appear, and seaweed body gradually whitened. Although some of the individuals are still able to grow to some degree, the rate of accumulation in biomass decreases significantly due to seaweed ulceration. The highest daily weight gain of *U. pertusa* is observed at a light intensity of 240 μE/(m^2·s) and a photoperiod of 13:11.

There is an interaction effect between photoperiod and light intensity on the growth of *U. pertusa*. At a light intensity of 110 μE/(m^2·s), the content of chlorophyll *a* increases gradually with decreasing photoperiod. This phenomenon could be attributed to a mechanism by which the algae compensate for the low light energy utilization and slow growth caused by insufficient light with the increase in photosynthetic pigments (Liu and Dong 2001a).

The content of free proline in *U. pertusa* is lower with daylight duration of 10–16 h than other photoperiod treatments. As a cellular defense substance, the lower content of free proline indicates that *U. pertusa* is more favorable for survival and growth in this light–dark cycle than other photoperiods.

6.4.1.2 Effects of Rhythmic Fluctuations in Light Intensity on *U. Pertusa*

Appropriate fluctuations in light intensity significantly promote the growth of *U. pertusa*. The growth rates of *U. pertusa* are significantly higher at circadian fluctuations in light intensity of ±40, ±80, and ±120 μmol/(m^2·s) than those at corresponding constant light intensities (L:D = 12:12; 20 °C; Table 6.6). However, no significant enhancement in the growth is observed when fluctuation amplitudes are above ±160 μmol/(m^2·s).

Circadian rhythmic fluctuations in light intensity have significant effects on the contents of chlorophyll *a*, chlorophyll *b*, protein, soluble sugars, and free proline in *U. pertusa*. The contents of chlorophyll *a* and chlorophyll *b* are significantly higher

Table 6.6 Effects of circadian fluctuation of light intensity on growth of *Ulva pertusa* under 200 μmol/(m^2·s) mean light intensity (L:D = 12:12, 20 °C) (from Wang 2008b)

Treatments	Weight increments (mg/d)	Treatments	Weight increments (mg/d)
200 ± 0	15.86^{a}	200 ± 120	27.74^{d}
200 ± 40	20.59^{bc}	200 ± 160	18.26^{ab}
200 ± 80	23.36^{c}	200 ± 180	17.19^{a}

Means with different letters in the same column were significantly different ($P < 0.05$)

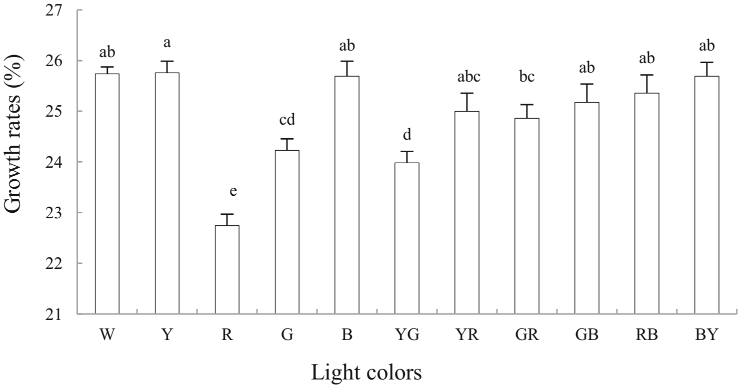

Fig. 6.8 Effects of light spectra on growth rates of *Ulva pertusa* (from Wang 2008b). The letters W, Y, G, R, B, YG, YR, GR, GB, RB, and BY represent the lights of white, yellow, green, red, blue lights, and yellow: green (6: 6 h), yellow: red (6: 6 h), green: red (6: 6 h), green: blue (6: 6 h), red: blue (6: 6 h) and blue: yellow (6: 6 h)

at the fluctuations of ±80 μmol/(m^2·s) in light intensity than those at ±120 and ± 60 μmol/(m^2·s). Protein and soluble sugar contents tend to decrease with increasing fluctuations in light intensity. Free proline content is higher at constant light intensity than that at fluctuated light intensities.

6.4.1.3 Effects of Light Color Changes on *U. Pertusa*

Due to the selective absorption of different wavelengths of light by water, the spectral composition or spectrum perceived by aquatic organisms differ in various water layers (water depth). The growth rates of *U. pertusa* in orange and blue light do not differ significantly from those in white light, while they are inhibited in red and green light. The inhibition effect of red light is especially significant (Fig. 6.8).

The changes in light color do not significantly promote the growth of *U. pertusa*. However, the contents of chlorophyll, protein, and soluble sugar are higher in the treatments of light color change than those in the corresponding single light color. While those of free proline, a cellular defense substance, in the treatments of light color change show a tendency to be lower than in the corresponding single light color.

The water depth for intertidal seaweeds changes due to flood and ebb tides, and the composition of light incident on the seafloor changes accordingly with the water depth. This characteristic changes in cellular contents of *U. pertusa* in response to light color changes may be related to its adaptation to changes in spectral composition caused by the tides.

6.4.2 Effects of Rhythmic Fluctuations in Light on Shrimp

In natural waters or aquaculture ponds, shrimp experience diel and seasonal changes in light intensity and light color, and they can even experience different light intensities and light colors in different water layers at the same time. Both light intensity fluctuations and light color changes have significant effects on shrimp (Guo et al. 2011, 2012a, 2012b).

6.4.2.1 Effects of Periodic Fluctuations in Light Intensity on Shrimp

Appropriate diurnal fluctuations in light intensity can increase food intake, reduce metabolic rate, and enhance the growth of *L. vannamei*. The changes in light intensity do not significantly affect the molting rate of the shrimp at light intensity of 2700 ± 0, 2700 ± 600, 2700 ± 1200, 2700 ± 1800, and 2700 ± 2400 Lx. However, the weight gains of the shrimp at ±600, ±1200, and ± 1800 Lx are significantly higher than those at constant light intensity; and those at ±1800 Lx are greatest (Table 6.7). The feeding rate of shrimp at ±600, ±1200, and ±1800 Lx is significantly higher than that at the constant light intensity. The proportion of ingested energy allocated to growth at both ±1200 and ±1800 Lx are significantly higher than that at constant light intensity, while the proportion of energy used for respiration is significantly lower than that at constant light intensity.

6.4.2.2 Effects of Rhythmic Changes in Light Color on the Growth of Shrimp

Diurnal changes in light color also significantly affect shrimp molt and growth. Survival, growth rate, and molting rate of *L. vannamei* at constant or single light color and 7 h of short wavelength light plus 7 h of long wavelength light treatments are shown in Table 6.8. The molt rates of the shrimp at light color change are

Table 6.7 Growth, survival, and molting of *Litopenaeus vannamei* at different diurnal light intensity regimes (from Guo et al. 2012a)

Treatments/Lx	Initial weight/g	Weight gain/%	Survival/%	Molt rate/(%/d)
2700	2.738 ± 0.008	98.4 ± 2.0^a	95.0 ± 5.0	7.53 ± 0.36
2700 ± 600	2.731 ± 0.007	115.2 ± 4.4^b	95.0 ± 5.0	7.69 ± 0.66
2700 ± 1200	2.747 ± 0.004	122.6 ± 2.0^b	95.0 ± 5.0	7.11 ± 0.45
2700 ± 1800	2.740 ± 0.004	132.7 ± 1.9^c	100.0 ± 0.0	7.69 ± 0.28
2700 ± 2400	2.740 ± 0.008	103.9 ± 2.1^a	95.0 ± 0.0	6.97 ± 0.43

Means with different letters in the same column were significantly different ($P < 0.05$)

Table 6.8 Survival, growth, and molting rate of *Litopenaeus vannamei* at various light color (from Guo et al. 2012b)

Treatments	Initial weight (g)	Survival (%)	*SGR*(%/d)	Molt rate (%/d)
Y	1.21 ± 0.01	90.0 ± 5.8	3.12 ± 0.12^{a}	5.05 ± 0.17^{ab}
G	1.21 ± 0.01	90.0 ± 5.8	3.39 ± 0.02^{bc}	5.97 ± 0.15^{b}
B	1.21 ± 0.01	95.0 ± 5.0	3.12 ± 0.10^{a}	4.82 ± 0.32^{a}
GY	1.21 ± 0.00	95.0 ± 5.0	3.29 ± 0.03^{ab}	7.10 ± 0.48^{c}
BY	1.21 ± 0.00	90.0 ± 5.8	3.52 ± 0.05^{c}	7.98 ± 0.42^{c}
BG	1.21 ± 0.00	95.0 ± 5.0	3.58 ± 0.03^{c}	7.44 ± 0.31^{c}

Note: *B* blue, *BG* blue to green, *BY* blue to yellow, *G* green, *GY* green to yellow, *Y* yellow. In light color change treatment, the first color was kept for 7 h and then changed to the second color for 7 h every day. Temperature, 24–26 °C; salinity, 28–31 ppt; photoperiod, 14 L: 10D. The duration of the experiment was 45 d

Means with different letters in the same column were significantly different ($P < 0.05$)

significantly higher than those at constant light color, and the specific growth rate of the shrimp in both blue → green (BG) and blue → yellow (BY) treatments are significantly higher than that at constant light color. This indicates that the changes in light color significantly enhance the growth and molting rate of the shrimp. The proportion of energy spent for excretion is significantly lower in shrimp of BG and BY treatments than that at single light color, while the energy assimilated in growth is significantly higher than at blue light color.

6.4.3 Effects of Gradual Changes in Photoperiod on Fish

Fish behavior, growth, and reproduction are controlled by the internal biological clock, and the main environmental factors that trigger the biological clock are changes in light, temperature, tides, etc. Light and temperature changes in natural water often mutually correlate, and longer daylight and stronger light intensity can also lead to higher water temperature. The effect of gradual changes in photoperiods on rainbow trout *Oncorhynchus mykiss* (initial weight of 34.1 g) was studied by Dong (2020). Two gradual change patterns in photoperiod were designed, i.e., a gradual increasing pattern (L12:D12 → L16:D8) and a decreasing pattern (L12: D12 → L8:D16). The growth rate and conditional factor of rainbow trout in the increasing pattern were significantly higher than those in the decreasing pattern or constant photoperiod, while food conversion rate was significantly lower than the other treatments after 60 days of culture (Table 6.9). However, no significant difference was observed in food ingestion rate. This suggests that gradual increasing of light time under the experimental conditions is beneficial to the growth of the animals, and extended light time is helpful to improve food conversion efficiency.

Fish adaptations to changes in photoperiod are related to season, fish size, etc. For example, the growth rate and food conversion efficiency of sea bream *Pagrus major* increase with longer light time; conversely, the growth rate and food conversion efficiency of *Argyrosomus japonicus* and turbot *Scophthalmus maximus* are inhibited at long light time.

Table 6.9 Growth parameter of juvenile rainbow trout under different photoperiods (from Dong 2020)

Parameters (%)	L12:D12	L12:D12 → L8:D16	L12:D12 → L16:D8
Survival	91.11 ± 7.70	97.78 ± 3.85	91.11 ± 3.85
Condition factor	1.62 ± 0.08^b	1.78 ± 0.05^a	1.61 ± 0.06^b
Specific growth rate	1.61 ± 0.04^b	1.84 ± 0.05^a	1.63 ± 0.03^b
Food conversion rate	1.03 ± 0.06^b	0.92 ± 0.03^c	1.18 ± 0.06^a
Food ingestion rate	1.54 ± 0.05^b	1.54 ± 0.04^b	1.78 ± 0.06^a

Note: The initial photoperiod was L12:D12. Treatment L12:D12 was keeping this photoperiod during 60 days' experiment; Treatment L12:D12 → L16:D8 was increasing the light time for 4 min every day until the end of the 60 days' experiment; Treatment L12:D12 → L8:D16 was decreasing the light time for 4 min every day until the end of the 60 days' experiment. Water temperature was 17.3 ± 0.9 °C

Means with different letters in the same column were significantly different ($P < 0.05$)

6.5 Effects of Ca^{2+} Concentration and pH Fluctuations on Shrimp

Both Ca^{2+} concentration and pH in aquaculture water vary with the intensity of photosynthesis, especially in waterlogged salt-alkali ponds (see Sects. 2.3.2 and 11.1.2). Diel rhythmic changes in Ca^{2+} concentration and pH have a significant impact on aquaculture animals, especially shrimp.

6.5.1 Effects of Ca^{2+} Concentration Fluctuations on Shrimp

The maintenance of certain Ca^{2+} concentrations in water is necessary for the survival, molting, and growth of aquatic crustaceans. The molt frequencies for juvenile *L. vannamei* at Ca^{2+} concentrations of 591, 803, 985, and 1155 mg/L are significantly higher than that in 385 mg/L (seawater) and highest at 803 mg/L (Li 2010). The synchronization of molts at Ca^{2+} concentrations of 591 mg/L is the best. Therefore, it is reasonable to believe that one can achieve better synchronization of molting by controlling the Ca^{2+} concentration in water to solve the problem of severe intraspecific carnivorism in shrimp farming.

The molt frequencies of shrimp at fluctuating amplitude of 360 ± 240 mg/L are the highest (11.0%/d) among all treatments of 360 ± 0, 360 ± 60, 360 ± 120, 360 ± 180, and 360 ± 240 mg/L in seawater (30 ppt) and fluctuation period of 4 days; however, its weight gain is the lowest (Hou et al. 2010a). No significant differences are found in weight gain of the shrimp among other treatments.

The *G/C* ratios and food ingestion rates of *L. vannamei* in the treatments of increasing Ca^{2+} concentration from 385 mg/L to 591 or 803 mg/L (C591 or C803) periodically are significantly greater than those in other treatments (Table 6.10). The molting rates in C591 and C803 are also significantly higher than those in C385 and

Table 6.10 Molting frequencies and energy budgets of juvenile *Litopenaeus vannamei* under different Ca^{2+} concentration fluctuations (from Hou et al. 2010b)

Treatments	Molting/(%/d)	$G/C/\%$	$R/C/\%$	$U/C/\%$	$F/C/\%$	$E/C/\%$
C385	5.1 ± 0.2^{a}	17.76 ± 0.50^{a}	55.12 ± 0.58^{b}	5.49 ± 0.11^{b}	21.27 ± 0.50^{a}	0.36 ± 0.04^{a}
C591	7.0 ± 0.8^{b}	19.71 ± 0.14^{b}	51.61 ± 0.88^{a}	5.26 ± 1.27^{b}	22.73 ± 0.76^{ab}	0.69 ± 0.04^{b}
C803	7.5 ± 0.6^{b}	20.71 ± 0.22^{b}	50.98 ± 0.80^{a}	4.31 ± 0.36^{a}	23.23 ± 0.78^{b}	0.77 ± 0.12^{b}
C1155	7.3 ± 0.3^{b}	18.59 ± 0.46^{a}	55.48 ± 0.19^{b}	4.39 ± 0.06^{a}	20.86 ± 0.33^{a}	0.68 ± 0.02^{b}
C2380	6.9 ± 0.6^{b}	18.43 ± 0.44^{a}	53.73 ± 0.43^{b}	4.66 ± 0.14^{a}	22.45 ± 0.47^{ab}	0.73 ± 0.05^{b}

Note: C energy consumed in food, E energy spent for molt, F energy in feces, G energy allocated for growth, R energy used for respiration, U energy from excretion. The Ca^{2+} concentration in the C385 group was 385 mg/L during the experiment, while those in the C591, C803, C1155, and C2380 groups periodically fluctuated from 385 to 591, 803, 1155, and 2380 mg/L, respectively

Means with different letters in the same column were significantly different ($P < 0.05$)

C2380 mg/L (Hou et al. 2010b). The appropriate rhythmic addition of Ca^{2+} can increase the molting frequency and growth rate and decrease the metabolic rate and excretion rate of the shrimp. According to calculation, the optimum addition of Ca^{2+} periodically for shrimp farming in seawater is 295 mg/L.

6.5.2 Effects of pH Fluctuations on Shrimp

6.5.2.1 Effects of pH Fluctuation Amplitudes on Shrimp

Previous studies have shown that pH below 4.8 or above 10.6 is lethal for shrimp and crabs, whose optimum adaptation range is 6.6–8.5. However, most studies on the effect of pH on farmed shrimp focus on the impact of static pH gradients; those on the effect of rhythmic pH changes on farmed shrimp are still rare. pH of seawater generally ranges from 7.5 to 8.2, but due to photosynthesis, the pH of cultured water always varies rhythmically throughout the day. Generally, the normal diel fluctuation of pH in shrimp ponds is from 1 to 2, and fluctuation amplitude of pH in salt-alkali ponds or those ponds with high phytoplankton biomass can be somewhat greater. Therefore, it is of great theoretical and practical importance to understand the effects of periodic pH fluctuations on cultured shrimp.

The effects of periodic changes in pH on *L. vannamei* are significant (Zheng 2006). The survival rate of the shrimp treated with pH 4.0 rhythmically is reduced to 68.8% and is significantly lower than that of other treatments (Table 6.11). The specific growth rate of the shrimp in treatment G is significantly greater than other treatments except for treatment F. Food intake of the shrimp in treatment F and G is significantly higher than treatments A and H. The food conversion efficiency of shrimp in treatment A is significantly lower than other treatments, while that in treatment G is significantly higher than that of other treatments except for H. The results also show that stimulation of 9 h at pH 8.9 every 2 d significantly improves food conversion efficiency and growth rate of *L. vannamei*.

Table 6.11 Effects of fluctuating pH on survival rates, molting frequencies, and growth rates of *Litopenaeus vannamei* (from Zheng 2006)

Treatments	Survival rates/%	Molting frequencies/(%/d)	*SGR*/(%/d)
A (pH 4.0)	68.75 ± 6.25^{a}	8.17 ± 0.74^{a}	1.33 ± 0.12^{a}
B (pH 5.0)	100.00 ± 0.00^{b}	5.00 ± 0.68^{ab}	1.79 ± 0.15^{b}
C (pH 6.0)	93.75 ± 6.25^{ab}	4.47 ± 0.72^{b}	1.78 ± 0.12^{b}
D (pH 7.0)	93.75 ± 6.25^{ab}	6.11 ± 0.39^{ab}	1.76 ± 0.09^{b}
E (pH 7.9)	91.67 ± 8.33^{ab}	6.03 ± 1.07^{ab}	1.93 ± 0.04^{b}
F (pH 8.4)	100.00 ± 0.00^{b}	4.31 ± 1.27^{b}	2.01 ± 0.08^{bc}
G (pH 8.9)	100.00 ± 0.00^{b}	6.85 ± 1.96^{ab}	2.28 ± 0.08^{c}
H (pH 9.4)	100.00 ± 0.00^{b}	4.81 ± 1.21^{ab}	1.69 ± 0.16^{b}

Note: The experimental water with pH 7.9 ± 0.15 was kept for 39 h and then was changed to pH 4.0, 5.0, 6.0, 7.0, 7.9, 8.4, 8.9, or 9.4 for 9 h. These regimes were repeated and lasted for 45 d
Means with different letters in the same column were significantly different ($P < 0.05$)

Table 6.12 Effects of pH fluctuation patterns on survival rates, molting frequencies, and growth rates of *Litopenaeus vannamei* (from Zheng 2006)

Treatments	Survival rates (%)	Molting frequencies (%/d)	*SGR*/(%/d)
pH 7.9	100.0 ± 0.0^{a}	4.38 ± 0.92^{ab}	3.04 ± 0.39^{b}
0.5 h	100.0 ± 0.0^{a}	3.75 ± 0.87^{a}	3.67 ± 0.25^{bc}
1 h	100.0 ± 0.0^{a}	5.42 ± 0.54^{abc}	4.23 ± 0.05^{c}
2 h	100.0 ± 0.0^{a}	7.08 ± 0.80^{bc}	3.91 ± 0.09^{c}
4 h	93.80 ± 0.06^{a}	6.46 ± 1.04^{abc}	3.63 ± 0.13^{bc}
8 h	100.0 ± 0.0^{a}	8.13 ± 1.04^{c}	3.62 ± 0.14^{bc}
12 h	100.0 ± 0.0^{a}	6.25 ± 0.99^{abc}	2.20 ± 0.37^{a}

Note: pH 7.9 (control) was 7.9 ± 0.15. The 0.5 h–-12 h were kept at pH 7.9; however, every day they were changed to pH 8.9 for 0.5, 1, 2, 4, 8, or 12 h. The experiment lasted for 30 d
Means with different letters in the same column were significantly different ($P < 0.05$)

The patterns of energy allocation for treatment A and G are as follows

$$\text{Treatment A}: 100\text{C} = 7.3\text{G} + 19.9\text{F} + 2.2\text{E} + 7.1\text{U} + 63.5\text{R}$$

$$\text{Treatment G}: 100\text{C} = 14.0\text{G} + 26.0\text{F} + 1.6\text{E} + 5.7\text{U} + 52.7\text{R}$$

6.5.2.2 Effects of pH Fluctuation Periods on Shrimp

To explore the impact of periodic pH changes on *L. vannamei*, Zheng (2006) also studied the growth of shrimp treated with pH 8.9 ± 0.10 for 0.5, 1, 2, 4, 8, and 12 h/day for 30 days. The shrimp cultured in pH 7.9 ± 0.15 as the control. The growth rates of shrimp treated with pH 8.9 ± 0.10 for 1 and 2 h/day are significantly greater than the control and treated for 12 h, while the specific growth rate of shrimp treated with 12 h daily is significantly lower than that in the control and other treatments (Table 6.12). Food intake of the shrimp treated for 2 h is greatest and only significantly different from that treated for 12 h. Food conversion efficiency of the shrimp treated for 1 h is the highest. This study indicates that the daily administration of weak alkaline pH stimulation for 2 or 4 h to *L. vannamei* improves their food consumption or food conversion efficiency and significantly enhances their growth.

6.6 Effect of Periodic Changes in Nutrient Factors on Shrimp

The effects of periodic changes in environmental factors including water temperature, salinity, light, Ca^{2+}, and pH on the growth of aquatic organisms have been introduced earlier. In fact, under natural conditions, the nutrient intake of aquatic animals is not constant either and varies with the type of organisms preyed upon. Therefore, periodic changes in nutrients, an environmental factor in a broad sense, can also lead to changes in the physiological ecology of aquatic animals.

Due to the variability of the natural environment and the diversity of diet species availability and adaptation to starvation stress, shrimp have developed an omnivorous habitat. When food species are relatively abundant, shrimp are selective to their diet, but when food is scarce, they also have to consume diets that they do not prefer very much. Shrimp may have evolved some adaptations in physiological ecology in response to the changes in food sources. In shrimp culture practice, shrimp are always fed the 'best' diet as much as possible, but this may not be the best feeding strategy.

Zheng et al. (2008) experimentally investigated the growth and food utilization of *L. vannamei* by intermittent feeding of commercial formulated feed and polychaete worm (*Neanthes japonicus*). As natural diet, polychaete worm are more easily digested and absorbed for the shrimp than commercial formulated feed. The growth rate and food conversion efficiency of the shrimp improve with increasing proportion of polychaete worm fed. When fed with the ratio of 4:1 (i.e., R6, feeding cycle of 4 polychaete worm: 1 commercial formulated feed), the growth rate and food conversion efficiency of shrimp are enhanced significantly as compared to the estimated value assuming no interaction between the diets (Table 6.13).

The growth rates of shrimp, including *L. vannamei*, *F. chinensis*, *Marsupenaeus* japonicus, are significantly higher when they consume mixed diets than any diet alone (Chamberlain and Lawrene 1981; Huang et al. 2005). The combination of various diets may improve the nutritional balance of the ingested food, thus achieving conservation of diet resources and creating an additive effect between diets.

In addition, the proportion of consumed energy spent in excretion for shrimp in the treatment R7 (feeding polychaete worm always) is significantly higher than in R5 and R6 (feeding cycle of 2 polychaete worm: 1 commercial formulated feed and 4 polychaete worm: 1 commercial formulated feed) (Zheng et al. 2008). This suggests that shrimp in treatment R7 consume too much protein that cannot be utilized efficiently and is excreted as nitrogenous waste, while periodic feeding of relatively low protein feeds can improve protein utilization and reduce excretory energy consumption.

In addition, periodic protein starvation can also promote the utilization of feed nutrients, especially protein. Please refer to Sect. 5.7.4 for detail.

Brief Summary

1. Sheffield's law of tolerance states that there is an optimal value for animals to adapt to various environmental factors, where they can obtain the maximum survival and growth rate. Based on this idea, people usually try to find the certain optimal value of an environmental factor for the farmed aquatic animals through experiments (trials), and try to control the environment under this optimal condition to farm the animals in order to obtain the highest yield. In fact, aquatic organisms are adapted to periodic changes in environmental factors, and in most cases, there is an optimal range of suitability for aquatic organisms to adapt to periodic changing factors. For example, the most favorable diel temperature fluctuation for the growth of *Ulva pertusa* at an average temperature of 20 °C is ± 3.69 °C. The responses to diel periodic fluctuations in temperature vary among different species of macroalgae or those distributed at different locations in the intertidal zone.

Table 6.13 The estimated weight gain (eWG), observed weight gain (WG), estimated food conversion efficiency (eFCE), and observed food conversion efficiency (FCE) of *Litopenaeus vannamei* under various treatments (from Zheng et al. 2008)

	Wet body weight (g)		Weight gain (%)		FCE_d (%)	
Treatments	Initial weight	Final weight	eWG	WG	eFCE	FCE
R1	1.381 ± 0.001^{a}	3.32 ± 0.21^{a}	141.00	141.00 ± 15.50^{a}	13.96	13.96 ± 1.02^{a}
R2	1.380 ± 0.001^{a}	4.44 ± 0.31^{b}	183.82 ± 1.14	221.58 ± 22.28^{b}	18.36 ± 0.11	19.86 ± 0.80^{b}
R3	1.381 ± 0.003^{a}	5.09 ± 0.28^{bc}	216.54 ± 2.62	268.99 ± 19.89^{bc}	21.72 ± 0.27	24.12 ± 1.07^{c}
R4	1.380 ± 0.001^{a}	5.45 ± 0.30^{c}	243.52 ± 2.67	294.84 ± 21.98^{c}	24.49 ± 0.27	26.34 ± 0.87^{cd}
R5	1.381 ± 0.001^{a}	5.68 ± 0.24^{cd}	262.88 ± 2.95	311.01 ± 17.20^{c}	26.48 ± 0.30*	29.24 ± 0.65^{de}
R6	1.380 ± 0.001^{a}	6.49 ± 0.18^{d}	270.48 ± 0.74*	370.57 ± 13.32^{d}	27.26 ± 0.08*	31.06 ± 0.22^{e}
R7	1.382 ± 0.001^{a}	5.49 ± 0.34^{c}	297.83	297.06 ± 24.16^{c}	30.03	30.03 ± 2.70^{de}

Note: The treatments of R1 and R7 represent feeding formulated diet and polychaete worm always; The feeding times per feeding cycle for R2, R3, R4, R5, and R6 were 1:4, 1:2, 1:1, 2:1, and 4:1, respectively. For example, R2 means that after feeding the polychaete worm once, feeding formulated diet four times.
*represent significant differences of estimated values from observed values
Means with different letters in the same column were significantly different ($P < 0.05$)

2. Appropriate periodic temperature fluctuations accelerate the growth of many species of aquatic animals. The optimal mean temperature of aquatic animals under fluctuating temperature conditions shifts downwards from the optimal temperature at constant temperatures. For example, the optimal growth temperature of Chinese shrimp under constant temperature is 31 °C and the optimal growth temperature of Chinese shrimp under diel fluctuating temperature is 28 ± 2.0 °C, and the growth rate of the latter is significantly higher than that of the former.
3. Parameters for periodic temperature fluctuations include the rise and fall rate of temperature, the amplitude of fluctuations, etc. The growth rate of shrimp is highest under the diurnal temperature rhythm closest to natural conditions at 27 ± 3 °C, and the growth-promoting effect on aquatic animals could be affected by too large or too small a temperature change. The optimal amplitude of fluctuating temperatures for the enhancement in the growth of Chinese shrimp is ±2.2, ±2.0, and ±1.4 °C at mean temperatures of 25, 28, and 31 °C, respectively. In general, the rate of temperature change that positively promotes the growth of eurythermic species is higher than that of stenothermic ones.
4. The degree of satiation of shrimp affects the growth-promoting effect of temperature fluctuations. Under overfeeding, the specific growth rates of shrimp at different temperature fluctuations do not differ significantly when compared with the corresponding constant temperatures. The growth rate of Chinese shrimp at diel fluctuating temperature of 28 ± 2 °C is significantly higher than the other fluctuating thermal regimes and constant temperature at 70% and 40% satiation, and their maintenance ration is also the lowest.
5. Mechanisms of growth enhancement for aquatic animals under fluctuating thermal regimes: (1) increased food consumption of aquatic animals at fluctuating thermal regimes; (2) reduced metabolic rate at fluctuating thermal regimes; (3) increased food consumption at fluctuating thermal regimes, accompanied by reduced metabolic rate.
6. The growth rate of shrimp can be promoted by appropriate amplitude and change rate of salinity fluctuations; e.g., a rhythmic salinity fluctuation of ±4 at 30 ppt can significantly promote Chinese shrimp growth. The metabolic rate of the shrimp is reduced and the food conversion efficiency is significantly increased under these conditions.
7. The exposure to air for an appropriate period promotes the growth of some seaweeds. For example, an exposure time of 0.5 h every 12 h significantly promotes the growth of *U. pertusa* compared with the control, but an exposure time of 5 h significantly inhibits the growth of *U. pertusa*. The responses of seaweeds to exposure vary between species or locations in the intertidal zone.
8. The growth of seaweeds is significantly promoted by appropriate fluctuations in light intensity; e.g., the growth rate of *U. pertusa* in light intensity of 200 ± 120 μmol/(m2·s) is the highest.
9. Appropriate daily fluctuations in light intensity can increase food intake, reduce metabolic rate, accelerate the growth rate of shrimp. For example, the growth rate of *L. vannamei* in light intensity of 2700 ± 1800 Lx is the greatest.

Appropriate daily changes in light color also can promote the growth of shrimp. For example, the growth rates of *L. vannamei* under light color change conditions of blue → green and blue → yellow are significantly higher than those in continuous single light color of blue, green, or yellow.

10. Gradual changes in photoperiod per day can affect the growth of rainbow trout; e.g., L12:D12 → L8:D16 (i.e., initial photoperiod of L12:D12, light time decreasing for 4 minutes per day) favors the growth of juvenile rainbow trout (34.1 g) and improves food conversion efficiency.
11. When shrimp culture in seawater, intermittently increasing the calcium ion concentration in water to 591–803 mg/L or intermittently increasing the pH to 8.9 can improve the feeding rates and growth rate of *L. vannamei*.
12. The shrimp feeding on a mixed diet grow faster than that feeding on one of the feeds alone due to the improvement of nutritional balance.
13. Living in the environment with periodic changes of environmental factors for a long time, organisms must develop some kind of adaptation mechanism! The constant ‘optimal’ culture environment created artificially may be a disturbance to organisms! Identifying the adaptations and mechanisms of aquatic organisms to a periodically changing environment and using them in aquaculture should be a new research field.

Biological Regulation of Water Quality in Aquaculture

7

Shuang-Lin Dong

Aquatic organisms that can be used to regulate water quality and sediment quality in aquaculture mainly include macrophytes, filter-feeding fishes, bivalves, deposit-feeding sea cucumbers, etc. These instrumental species in aquaculture are the integrated organisms with main target organism. These instrumental species not only play a role in regulating and improving the water quality or/and sediment quality of aquaculture waters, but also normally possess high commercial value. For these instrumental species, we should not only understand the characteristics and mechanisms of their growth and survival, but also pay more attention to their effects on aquaculture environment.

7.1 Biomanipulation of Aquatic Ecosystems

Water quality of aquaculture waters is often deteriorated by feeding activities. In order to implement healthy production, it is necessary to regulate and improve water quality of fed aquaculture systems, which is also known as environmental remediation in environmental science. There are three kinds of methods to regulate water quality, namely, physical, chemical, and biological methods. The physical methods of water quality regulation or environmental remediation mainly involve removing pollutants through physical processes, such as dredging, sedimentation, and filtration. Chemical methods are mainly involving the application of chemical compounds to oxidize or decompose the pollutants, and ultimately transform the pollutants into harmless substances. This type of methods is fast but expensive and sometime may cause secondary pollution. Biological methods use microorganisms,

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aquatic plants and animals to degrade the pollutants into carbon dioxide and water or convert them into other harmless substances. The biological methods can be further subdivided into in situ remediation and ex situ remediation. In general, biological methods are inexpensive, simple to treat, and safer.

Biomanipulation of aquatic ecosystems is an important technique for water quality regulation. The concept of biomanipulation was first introduced by Shapiro et al. (1975), which was defined as management of aquatic communities by controlling natural populations of organisms aiming at water quality improvement. Shapiro and Wright (1984) found that after removing zooplanktivorous fish from an experimental ecosystem, the phytoplanktivorous zooplankton biomass increased significantly and phytoplankton biomass decreased. The nutrient loading does not change significantly during the above process, and the food web theory is at work. Later, many managers stopped using copper sulfate to kill algae and switched to biological manipulation to control algae, i.e., to suppress phytoplankton biomass by stocking piscivorous fish or directly reducing the quantity of zooplanktivorous fish. Carpenter et al. (1985) proposed the concept of trophic cascade, and McQueen et al. (1986) also proposed the concepts and methods of bottom-up effect and top-down effect. These theories or concepts lay the theoretical foundation for the biomanipulation of aquatic ecosystems and the biological regulation of water quality in aquaculture.

The regulation of biomass and structure of the phytoplankton community in aquaculture waters is the core of biological regulation of water quality. The biomass and structure of phytoplankton community in a given moment in water are usually the result of a combined action of bottom-up and top-down effects. Bottom-up effects regulate the phytoplankton mainly by controlling the amount of inorganic nutrients input (increase or decrease) and/or the proportion of nutrient elements, such as N/P ratio, and in turn influence on the biomass of higher trophic levels. The pathway of the action is inorganic nutrients → phytoplankton → zooplankton → zooplanktivorous fish → piscivorous fish. Changes (pulses) in inorganic nutrient input have an impact on phytoplankton biomass and subsequently lead to the changes in biomass at subsequent trophic levels along the food chain (Fig. 7.1). The bottom-up effect is characterized by a time lag in the backward food chain and by a gradual decrease in the intensity of the effect (Reynolds 1997).

The top-down effects regulate phytoplankton mainly through controlling the quantity of zooplanktivorous fish. The pathway of the action is piscivorous fish → zooplanktivorous fish → zooplankton → phytoplankton. There is also a time lag in the top-down transmission of the effects, but the intensity of the effects may be gradually amplified along the food chain (Fig. 7.2). For example, after stocking carnivorous or piscivorous fish that prey on small zooplanktivorous fish into a water body with a relatively simple food web structure, it is likely to result in the phenomenon of clearer water with less phytoplankton biomass. Conversely, the biomass of phytoplankton may increase if the piscivorous fish are killed.

Zooplankton can influence the phytoplankton community through grazing intensity and size selectivity for food particles. When the growth rate of a phytoplankton is less than the grazing pressure of zooplankton, its population will gradually

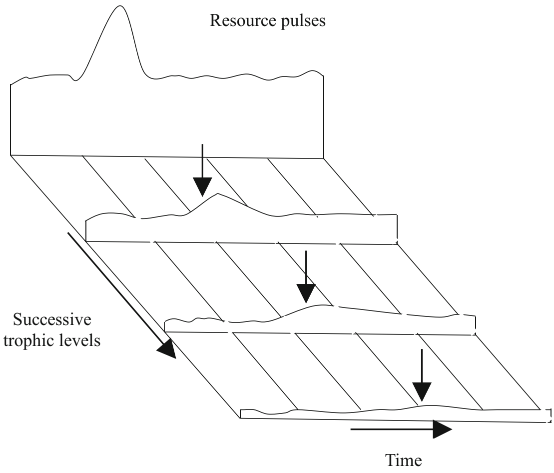


Fig. 7.1 Transmission of a resource pulse through a food chain (from Reynolds 1997)

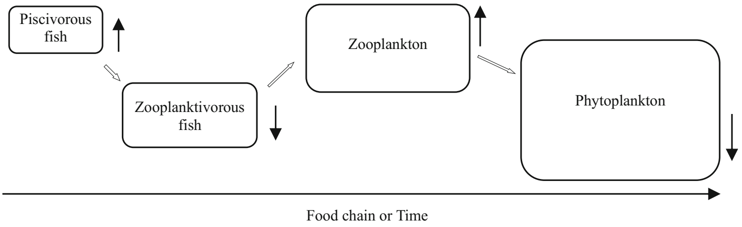


Fig. 7.2 Top-down effects in aquatic ecosystems

decrease or disappear from the community. Only the phytoplankton populations that grow fast enough can resist zooplankton grazing and maintain a certain population size. Zooplankton have difficulty in grazing on larger size of phytoplankton species, multicellular colonies, and filaments, while small unicellular phytoplankton are easily consumed by zooplankton. This is one of the main reasons why it is common to see certain groups of cyanobacteria dominating the phytoplankton community in ponds.

The key factor on which the classical biomanipulation theory relies is zooplankton, but some scholars have also proposed a non-classical biomanipulation approach, i.e., the use of filter-feeding fish or bivalve to directly manipulate phytoplankton, and have achieved certain results. Stocking certain amount of some filter-feeding fishes or bivalves in aquaculture waters can exert a top-down effect on the biomass and structure of phytoplankton community. Some fish can directly filter large and multicellular colonial phytoplankton, while others can indirectly influence the phytoplankton community by feeding on zooplankton (Dong et al. 1992; Dong 1994; Xie 2003). Filter-feeding bivalves, such as oysters and scallops, can filter phytoplankton as small as a few microns. Therefore, stocking these bivalves can significantly reduce the biomass of phytoplankton and significantly affect the water quality of aquaculture waters (Dong et al. 1999).

Previous studies have shown that filter-feeding fish play an important role in the development of phytoplankton communities only in low productivity (oligotrophic) systems. For some eutrophic waters, such as feed delivering (fed) or fertilization ponds, the restoration of macrophyte and/or reduction of overfeeding are more effective to regulate water quality of the waters (Boyd and Tucker 1998).

Filter-feeding fish and bivalves can feed directly on phytoplankton, convert the phytoplankton directly into their body tissues, and become commercial products. The integration of macrophytes with fed species can directly reduce nutrient loading in aquaculture waters. Thus, integration macrophyte and bivalves with target fed species can directly both reduce the nutrient loading and suppress the phytoplankton, and are therefore the most effective means of biological regulation of water quality in aquaculture waters.

Benthic and deposit-feeding sea cucumbers are also instrumental species for biological manipulation. The feeding activity of sea cucumber can reduce the organic content in the sediment of aquaculture waters and, in turn improve sediment quality, reduce the nutrient loading of the waters. Therefore, sea cucumbers can improve water quality through the bottom-up effect.

Macrophytes, filter-feeding fish, bivalves, sea cucumbers are major co-culture species in integrated aquaculture systems because of their ability to improve water quality and sediment quality (see Chap. 9 for details).

7.2 Phytoplankton Production and its Limiting Factors

The flora of freshwater ecosystems consists mainly of phytoplankton and aquatic vascular plants, while in seawater ecosystem it consists mainly of phytoplankton and seaweeds, with some areas where there are also abundant seawater vascular plants. Large vascular plants and seaweeds are mainly found in shallower areas due to the limitation of light incidence depth, and phytoplankton are the main primary producers in pelagic areas.

As the main primary producer, phytoplankton supports the production of farm animals through food chain or food web in extensive aquaculture systems. Even in semi-intensive systems, i.e., aquaculture with supplementary feeds, a significant part of the primary production of phytoplankton is still transferred to the production of farm animals. Another extremely important function of phytoplankton is the regulation of water quality, because phytoplankton are not only the main primary producers, but can also influence water quality factors such as dissolved oxygen (DO), CO_2, pH, redox potential, and un-ionized ammonia concentration through photosynthesis and respiration. Therefore, the regulation of the biomass and structure of phytoplankton community in aquaculture waters becomes extremely important in aquaculture practices.

7.2.1 Photosynthesis and Respiration of Phytoplankton

Phytoplankton species are highly diverse, containing such phyla as cyanobacteria (Cyanophyta), green algae (Chlorophyta), diatoms (Bacillariophyta), dinoflagellate (Pyrrophyta), euglenophytes (Euglenophyta), golden-brown algae (Chrysophyta), etc. They come in a variety of shapes and pigments and usually do not have active locomotion. A few species can use some structures such as flagella for weak locomotion or to regulate their buoyancy by changing shape, etc.

The phytoplankton commonly found in aquaculture ponds are some of the worldwide distributed species. The community composition of phytoplankton varies greatly in various farm pond. If you look down on a freshwater fish farm from a landing airplane, you will see the landscape made up of colorful ponds.

When the phytoplankton community reaches a certain density in water body, the water will have a certain color, which is related to the pigments of the dominant phytoplankton. When the quantity of phytoplankton is high, a so-called 'water bloom' will be formed. Different dominant phytoplankton displays different water color, and common color is green, blue-green, yellow, brown, and so on. Experienced experts can often determine the general dominant species and rough quantity of phytoplankton communities by the water color, transparency, and dynamic of water colors (He and Li 1983b).

Phytoplankton all contain pigments such as chlorophyll, which is used for photosynthesis. Photosynthesis is the process by which plants absorb light and convert light energy into chemical energy and inorganic matter into organic matter. Part of the energy produced by photosynthesis in phytoplankton will be used for tissue growth and cell division. The process of photosynthesis requires light as an energy source, as well as water, CO_2, inorganic nutrients, and other elements.

Photosynthesis is highly important for aquaculture ecosystems, as it is not only the process that uses solar energy for seaweed growing and phytoplankton production, but also maintain a good water quality by providing DO, absorbing CO_2 and NH_4^+, etc. Phytoplankton also consume DO and release CO_2 under dark conditions, i.e., respiration

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat}$$

Respiration is a reverse process of photosynthesis and has an important impact on the chemical environment of aquaculture waters.

7.2.2 Physical and Chemical Factors Affecting Phytoplankton Growth

Phytoplankton colonize new habitats often by passive transport, including water supply, wind, and waterfowl. Pond bottom mud is an important source of inoculum because many reproductive bodies of algae species that are quite resistant to desiccation and can survive long periods in damp soil. A new water body is often dominated by green algae first due to the presence of large quantity of single-celled green algae in the air and their large relative surface area and rapid reproduction rate. The subsequent succession process of phytoplankton communities in aquaculture waters is largely based on the ability of various phytoplankton to compete for resources. The main physical and chemical factors affecting phytoplankton growth and community succession in aquaculture waters, especially in ponds, are light, inorganic nutrients, and water temperature.

7.2.2.1 Light

Solar light is the energy source for photosynthesis and is the most important factor affecting phytoplankton growth. The light-promoting phytoplankton photosynthesis is mainly the intensity of light in 400–700 nm wavelengths (photosynthetically active radiation, PAR), which is usually measured in μE/(m^2·s) or Lx. Light is absorbed as it travels through water column by water and particles in the water (see Sect. 2.2 for details). Phytoplankton contain a variety of pigments, and their light absorption properties vary somewhat. Chlorophyll absorbs mainly blue and red-light wavelengths, carotene and xanthophyll in diatoms strongly absorb green light wavelengths, and phycobilin and phycoerythrin in cyanobacteria absorb green and yellow light.

Some phytoplankton require a minimum light intensity of less than 5 μE/(m^2·s) for net growth, while others require more than 20 μE/(m^2·s). The minimum light intensity required for phytoplankton growth is related to phytoplankton species, nutrient status, water temperature, and other factors. The midday incident solar radiation immediately beneath the water surface in temperate waters is about 200 μE/(m^2·s) on cloudy days and can be up to 1600 μE/(m^2·s) on sunny days in equatorial waters (Boyd and Tucker 1998). The water layer where the light intensity is about 1% of the light intensity immediately beneath the water surface is about the compensation depth or compensation point (see also Sect. 2.2.2 for details). The phytoplankton in the water absorb solar light strongly, so that the compensating depth of the water column is shallower when there is heavy phytoplankton blooms or the water is more turbid.

Phytoplankton have evolved mechanisms to adapt to low-light environments underwater and, at the same time, have lost the ability to tolerate strong light. Photosynthesis of phytoplankton is partially inhibited when PAR reaches 200–800 μE/(m^2·s) and ceases completely when PAR exceeds 1400 μE/(m^2·s) (Harris 1978). Primary productivity is not the highest immediately beneath the water surface due to the inhibition of phytoplankton photosynthesis by higher light intensity at noon on a sunny day. The most intense photosynthetic layer in temperate freshwater bodies tends to occur at about half-Secchi depth of the water column.

When phytoplankton biomass is high, the amount of solar radiation entering the deeper water column is significantly reduced due to the strong absorption of light by phytoplankton, and the amount of primary production per unit area of the water column is also reduced, a phenomenon known as phytoplankton ‘self-shading’. When ‘self-shading’ occurs, certain actively mobile phytoplankton, such as those with flagella or changeable buoyancy, move up or float upward the surface to obtain more light, thus gaining an advantage in the composition of phytoplankton community.

The responses of unicellular phytoplankton to light intensity are species-specific. Studies have shown that rhythmic changes in light intensity favor photosynthesis and biomass accumulation in some unicellular phytoplankton (Mallin and Paerl 1992), but there are also opposite cases (Kroon et al. 1992) or no specific response.

7.2.2.2 Inorganic Nutrients

About 20 elements are essential for the functioning of phytoplankton and need to be absorbed from the water. The concentrations of these elements vary considerably in water over time and location and can affect phytoplankton community growth and structure. The amount of these elements in the aquatic environment is not infinite for the needs of phytoplankton, and the community productivity is usually constrained by the availability of one or two key nutrients that are in shortest supply relative to the requirements of the organism, which are referred to as limiting nutrients. For example, where P is the limiting element, application of other elements to the water does not stimulate an increase in community productivity of phytoplankton; only the addition of P will result in an increase in the productivity. Dissolved iron and phosphorus available for phytoplankton in water is very little and can be 'reduced' further by means of chemical chelation or absorbents. Therefore, it is important for aquaculture to regulate water quality by adjusting the concentration of the iron and phosphorus in water.

It is important to note that any essential nutrient is a nutrient at a relative low concentration, but will become toxic when it is very high in concentration (Fig. 7.3). Similar patterns are seen in the effects of light, water temperature, Cu, and other physical and chemical factors on phytoplankton growth.

Experimental studies have proved that nitrogen and phosphorus ratio (N/P ratio) has a significant impact on phytoplankton growth. *Microcystis aeruginosa* possesses competitive advantage at low N/P ratio and high temperatures, while *Phormidium tenue* possesses competitive advantage at high N/P ratio and low temperatures.

When only one limiting nutrient is added to the waters in a certain amount, the ratio between nutrients changes qualitatively, so that the added nutrient is no longer a limiting nutrient for phytoplankton, and is replaced by another more deficient nutrient. In aquaculture waters, P and N are usually the first and second limiting

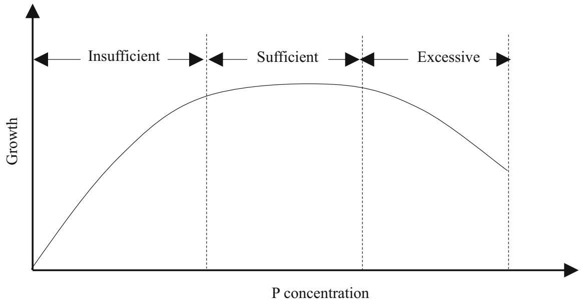


Fig. 7.3 The response of phytoplankton to additions of a single limiting nutrient (from Boyd and Tucker 1998)

Table 7.1 The optimal concentrations of N and P for phytoplankton to grow (from Zhang et al. 2002b)

	Optimal concentration (μmol/L)			
Phytoplankton	NH_4Cl-N	KH_2PO_4-P	Urea-N	KH_2PO_4-P
Heterosigma akashiwo	300	10	300	10
Thalassiosira sp.	150	5	100	5
Chaetoceros gracilis	200	5	300	5
Isochrysis sp.	150	10	150	5
Alexandrium sp.	100	10	300	10
Chroomonas sp.	200	10	300	10

nutrient or element. Results of a survey on 49 lakes in the United States indicate that P is the first limiting element in 35 of these lakes and N is the first limiting element in 8 of these lakes (Miller et al. 1974).

Most N/P ratios of phytoplankton in seawater are greater than the Redfield value (16:1). In fact, P is usually the first limiting nutrient in freshwater bodies and N is often the first limiting element in seawater and brackish waters. Valiela (1995) has conducted fertilization experiments on US offshore waters with salinity of 32 ppt and coastal ponds with the salinity of 4 ppt. He found that although most of these two types of waters exhibited dual nutrient limitation of N and P, the lower salinity ponds were more likely to be P limited, while the opposite was true for the high salinity offshore waters. Liu et al. (2003a) have studied the limiting elements in Laizhou Bay and Sanggou Bay, Shandong Province, by using oxygen evolution bioassay method (Li et al. 1988), and found that the ranking order of nutrient limiting strength in Laizhou Bay (near the mouth of the Yellow River) is $N > P > Si > Fe$, while in Sanggou Bay, the ranking order is $N > Si = Fe > P$.

The uptake capacity of nutrients varies among phytoplankton. Typically, phytoplankton with a relatively large surface area have a greater capacity to absorb nutrients. Differences in the nutrient uptake capacity of various phytoplankton affect their growth rates, and thus phytoplankton community succession and structure.

The optimum nitrogen and phosphorus ratio for growth of six marine phytoplankton were studied by Zhang et al. (2002b), and the results are shown in Table 7.1. At corresponding concentration levels, most phytoplankton grew at higher rates in the ammonia environment than in the urea environment, with the exception of Cryptophyta. *Alexandrium* showed an advantage in high concentration of organic nitrogen. Various phytoplankton required different nitrogen to phosphorus ratios, varying from 10:1 to 40:1.

7.2.2.3 Water Temperature

Phytoplankton have a wide range of adaptation to water temperature and are species-specific. Some species can survive in snow and ice, and some species can survive in hot springs above 70 °C. Cyanobacteria are usually more tolerant of high temperature and therefore are often the dominant taxon of phytoplankton in aquaculture waters in summer. Temperature has a significant effect on phytoplankton growth; the growth rate of common species found in aquaculture ponds increases by factors of 1.8 to about 3 as temperatures increase by 10 °C over the range 5–25 °C.

The above is only a brief introduction of the main factors affecting phytoplankton growth, and more detailed information can be found in the works of Wetzel (2001) and Reynolds (1984). In fact, phytoplankton growth and community succession are the result of a combination of many factors. The saddle-shaped annual variation in phytoplankton biomass (one biomass peak in spring and one in autumn) in deeper temperate waters is the result of a combined action of water thermocline, light, nutrients, and many other factors (see Sect. 2.2 for details). It should be noted that annual variations in phytoplankton biomass in shallow lakes and ponds in temperate regions show only one peak in summer; e.g., there is only one peak in summer for phytoplankton in Wuhan East Lake (Wang 1999a).

7.2.3 Phytoplankton Communities in Aquaculture Ponds

In high-yield fish ponds of Wuxi, China, there are four types of phytoplankton blooms, namely *Gonyostomum depressum*, *Cryptomonas* spp., *Gymnodinium cyaneum,* and *Chlorococcum* spp. (He and Li 1983b). Local farmers do not care much about what color the water is, and consider water 'alive' to be good water. 'Alive' means the water color changes daily, which is caused by the vertical movement of flagellated algae phototropism. The water with *Gonyostomum* bloom, for example, will become 'alive' in the afternoon, and the transparency of the water may decrease by 7–10 cm compared with that in the morning. *Gonyostomum* bloom is the most popular 'fertile water' in local fish ponds. This alga is of good size and easy to be filtered and digested by silver carp. *Cryptomonas* bloom and *Chlorococcum* bloom are general 'fertile water' of brown to green in color.

Chlorophyll *a* in natural waters at water depths of 1–1.5 m can reach 300–600 μg/L (Wetzel 2001; Reynolds 1984). The maximum sustained biomass of phytoplankton in waters is related to the physiological state of phytoplankton, community structure, abiotic turbidity, and hydrodynamic characteristics of the aquatic ecosystem. Results of simple empirical and mechanistic models under various simulation conditions indicate that net production of phytoplankton is higher when chlorophyll *a* is in the range of 50 to 250 μg/L. Chlorophyll *a* level in fertilized aquaculture ponds in the United States is typically in the range of 60–150 μg/L (Boyd and Tucker 1998).

Studies on aquaculture ponds using stable isotopes have shown that natural food organisms remain an important food source for farmed shrimp even in semi-intensive ponds (Dong et al. 2002). In addition, phytoplankton can regulate water quality of aquaculture pond through photosynthesis. Without the role of phytoplankton in maintaining water quality, the management costs spent on farming pond would be much higher. The core tasks of pond management include maximizing the use of natural processes to produce natural food organisms, supplying DO, and removing nitrogenous inorganic compounds from the water. The mentioned above is the beneficial side of phytoplankton in fed ponds, but the challenge in pond management is the inability to control the ‘blooming’ of phytoplankton. The DO depletion and the accumulation of toxic nitrogenous waste caused by excessive phytoplankton biomass are a common problem in aquaculture ponds around the world.

Although phytoplankton in ponds have been intensively studied by ecologists over a long period of time, it is not yet possible to predict the phytoplankton community structure that will occur in a particular pond at a particular time. Nutrient loading is an important factor influencing phytoplankton community structure. Diverse communities of green algae, diatoms often occur in the waters with low or medium nutrient loadings. However, in high nutrient loading ponds there are often several dominating species, such as large flagellated algae or colonial cyanobacteria.

Fertilized ponds are usually required to maintain moderate phytoplankton biomass, but fed ponds often have excessive phytoplankton biomass due to lots of nutrients brought in by feeds. The easiest way to control phytoplankton blooms is to reduce nutrient inputs, but this is difficult to do in fed ponds. The use of aerators has become common in aquaculture practices and seems to be more cost-effective than direct control of phytoplankton, but this is only the way to treat the symptoms rather than the root causes (Boyd and Tucker 1998).

Excess nutrients in fed ponds for farming fish or shrimp are usually diluted and discharged through water exchange, which seems the way to treat the causes, but on a larger spatial and temporal scale, it is still the way to treat the symptom. The excess nutrients discharged to adjacent waters may led to broader issues. One of feasible treatments that addresses the root causes is to implement integrated multi-trophic aquaculture in pond, by which zero nutrient discharge or standard discharge can be achieved while maintaining a reasonable aquaculture yield (see Chap. 9 for details).

The biomass of cyanobacteria in many freshwater ponds is very high in summer and can lead to water quality degradation. These bloom-forming cyanobacteria are *K*-selective species in terms of ecological strategy, i.e., slow-growing, highly competitive for limited resources, adapted to stable environments, and with population biomass often near a maximum (Reynolds 1984). Because of their slow growth, these algae are less capable of producing oxygen than most eukaryotic phytoplankton species. Sometimes cyanobacteria may form surface scums in ponds. The surface scums will further reduce oxygen production of photosynthesis because the scums prevent light from entering the water. The sudden death of dense cyanobacterial communities can have disastrous consequences in aquaculture ponds, such as massive anoxia suffocation of farmed fish because of large amounts of DO consumption by decomposition of dead algal cells.

In phytoplankton-based food webs, i.e., extensive aquaculture systems where the food for fish or crustaceans comes primarily natural food source, low growth rates of cyanobacterial blooms can affect farm yield. The transfer of primary production from cyanobacterial blooms to farmed animals is mainly through detritus food web or via grazing by zooplankton. Clearly, a longer food chain will reduce the conversion efficiency of primary production to farmed animals. Cyanobacterial blooms are poorly digested by stomachless phytoplanktivorous fish, such as silver carp, whereas tilapia with stomachs have highly acidic stomach acids that effectively lyse the cell walls of cyanobacteria and can digest *Microcystis* blooms up to 0.5 mm in diameter. For planktivorous tilapia, cyanobacterial blooms are both readily available and easily digested (Boyd and Tucker 1998).

Some cyanobacteria can produce odorous metabolites that are released into the water. These compounds, such as geosmin and 2-methylisoborneol, can be absorbed by fish skin and cause an ‘off-flavor’ to the flesh. Several cyanobacteria also produce compounds that are highly toxic to vertebrates.

Farmed aquatic animals in extensive and some semi-intensive systems grow mainly by feeding on natural food organisms; therefore, farm production in these waters has a high correlation with phytoplankton biomass. However, fish production no longer continues to increase when phytoplankton biomass exceeds a certain amount, and even decreases when the biomass is too high (Boyd and Tucker 1998). When phytoplankton biomass increases to a certain amount, self-shading occurs and net phytoplankton production decreases, and at the same time, water quality conditions deteriorate.

7.3 Nutrient Uptake Kinetics of Seaweeds

Seaweeds or macroalgae are not only primary producers and commercial aquatic products, but also water quality regulators in marine environment. The ability of the seaweeds in regulating water quality of aquaculture waters are related to their nutrient uptake kinetics.

7.3.1 Nutrient Requirement of Seaweeds

The elemental composition of seaweed ash is similar to that of marine phytoplankton, with C, H, O, N, P, Fe, Mg, Cu, Mn, Zn, and Mo being essential elements for their growth. Usually, the accumulated concentrations of both essential and non-essential elements (except H) in seaweeds are greater than those in seawater. Three vitamins, namely vitamin B_1, vitamin H, and vitamin B_{12}, are generally required in algal culture media. Since concentrations of vitamins are usually low in seawater (about 1 ng/L for vitamin B_{12}, 10 ng/L for vitamin $B_{1,}$ and 2 ng/L for vitamin H), they are the most widely required substances in algal culture media (Lobban and Harrison 1994).

N, P, and Fe are often the main limiting elements for seaweed growth and are highly variable in concentrations in seawater (DeBoer 1981; Bruland 1983). The concentrations of these elements are much higher in seaweed than in seawater. Although nutrient concentration can be an indicator of whether a nutrient is limiting, the ratio between nutrients, availability, and turnover time are more important in determining the degree of nutrient limitation. In the case of seaweed communities, dual nutrient limitation (i.e., two elements acting simultaneously as limiting factors) may exist. The ratio of two nutrient requirements (e.g., N: P) may varied among different seaweed species e.g., the same water body may be N-limited for A species and P-limited for B species. Fe and Mn are essential elements in many biochemical reactions in seaweed and can sometimes be limiting factors for seaweed growth. Whether or not Fe will be a limiting element for seaweed growth often depends on the amount of available form of Fe rather than total iron concentration in seawater. Because the concentration of phosphorus and iron in natural seawater is very low and easy to be adsorbed and chelated, they are the potential tools to regulate water quality in aquaculture.

In natural seawater, the average concentration of nitrogen is 0.420 μg/g. Nitrogen in seawater exists mainly as inorganic nitrogen (N_2, NH_4^+, NO_3^-, and NO_2^-), soluble organic nitrogen (urea, free amino acids, amides, and vitamins), and particulate organic nitrogen (organic nitrogen debris and planktonic components). Almost all seaweeds can use NH_4^+, NO_3^- and NO_2^- as a source of nitrogen, but high concentrations (>30–50 mol/L) of NH_4^+, NO_3^- or NO_2^- are toxic to seaweed. Generally, NO_2^- can be used as a source of nitrogen only at concentrations as low as 1 μmol/L, and higher concentrations of NO_2^- will inhibit algal growth. Seaweed can also use some soluble organic nitrogen in water as a source of N, such as urea, amides, and amino acids, especially glycine, serine, alanine, and glutamate.

In natural seawater, the average concentration of phosphorus is 0.071 μg/g. At natural seawater pH (~8.2) and 20 °C, phosphorus is present mainly in an equilibrium system in three free forms, 95% of HPO_4^{2-}, 2.5% of $H_2PO_4^-$, and 1% of PO_4^{3-}. Seaweeds mainly use inorganic orthophosphates. Some seaweeds can hydrolyze and utilize organic phosphorus (e.g., phosphoglycerol) by producing extracellular alkaline phosphatases. When extracellular inorganic phosphorus concentrations are high, the synthesis of alkaline phosphatase is inhibited and the cells are less able to utilize organic phosphorus at this time. When extracellular inorganic phosphorus is depleted, intracellular stores of polyphosphate and orthophosphate are quickly utilized, followed by an increase in alkaline phosphorylase activity. Phosphorus limitation and light can activate alkaline phosphorylase activity in *Ulva lactuca*.

In natural seawater, the average concentration of iron is 0.000 06 μg/g. Iron is an important nutrient in the metabolism of seaweed and is essential for photosynthesis and many biochemical reactions in organisms. Iron is bound to proteins in various forms in plants and is involved in a variety of life activities as an important electron transmitter or catalyst. Under natural seawater pH conditions, Fe^{3+} combines with OH^- to form $Fe(OH)_3$, a relatively insoluble compound (Ksp $\approx 10^{-38}$ mol). Therefore, the only iron in the soluble state are those complexes formed with chelating agents or ligands (e.g., humic acids) in natural seawater.

Based on the iron requirements of seaweeds and the form of iron present in seawater, it is speculated that iron may be a limiting factor for the growth of some seaweeds. Many studies have shown that iron can limit phytoplankton growth in the central equatorial region, northeastern Pacific Ocean, and some other areas (van Leeuwe 1998). The soluble Fe in surface water of these areas is less than 0.5 nmol/L, with NO_3^- concentrations of 21–27 μmol/L, and chlorophyll concentrations less than 0.2 μg/L. Although seaweeds cannot effectively use Fe^{3+} forms of Fe under aerobic conditions, most organisms are able to obtain Fe for growth through some specific mechanism.

7.3.2 Response of Seaweeds to Iron Stress

Iron is essential for many biochemical reactions in seaweeds and can sometimes be a limiting element. In aquaculture systems, iron can be increased by iron fertilization or 'reduced' by chemical chelation. It is not only of theoretical but also of practical importance to discuss the regulation of water quality by controlling the concentrations of the iron.

The growth rates of *Gracilaria tenuistipitata* var. *liui* (a red alga) and *Ulva pertusa* (a green alga) decreased rapidly in a Fe-limited culture. After 6 weeks, the growth of the *G. tenuistipitata* stopped, and chlorosis and even death occurred. During the experiment, the *U. pertusa* became very thin and soft, although the seaweed did not become chlorosis (Liu et al. 2000b, 2002a).

The levels of total nitrogen (TN), total carbon (TC), and total phosphorus (TP) especially TC decreased in the tissues of the two seaweeds during the iron limitation process. The C:N ratio in *U. pertusa* decreased during Fe-limited cultures and kept constant in *G. tenuistipitata*. N: Fe and C: Fe ratio increased. The decrease in N: P ratios in the tissues of both seaweeds indicated that iron limitation has a greater impact on nitrogen uptake than phosphorus. In *G. tenuistipitata*, total amino content decreased after 60 days' Fe-limited cultures and was the 83.7% of original level; however, in *U. pertusa*, it increased and was 1.02-fold of non-Fe-limited cultures.

Doucette and Harrison (1990) reported that the half-saturation constants for iron-limited growth of 10 phytoplankton ranged from 10^{-23} to 10^{-21} mol/L. Iron limitation in a marine dinoflagellate (*Gymnodinium sanguineum*) resulted in reductions in chloroplast quantity and some degeneration of lamellar organization. Nitrogen metabolism is very sensitive to iron limitation because many of the enzymes involved in nitrogen metabolism are iron-containing proteins.

Chlorophyll (Chl), phycoerythrin (PE) in the seaweeds were decreasing exponentially with the decrease in tissue iron content, especially in the first 10 days of Fe-limitation. Absorbance spectrum of Chl and PE reduced both in *G. tenuistipitata* and in *U. pertusa* after 2 weeks Fe-limitation. After 6 weeks, the PE content in *G. tenuistipitata*. Decreased to 33.8% of that in non-Fe-limitation group, and the Chl contents in *G. tenuistipitata* and *U. pertusa* were only 7.9% and 4.9%, respectively, of that in non-Fe-limitation group.

The maximum carbon fixation rate under Fe-limitation decreased significantly from 1.69 mgC/(gdw·h) to 0.08 mgC/(gdw·h) in *G. tenuistipitata* and 13.6 μgC/(cm^2·h) to 0.365 μgC/(cm^2·h) in *U. pertusa*. Photosynthesis in Fe-deficient cells became light-saturated at lower irradiant than that of non-Fe-limitation group.

7.3.3 Kinetics of Nitrogen Uptake by Seaweeds

The main objective of studying the nutrient uptake kinetics of seaweeds is to obtain parameters related to their nutrient uptake and, accordingly, to discern trends in their effects on water quality. Kinetics of nutrient uptake are dependent on the uptake mechanisms involving in the uptake process. Passive diffusion occurs down an electrochemical gradient without the expenditure of cellular metabolic energy. The transport rate of passive diffusion is directly proportional to the electrochemical potential gradient (external concentration). Active transport is the transfer of ions or molecules across a membrane against an electrochemical potential gradient, which is also called ‘uphill’ transport (Lobban and Harrison 1994). Active transport exhibits a saturation of the membrane carriers as the external concentration of the ion increases (Grover 1997).

The relationship between the uptake rate of ion and its external concentration can be described by a rectangular hyperbola: $V = V_{\max} S/(K_s + S)$. Where V is initial uptake rate, $V_{\max}$ is maximum uptake rate at saturating substrate concentration, S is substrate (nutrient-ion) concentration, and K_s (equivalent to K_m) is half-saturation constant for substrate.

The ion transfer capacity of some seaweeds can be described by $V_{\max}$ and K_s (or K_m). However, active uptake does not always follow this simple saturation kinetic model, and it is closely related to the form of nutrients in the medium, the physiological state of the seaweeds themselves, etc. When seaweeds under some forms of nutrient limitation are moved into that nutrient-rich environment, their rates of nutrient uptake increase significantly. The greater the degree of prior nutrient limitation, the more pronounced the increase in $V_{\max}$. Under conditions of nutrient limiting, an uptake is controlled primarily by nutrient level within the tissue rather than by external nutrient concentrations.

The main techniques for measuring nutrient uptake rates are the disappearance of nutrient from the medium. If the uptake rate varies with time, the uptake rate must be determined by combining multiple flask and perturbation. This change in uptake rate over time can generally be divided into three phases, namely, surge uptake, internally controlled uptake, and externally controlled uptake. Many studies have shown that the internally controlled uptake is very close to the seaweed assimilation rate and can be used to represent the assimilation rate (Liu and Dong 2001b).

7.3.3.1 Nitrogen Storage and Uptake Capacity

Ammonia is major excreta of most aquatic animals and a nitrogenous degradant of artificial feeds, and high levels of ammonia in aquaculture waters are toxic to farmed animals. Elimination of excess ammonia and other inorganic nutrients can improve water quality in aquaculture and also alleviate problems such as eutrophication in coastal waters. It is generally accepted by scholars that co-culture of seaweeds is one of the effective measures to absorb and utilize nutrients and delay eutrophication of waters. Liu and Dong (2001a, b) conducted a comparative study on the storage and uptake capacity of nitrogen by *G. tenuistipitata* and *U. pertusa*, aiming to lay the theoretical foundation for better utilization of these two instrumental species in regulating water quality.

7.3.3.1.1 Growth Rate and Nitrogen Storage under Nitrogen Enrichment and Starvation

All nitrogen storages in both *G. tenuistipitata* and *U. pertusa* increase significantly after 10 days' N-enrichment cultivation. TN content in *G. tenuistipitata* increases from an initial level of 3.65% (dry weight) to 5.78%, and increases from 2.54% to 4.79% in *U. pertusa*. Before and after N-enrichment, amino acids and proteins are the largest nitrogen storages, accounting for 14.9%–16.9% and 69.04%–58.6% of tissue TN in *G. tenuistipitata*, respectively, and 5.87%–9.2% and 42.8%–66.6% in *U. pertusa*, respectively. Phycoerythrin is also a relatively large nitrogen storage in *G. tenuistipitata* tissue, which accounts for 4.8%–5.83% of TN. Chlorophyll is a relatively small nitrogen storage, accounting for 0.9%–1.09% and 1.4%–1.61% of the TN in the two seaweeds, respectively.

All nitrogen storages in the tissues of both *G. tenuistipitata* and *U. pertusa* decline exponentially with increasing starvation time during 20 days' N-starvation cultivation, and all nitrogen storages in *U. pertusa* decline more rapidly than the corresponding nitrogen storages in *G. tenuistipitata*. The relationships between specific growth rate and tissue TN in both *G. tenuistipitata* and *U. pertusa* conform to the Droop equation: $\mu = \mu_{\max}[1- (N_Q/N)]$ (where μ is the specific growth rate; $\mu_{\max}$ is the maximum specific growth rate; N_Q is subsistence cell quota, i.e., the minimum tissue TN concentration required to maintain growth; and N is the actual TN concentration in the tissue). The equations are

$$\mu_G = 26.656(1 - 2.204/N) \quad (R^2 = 0.9217)$$
$$\mu_U = 32.400(1 - 1.375/N) \quad (R^2 = 0.8533)$$

The relationship between tissue TN content and specific growth rate in short term (24 h) during 20 days' starvation following N-enrichment is generally consistent with the Droop equation for both seaweeds. The maximum specific growth rate is higher in U. pertusa (32.4%/d) than that in *G. tenuistipitata* (26.7%/d), whereas the tissue TN concentration required to maintain the minimum growth rate is lower in *U. pertusa* (1.38% dry weight) than that in *G. tenuistipitata* (2.20% dry weight).

After 20 days' N starvation, the TN contents in *G. tenuistipitata* and *U. pertusa* decrease from 5.78% and 4.79% to 2.56% and 1.38%, respectively. Unlike the other N storages, the protein storages in both seaweed tissues increase as a percentage of TN after N starvation, from 58.6% to 72.5% for *G. tenuistipitata*, and from 66.5% to 76.2% for *U. pertusa*. The growth rates of *G. tenuistipitata* and *U. pertusa* remain high during the first 2–5 days of N starvation, 18.2% and 24.3%, respectively. After next 20 days' starvation, the growth rates decrease to 2.56% and 0.99%, respectively.

7.3.3.1.2 Kinetics of NH_4^+ Uptake of Nitrogen-Starved Seaweeds

When NH_4^+ uptake rates of nitrogen-starved *G. tenuistipitata* and *U. pertusa* are plotted against the uptake time, the curves show three different uptake trends: a surge uptake phase at high starting concentrations, denoted by V_s, where the magnitude of the uptake rate is related to the starting concentration; a subsequent phase where both the concentration and the uptake rate in the medium decrease slowly, called internally controlled uptake, denoted by V_i, where NH_4^+ concentration in the medium is still relatively high, and the magnitude of NH_4^+ concentration is related to its starting concentration; finally, as NH_4^+ concentration in medium decreases, the uptake rate decreases rapidly to almost zero, and this phase is externally controlled uptake phase, denoted by V_e.

In surge uptake phase, the uptake kinetics of *G. tenuistipitata* and *U. pertusa* do not conform to the saturation kinetics of Michaelis–Menten equation. Therefore, a combination of multiple flask and perturbation techniques is used to determine the uptake rates of the seaweeds at different starting concentrations for different time intervals. The uptake rates at different time intervals are analyzed by nonlinear regression, and the results show that they both conform to the saturation uptake kinetics. Their maximum uptake rates (V_{max}) and half-saturation constants (K_s) decrease with increasing uptake time until they reached a more stable internally controlled uptake phase at about 120 min.

The initial slope of uptake curve a (V_{max}/K_s) does not vary much throughout uptake process, indicating that the uptake rate at low concentrations remains relatively stable independently of the short-time fast uptake. The values of V_{max}, K_s, and a for *U. pertusa* are greater than the corresponding values for *G. tenuistipitata* (Table 7.2).

Table 7.2 Kinetic parameters of ammonium uptake curves measured during separate time intervals in several independent perturbation experiments (from Liu and Dong 2001b)

Species	Time interval (min)	V_{max} [μmolN/(gdw·h)]	K_s (μmol/L)	a [μmolN/(gdw·h)]	R^2
Gracilaria tenuistipitata var. *liui*	0–15	$230 \pm 25.0^{**}$	24.0 ± 7.8	9.6	0.93
	15–30	$120 \pm 14.0^{**}$	11.8 ± 4.1	10.2	0.92
	30–60	$75 \pm 5.0^{**}$	7.0 ± 2.0	10.7	0.95
	90–120	$68 \pm 3.5^{**}$	6.0 ± 2.0	11.3	0.88
	120–240	$35 \pm 1.5^{**}$	2.8 ± 0.8	12.5	0.92
Ulva pertusa	0–15	$340 \pm 26.5^{**}$	31.1 ± 8.4	10.9	0.89
	15–30	$210 \pm 22.7^{**}$	16.6 ± 5.5	12.7	0.96
	30–60	$141 \pm 14.0^{**}$	10.5 ± 2.8	13.4	0.97
	90–120	$96 \pm 6.0^{**}$	7.6 ± 2.3	12.6	0.86
	120–240	$50 \pm 2.1^{**}$	3.8 ± 1.5	13.2	0.94

$^{**}P < 0.01$

7.3.3.1.3 NH_4^+ Uptake and Assimilation during Nitrogen Starvation

On the first day of N starvation, both *G. tenuistipitata* and *U. pertusa* show two phases of fast uptake from 0 to 15 min and assimilative uptake from 120 to 150 min. The uptake rates of both phases increase gradually with increasing concentration of NH_4^+ in medium and come to saturate. At the same time, the uptake rates of both phases increase rapidly with the extent of N starvation. At the approximate in vivo TN level, the uptake rates of both phases of *U. pertusa* are higher than those of *G. tenuistipitata*, indicating the species-specific in uptake kinetic parameters.

In surge uptake phase, the kinetic parameters change correspondingly with the level of TN in seaweed tissues. When TN levels in the tissues of *U. pertusa* decrease from 4.42% to 1.38%, the corresponding maximum uptake rates ($V_{\max}^{s}$) increase from 88.6 to 346 μmolN/(gdw·h). In contrast, when the TN contents of *G. tenuistipitata* decrease from 5.23% to 2.86%, its $V_{\max}^{s}$ increase from 61.8 to 250 μmolN/(gdw·h). Meanwhile, the half-saturation constants (K_s) increase from 9.0 to 31.1 μmolN/L in *U. pertusa* and from 8.1 to 25.6 μmolN/L in *G. tenuistipitata*. The slope a values (i.e., affinity for low concentrations of NH_4^+) remain higher for *U. pertusa* than for *G. tenuistipitata*, with their mean values of 11.2 and 8.94, respectively.

In internally controlled uptake phase, the uptake rates of seaweeds are significantly lower than that of surge uptake phase. The maximum uptake rates in internally controlled uptake phase ($V_{\max}^{ass}$) of *U. pertusa* and *G. tenuistipitata* increase from 41 to 90 μmolN/(gdw·h) and from 28.8 to 60 μmolN/(gdw·h), respectively, as the TN level in the tissues decrease. K_s of the seaweeds in this phase is also lower than in surge uptake phase, increasing from 4.0 to 7.6 μmolN/L in *U. pertusa* and from 3.0 to 5.6 μmolN/L in *G. tenuistipitata*. The slope a values are 11.9 and 10.6 in average for *U. pertusa* and *G. tenuistipitata*, respectively.

The $V_{\max}$ and K_s increase with extent of N starvation in both surge uptake phase and internally controlled uptake phase for *G. tenuistipitata* and *U. pertusa*, particularly in surge uptake phase. The insignificant changes of the same species in a values in both phases suggest that the fast uptake rate does not start at low NH_4^+ concentrations; i.e., the initial fast uptake may only occur at higher external NH_4^+ concentrations.

7.3.3.2 Effects of Temperature and Salinity on Nitrogen Uptake of Seaweeds

7.3.3.2.1 Effect of Temperature and Salinity on Nitrogen Uptake of N-Starved *Gracilaria*

At water temperature of 20 and 25 °C and salinities of 10 ppt and 20 ppt, *G. tenuistipitata* can uptake 99% of NH_4^+-N within 24 h, while it can uptake almost all NO_3^--N in the medium within 24 h. The uptake rates of NH_4^+-N and NO_3^--N by *G. tenuistipitata* are greater at lower salinities (10 and 20 ppt) than those at higher salinities (30 and 40 ppt). Its uptake rates for NO_3^--N are greater at temperature of

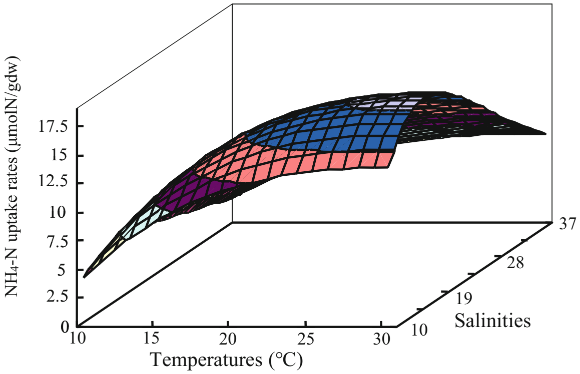


Fig. 7.4 NH_4^+uptake rates of *G. tenuistipitata* var. *liui* at different temperatures and salinities (from Liu and Dong 2001c)

15–20 °C, while its uptake rates for NH_4^+-N are greater at 25–30 °C (Liu and Dong 2001c).

In the first day, the following relationship exists among the relative uptake rate of NH_4^+-N [μmolN/(gdw·h)], temperature (T), and salinity (S):

$$V_{NH_4} = 0.489(S - 4.59)e^{-0.082(S-4.59)}(T - 7.09)e^{-0.045(T-7.09)} \quad (R^2 = 0.878)$$

The relationship among them is shown in Fig. 7.4.

The relationship among the relative uptake rate of NO_3^- -N [μmolN/(gdw·h)], temperature (T), and salinity (S) is

$$V_{NO_3} = 11.81(S - 4.081)(T - 9.221)e^{(-0.1S - 0.148T)} \quad (R^2 = 0.9122)$$

The effect of salinity on the uptake of both forms of inorganic N is similar, but the effect of temperature is somewhat different; i.e., NO_3^- -N uptake is faster at low temperatures and more favorable for NH_4^+-N uptake at high temperatures.

In addition, light, temperature, and their interaction have significant effects on the growth rate of *G. tenuistipitata*. It grows fastest under light of 10,000 Lx and temperature of 25 °C. Light saturation point of its growth increases with increasing temperature within suitable temperature range (Liu and Dong 2001d).

7.3.3.2.2 Effects of Temperature, Salinity, and Light on Nitrogen Uptake of *Sargassum Thunbergii*

Both temperature and salinity have significant effects on the total inorganic nitrogen (TIN) uptake rate of *Sargassum thunbergii* (a brown alga). At salinity of 10 ppt, the TIN uptake rate of the seaweed increases with temperature rise, reaching the maximum at 15 °C (Jiang et al. 2007a). At salinity of 20 ppt, the maximum [11.26 μmol/(gdw·h)] is at 25 °C. At salinities of 30 ppt and 40 ppt, the maximum occurs at higher temperature. The regression relationship among TIN uptake rate [U, μmol/(gdw·h)], temperature (T), and salinity (S) can be expressed as:

$$U = -0.059 + 0.048\,54S + 0.724\,T - 0.004\,32S^2 - 0.023T^2 + 0.011ST\ (R^2 = 0.736)$$

Light intensity influences TIN uptake rates of the seaweed significantly, and the interaction between temperature and light intensity on TIN uptake rates is also significant. At 15 °C, the maximum uptake rate occurs at light intensity of 180 μE/(m^2·s), reaching 10.55 μmol/(gdw·h). However, with the increase of temperature, the maximum uptake rate occurs at lower light intensity. The relationship among the TIN uptake rates [U, μmol/(gdw·h)] of the seaweed, temperature (T), and light intensity [L, μE/(m^2·s)] can be expressed as:

$$U = -13.799 + 2.046\,T + 0.083\,L - 0.049T^2 - 0.000\,3L^2 - 0.002\,T \times L\ (R^2 = 0.747)$$

7.3.4 Kinetics of Phosphorus Uptake of Seaweeds

Phosphorus is not generally considered a limiting nutrient element in sea waters, but in recent years the use of phosphorus-free detergents, among other things, has made phosphorus limiting in certain areas, such as the northwestern Atlantic Ocean and the southern coast of China. *Gracilaria tikvahiae*, growing in Florida, is phosphorus-limited in summer and doubly nitrogen and phosphorus-limited in winter. Studies on phosphorus uptake and growth kinetics in marine phytoplankton have shown that phosphorus uptake is active transport.

7.3.4.1 Theory of Resources Competition

The theory of resource competition was developed mainly on the basis of the Monod and Droop equations. The function of resource-dependent population growth rate [$\mu(R)$] is as follows:

$$\mu(R) = \mu_{\max} S / \left(K_\mu + S\right) \tag{7.1}$$

where $\mu_{\max}$ is the maximal per capita rate (/time) at which the population can grow, and K_μ is the substrate concentration (mass/volume) at which half this maximal growth rate is reached (Fig. 7.5). Two features of Monod equation are biologically reasonable for many populations. First, even if resource availability became infinite, population growth rate would plateau at a finite rate, and second, a principle of diminishing returns (saturation) applies at every resource availability. Successive increases in resource availability cause less than proportional increases in the rate of population growth (Grover 1997).

Tilman (1977) extended the Monod equation to competition among multiple populations for multiple resources (e.g., multiple nutrients). Among the multiple

Fig. 7.5 Graphical explanation of Monod equation (from Grover 1997)

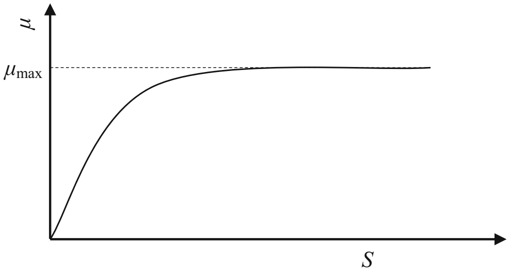
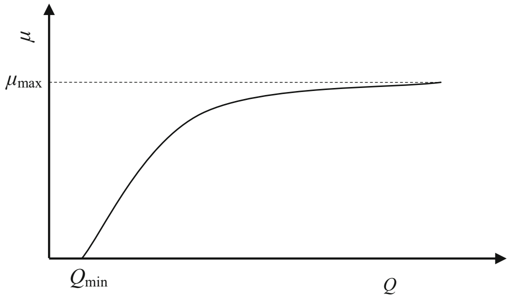


Fig. 7.6 Graphical explanation of Droop equation (from Grover 1997)



resources required by multiple populations, the differential form of the Monod equation for population *i* of *n* and resource *j* of *m* is as follows:

$$\frac{dN_i}{N_i dt} = \min_{j=1,m}\left(\frac{r_i R_j}{k_{ij} + R_i} - D_i\right)$$

$$\frac{dR_j}{dt} = F_j(S_i - R_i) - \sum_{i=1}^{n}\left(\frac{dN_i}{dt} + N_i D_i\right) Q_{ij}$$

where r_i is the maximum growth rate per individual of population *i*; k_{ij} is the half-saturation growth constant of population *i* under the restriction of resource *j*; D_i is the loss or dilution rate per individual of population *i*; Q_{ij} is the amount of resource *j* contained in a unit of population *i*; R_j is the available concentration of resource *j*; S_i represents the maximum possible availability of resource *j* in a habitat, or the inflow of resource *j* in a culture system; F_j is the circulation or supply rate of resource *j*; *n* is the number of populations; and *m* is the number of limiting resources.

Droop in 1968 proposed a population growth (μ) model with limited by quota of resource per individual (Q):

$$\mu(Q) = \mu'_{\max}(1 - Q_{\min}/Q)$$

where $Q_{\min}$ represents a subsistence quota, the value at which population growth ceases. According to equation $\mu(Q)$ is a rectangular hyperbola (Fig. 7.6), intercepting the quota axis at the subsistence quota, and rising to an asymptotic value $\mu(Q)$. This asymptote is an ‘apparent’ maximal growth rate, since it could only be achieved if Q were infinite. In reality, there is a finite maximum for quota, $Q_{\max}$, at which $\mu(Q)$ is truncated, giving a true maximal growth rate $\mu_{\max}$, which is less than $\mu'_{\max}$.

In the Monod equation, let eq. (7.1) be equal to zero to obtain a value for the resource requirements of a population in equilibrium:

$$R_i^* = D_i k_i / (r_i - D_i)$$

where R_i^* is the equilibrium resource availability, i.e., concentration of the limiting resource of i for a population when its growth rate is equal to its death rate. In the case of multiple populations competing for the same abiotic resource, if their resource requirements are ranked as follows:

$$R_1^* < R_2^* < R_3^* < R_4^* \cdots$$

Then according to the Monod equation, population 1 will be able to eliminate other populations in competition, population 2 will be able to eliminate all other populations except for population 1, and so on. This is the R^*-rule of competition for a single abiotic resource in steady state.

In the long term, resource availability goes to the level defined by the lowest R_i^* among the competing populations. If R is below this level, then no population can increase, all decrease, and consequently R increases toward this R_i^*. When R is above this level, at least one population can increase (the one with the lowest R_i^*). Consequently, R decreases, and will do so until it reaches this lowest R_i^*. For R very near R_i^*, the net growth of the superior competitor is near zero – it is approximately at equilibrium – while all other populations have negative net growth and decline. As time goes on, R converges to R_i^* for the superior competitor, which goes to its own equilibrium population density (Grover 1997).

When two or more populations are constrained by more than one abiotic resource, R_i^* value remains an important predictive parameter of competition. When multiple populations are constrained by multiple resources, eq. (7.1) limits the amount of each resource required for each population to maintain equilibrium. Let formula (7.1) be equal to zero, and get:

$$R_{ij}^* = D_i k_{ij} / (r_i - D_i)$$

where R_{ij}^* is the amount of resource j required when the growth rate of population i equals the death rate. This equation shows that for each population, there are as many limiting resources as there are R^* values. This is the competing-resource-ratio hypothesis for two abiotic resources. This equation gives the range of resources within which a population declines, grows, or remains unchanged under two resource constraints.

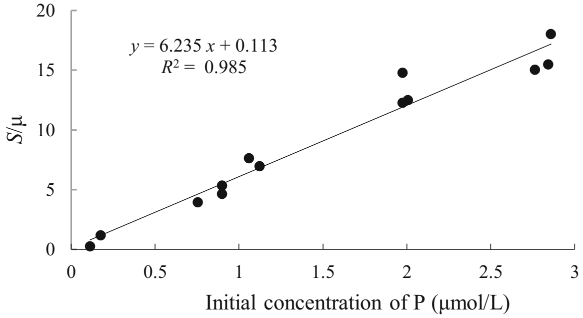


Fig. 7.7 Linear form of the Monod model of *Ulva pertusa*, the initial phosphate concentrations S vs initial phosphate concentrations $S/$ growth rates μ (Nan et al. 2003)

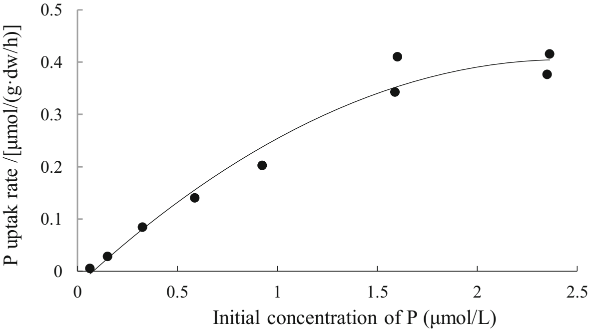


Fig. 7.8 Surge uptake rates of *Ulva pertusa* as a function of phosphate concentrations (Nan et al. 2003)

7.3.4.2 Phosphorus Uptake and Growth Kinetic Parameters of *Ulva*

The relationship of initial phosphate concentrations (S) and growth rates (μ) of *Ulva pertusa* is shown in Fig. 7.7, and the straight line in the figure is the linear form of the Monod equation. Its half-saturation growth constant (K) is 0.016 μmol/L, and its maximum growth rate ($\mu_{\max}$) is 0.16/d (Nan et al. 2003).

Figure 7.8 shows the uptake rate of *U. pertusa* at 60 min of cultivation at different phosphorus concentrations. The relationship between the rate of phosphate uptake by *U. pertusa* and its initial concentration is in accordance with the Monod equation. Its maximum rate of phosphorus uptake ($V_{\max}$) is 3.3 ± 0.6 μmolP/(gdw·h), and the half-saturation constant (K_s) is 5.1 ± 0.85 μmol/L. It can be obtained from the results of the Droop growth experiment that the maximum growth rate ($\mu_{\max}$) of *U. pertusa* is 0.15/d; the cellular subsistence quota ($Q_{\min}$) is 3.0 μmolP/gdw.

7.3.4.3 Effects of Temperature, Salinity, Light Intensity, and N:P on the P Uptake Rate of *Sargassum Thunbergii*

There is a significant annual variation in phosphorus content of naturally growing *S. thunbergii*. Generally, the content, which is usually above 0.25% dry weight, is higher from November to April, with the highest content (0.42%) in February. From May to October, the content (below 0.25%) is relatively low and the lowest value is 0.15% in July (Jiang et al. 2009).

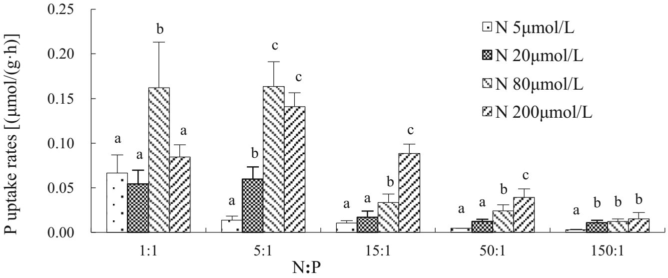


Fig. 7.9 The effects of N:P and N concentrations on P uptake rates of *Sargassum thunbergii* (from Jiang et al. 2007a)

There was a significant interaction between temperature and salinity on P uptake rate of the *S. thunbergii* (Jiang et al. 2007a). In water temperature range of 15–30 °C, the P uptake rate at salinity of 40 ppt is significantly higher than that at other salinities, above 1.5 μmol/(gdw·h). The relationship among P uptake rate [*U*, μmol/(gdw·h)], water temperature (*T*), and salinity (*S*) can be expressed as:

$$U = 0.282 - 0.083S + 0.080T + 0.001S^2 - 0.002T^2 + 0.002ST \quad (R^2 = 0.740)$$

There is an interaction between light intensity and temperature on the P uptake rate of the seaweed (Bao et al. 2008). The maximum rate of P uptake is 1.30 μmol/(gdw·h) at temperature of 25 °C and light intensity of 60 μE/(m^2·s). The relationship between the rate of P uptake [*U*, μmol/(gdw·h)], temperature (*T*), and light intensity (*L*) can be expressed as:

$$U = 0.581 - 0.005T + 0.003L + 0.001T^2 - 0.000\,02L^2 - 0.000\,02TL \quad (R^2 = 0.812)$$

The effects of N:P ratio and N concentration on the P uptake rate of *S. thunbergii* are highly significant, and there is an interaction between N:P ratio and N concentration on the rate. The maximum P uptake rate of 0.16 μmol/(g·h) is achieved at the N concentration of 80 μmol/L and N:P ratio of 5:1 (Fig. 7.9). The maximum N uptake rate of the seaweed occurs at the N concentration of 200 μmol/(g·h) and N:P ratio of 5:1.

7.3.5 Purification of Aquaculture Water by Seaweeds

One of the biggest problems with fed aquaculture systems is 'waste' discharge, so the use of aquatic plants to treat the tailwater of fed aquaculture systems has become the main way to solve this persistent problem. Aquaculture tailwater is rich in dissolved nutrients, such as ammonia and phosphate that can be absorbed by aquatic plants and converted into economic biomass. Meanwhile, the co-cultured aquatic plants can also stabilize DO, pH, and CO$_2$ in the aquatic environment.

Table 7.3 Biological and nutrient uptake parameters of the seaweed species in the experiment (Ashkenazi et al. 2018)

Parameters	*Ulva rigida*	*Gracilaria conferta*	*Hypnea musciformis*
SGR (%/d)	18.27 ± 2.44	10.91 ± 3.29	11.36 ± 2.13
Biomass yield [g/(m^2·d)]	171.28 ± 20.91	94.18 ± 12.83	81.24 ± 48.05
Protein (%)	22.72 ± 1.39	17.7 ± 1.52	25.32 ± 1.25
Total carbohydrates (%)	34.15 ± 2.2	41.48 ± 3.04	48.97 ± 1.3
TAN uptake rate [g/(m^2·d)]	1.6 ± 0.44	0.51 ± 0.27	0.52 ± 0.31
TAN uptake efficiency (%)	100	50	60

Co-culture patterns of macrophytes with fed animals are divided into three categories: partitioned aquaculture systems in ponds, recirculating aquaculture systems, and interculture in large open waters (see Chap. 9 for detail). For the former two systems, the purification effects of the macrophytes are related to plant species, stocking density, water exchange rate daily, etc. For interculture in large open waters, the purification effects are mainly related to the stocking density of fed species and extractive species and distance between them.

Ashkenazi et al. (2018) co-cultured three seaweeds (*Ulva rigida*, *Gracilaria Conferta*, and *Hypnea musciformis*) with the gilthead sea bream (*Sparus aurata*) and compared the water purification effects of the three seaweeds. Results indicated that *U. rigida* was the fastest growing species and displayed the highest total ammonia nitrogen uptake rates and removal efficiency (Table 7.3). The seaweeds integrated in a two-stage system did not inhibit the performance of each individual species and improved overall production.

However, Al-Hafedh et al. (2012) found that *Gracilaria arcuata* grew at a significantly higher rate (2.71% wet weight/d) than *Ulva lactuca* (1.77% wet weight/d), and *G. arcuata* removed 0.45 g/(m^2·d) of total ammonia nitrogen (TAN) with 80.15% removal efficiency and 1.03 g/(m^2·d) of soluble phosphate with 41.06% efficiency. *U. lactuca* removed 0.42 g/(m^2·d) of TAN with 83.06% removal efficiency and 1.07 g/(m^2·d) of soluble phosphate with 41.11% efficiency. Both seaweeds are suitable for integrated aquaculture and bioremediation, but *G. arcuata* has relatively higher growth potential.

Kerrigan and Suckling (2018) conducted a statistical analysis of the interculture of filter-feeding shellfish, seaweeds, and finfish farming in net cages in open seas. The results showed that shellfish cultured in fish-farming net cages or at 1–60 m from the net cages grew significantly faster than those cultured 61 m away from the net cages, but for seaweeds the closer to the net cages the better for growth.

7.4 Interactions between Seaweeds and Microalgae

The use of seaweeds for improving water quality or directly treating tailwater in aquaculture has been introduced previously. In addition, seaweeds can also improve water quality through interactions with microalgae. The function of seaweeds in regulating water quality is achieved by influencing microalgae: (1) by shading the photosynthesis of microalgae; (2) by competing for nutrients; and (3) by allelopathy. The latter two scenarios are described below.

7.4.1 Nutrient Competition between Seaweeds and Microalgae

Traditional ecology considers that logistic growth is a universal rule of population growth. An extension of the logistics equation to competition between two populations results in the Lotka–Volterra model. The Lotka–Volterra model has been used by traditional ecologists as a theory of competition, but its theoretical status has been questioned in recent years. The Lotka-Volterra model has no relationship to any objective conditions other than the density of the two competing populations, and it is therefore difficult to predict experimental results with it. A new theory of competition based on resource consumption was born, that is, a theory of resource competition based on the Monod equation and the Droop equation. The following describes the nutrient competition between seaweeds and microalgae.

7.4.1.1 P Uptake and Growth Kinetic Parameters of Seaweed and Microalgae

At water temperature of 20 °C, light intensity of 140 μE/(m^2·s) and photoperiod of 14-h light: 10-h dark, the parameters of Monod growth kinetic at different PO_4^{3-} concentrations for seaweed *Ulva pertusa* and microalga *Platymonas subcordiformis* are shown in Table 7.4. The half-saturation growth constant and maximum growth rate of *U. pertusa* are 0.016 μmol/L and 0.16/d, respectively, while the corresponding parameters of *P. subcordiformis* are 0.021 μmol/L and 0.83/d, respectively. The half-saturation uptake constants and maximum uptake rates of *U. pertusa* are 5.1 μmol/L and 3.3 μmol/(gdw·h), respectively, and the corresponding parameters of *P. subcordiformis* are 1.5 μmol/L and 5.0×10^{-8} μmol/(cell·h), respectively.

Table 7.4 Phosphorous kinetic parameters for seaweed *Ulva pertusa* and microalga *Platymonas subcordiformis* (from Nan et al. 2003)

Species	μ_m (/d)	*K* (μmol/L)	*f* (/d)	R^* (μmol/L)	*Q* (μmol/(L·cell) or μmol/(L·g wwt)
P. subcordiformis	0.83 ± 0.04	0.021 ± 0.02	0.10	0.003	1.08×10^{-6}
			0.30	0.015	1.76×10^{-6}
			0.50	0.106	1.08×10^{-5}
U. pertusa	0.16 ± 0.03	0.016 ± 0.02	0.05	0.007	1.17
			0.075	0.015	2.31
			0.10	0.031	3.33

Note: μ_m is maximal growth rate, *f* is removal rate, *K* is half-saturation constant, *Q* is subsistence quota, R^* is equilibrium resource availability

Under phosphorus limitation, the maximal growth rate and the subsistence quota are 3.0 μmol P/gdw and 0.17%/d for *U. pertusa*, respectively, and 2.4×10^{-9} μmol P/cell and 0.80%/d for *P. subcordiformis*, respectively. Due to the different morphology of seaweeds and microalgae, they have different calculation units for nutrient uptake rate. Seaweeds usually use uptake rate per gram of dry weight, while microalgae usually use uptake rate per cell, so there is no comparison between them. Therefore, the maximum specific uptake rate can be used to compare the uptake rates between seaweeds and microalgae. Eppley and Thomas (1969) proposed the specific maximum uptake rate $V_{\mathrm{m}}^{\mathrm{sp}} = V_{\max}/Q$, where $V_{\max}$ is uptake rate and Q is subsistence quota. That is, the maximum uptake rate of an alga can be compared on the basis of that element quantity in its cells. By the calculation, the maximum specific uptake rates pf *U. pertusa* and *P. subcordiformis* are 1.1/h and 20/h, respectively; the latter is significantly higher than the former.

7.4.1.2 Competition between Seaweed and Microalgae under Nutrient Limitation

The R^*-rule is the core of resource competition theory. If several populations compete for the same resource and their mortality rates are known, the outcome of the competition can be predicted by calculating R^* value, i.e., the population with the lowest R^* value will win the competition. The effect of competition between seaweed and microalgae can be examined by applying the same or different removal rates (death rates) of *U. pertusa* and *P. subcordiformis*. Figure 7.10 shows the results of the competition between the two species for a removal rate (f) of 0.10/d for both species. Under these conditions, the equilibrium resource availability (R^*) of *P. subcordiformis* is significantly lower than that of *U. pertusa*. Therefore, *P. subcordiformis* always win in nutrient competition and the results are independent of the initial density of algal population.

Figure 7.11 shows the competition results at $f = 0.50$/d for *P. subcordiformis* and $f = 0.05$/d for *U. pertusa*. Under these conditions, the R^* of *U. pertusa* is significantly lower than that of *P. subcordiformis*, and *U. pertusa* will always win in the nutrient competition. A comparison of the Monod model predictions with

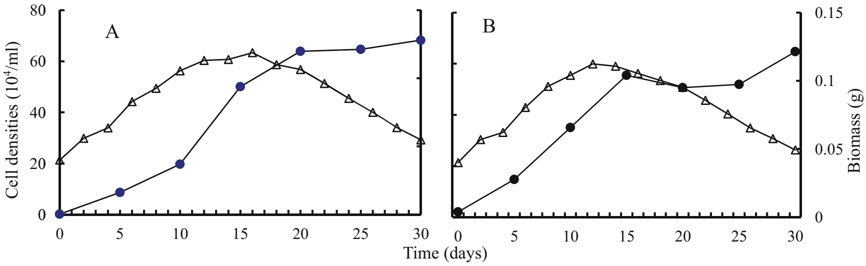


Fig. 7.10 Results of competition experiments at removal rates $f = 0.10$/d for both species (from Nan et al. 2003). (**a**) The initial cell density of *P. subcordiformis* is 2×10^3 cells/mL; (**b**) the initial cell density of *P. subcordiformis* is 2×10^4 cells/mL. The initial biomass of *U. pertusa* is 0.04 g wet weight in A and B experiments. ●- *P. subcordiformis*, △−*U. pertusa*

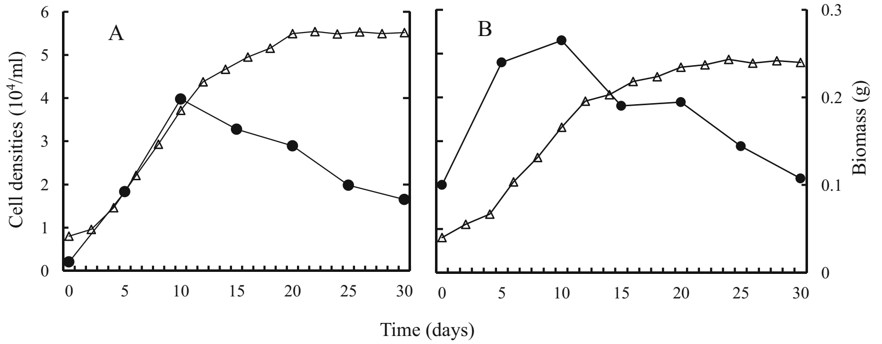


Fig. 7.11 Results of competition experiments at the flow rate (water exchange rate) $f = 0.50$/d for *Platymonas subcordiformis* and 0.05/d for *Ulva pertusa* (from Nan et al. 2003). (**a**) The initial cell density of *P. subcordiformis* is 2×10^3 cells/mL; (**b**) the initial cell density of *P. subcordiformis* is 2×10^4 cells/mL. The initial biomass of *U. pertusa* is 0.04 g wet weight in A and B experiments. ●- *P. subcordiformis*, △ – *U. pertusa*

experimental observations suggests that the Monod model can predict the outcome of competition between seaweed and microalgae only when the difference in R^* between the two is significant.

When competed nutritionally with seaweed *Gracilaria lemaneiformis*, the proliferation of five species of microalgae was significantly inhibited and the competition even led to the death of microalgae (Zhang 2006). Under nutrient-sufficient conditions, 1 g of fresh *G. lemaneiformis* possesses NO_3^- uptake capacity equivalent to 6.0×10^7 cells of microalga *Prorocentrum donghaiense* and possesses PO_4^{3-} uptake capacity equivalent to 2.4×10^7 cells of *P. donghaiense*. Compared with microalgae, *G. lemaneiformis* is more advantageous in uptake of inorganic nutrients. The maximum nitrate uptake rate of a microalga *Scrippsiella trochoidea* is higher than that of *G. lemaneiformis*, so the former can better adapt to low-nitrate environments. In a co-culture system, the latter can also compete with the former because of latter's greater ability to store nutrients (Zhang 2006).

7.4.1.3 *R-K* Selection Rule for Nutrient Competition between Seaweeds and Microalgae

Seaweeds and microalgae have different physiological characteristics and should have different responses and competitive characteristics to different resource supply patterns. According to logistic equation for population growth, any population has two basic parameters, the intrinsic rate of natural increase (r) and the carrying capacity (K). Based on habitat and evolutionary strategies, organisms can be classified into two major groups, r-selectors and K-selectors. In terms of nutrient kinetic parameters, the maximum specific uptake rate of phosphorus and maximum growth rate for microalga *P. subcordiformis* are significantly higher than those for seaweed *U. pertusa*. Comparatively, microalga *P. subcordiformis* belongs to r-selector and seaweed *U. pertusa* belongs to K-selector. Nutrient competition between seaweeds

Table 7.5 The percentages of biomass inhibited or promoted of *Platymonas subcordiformis* and *Ulva pertusa* in co-culture (compared with monoculture) under various phosphorous concentrations and pulses (from Nan and Dong 2004)

P concentration and pulse [μmol/(L·d)]		*P. subcordiformis*		*U. pertusa*	
		1st week	2nd week	1st week	2nd week
0.16	1-day pulse	−14.5	−28.3	+24.1	+27.2
	7-day pulse	−24.1	−38.3	+11.1	+22.2
0.8	1-day pulse	−25.5	−26.8	−9.4	−27.1
	7-day pulse	−21.3	−21.6	−14.8	−37.2
2.4	1-day pulse	−43.2	−58.5	−22.9	−52.8
	7-day pulse	−32.6	−48.7	−28.9	−58.0
5.0	1-day pulse	−32.4	−58.9	−20.0	−46.8
	7-day pulse	−18.7	−56.9	−27.2	−56.8

and microalgae can be seen as a competition between *r*-selectors and *K*-selectors. Table 7.5 shows the percentage of biomass inhibited or promoted in co-culture systems of the two algae at different P concentrations and pulses (Nan et al. 2003). The daily P addition (pulse) is 0.16, 0.8, 2.4, and 5.0 μmol/(L·d), while the weekly P pulse is sevenfold corresponding concentrations mentioned above.

Compared with monoculture, the biomass of *P. subcordiformis* is suppressed and biomass of *U. pertusa* is promoted in the co-culture system at a P concentration of 0.16 μmol/(L·d). When P concentrations are greater than 0.8 μmol/(L·d), their biomasses in monoculture are always greater than that of the corresponding biomasses in co-culture for both algae, regardless of daily or weekly P pulses. The relationship between the two algae shows nutrient competition at these higher P concentrations. As P concentration continued to increase, there is also an increasing tendency for the percentages of mutual inhibition between the two algae.

At P concentrations of 0.16 μmol/(L·d), the percentage of biomass inhibited during weekly P pulse is greater than the amount of daily P pulse for *P. subcordiformis*, whereas at P concentrations greater than 0.8 μmol/(L·d), the percentage of biomass inhibited during weekly P pulse is always less than the corresponding amount of daily P pulse. The opposite is true for *U. pertusa*.

The growth of *U. pertusa* is promoted and growth of *P. subcordiformis* is inhibited in co-culture of the two species at P concentration of 0.16 μmol/(L·d). There are two possible reasons for that. One is due to nutrient 'leakage' from the algal cells (Olsen et al. 1989). At low P concentrations in the environment, *U. pertusa* is able to take up the P 'leaked' from *P. subcordiformis* more efficiently. Another possibility is that there is a secretory interaction between the two algae (i.e., allelopathy, see following section for detail). At P concentrations of 0.8 μmol/(L·d) or more, *P. subcordiformis* proliferates rapidly and may become the dominant.

Pianka (1972) has related the D/S ratio (resource demand/resource supply) to the *r*-*K* selection continuum, suggesting that when resources are scarce, D/S → 1, *K*-selectors dominate; when D/S $<$ 1, *r*-selectors dominate. In above cases, at a P supply concentration of 0.16 μmol/(L·d), the resource demand of *U. pertusa* and

P. subcordiformis is close to the supply, so *U. pertusa* (*K*-selector) gradually dominates the competition; at a P supply concentration of 0.8 μmol/(L·d) or more, the resource supply exceeds the demand, so *P. subcordiformis* (*r*-selector) dominates.

7.4.1.4 Nutrient Competition between Seaweeds and Microalgae at Different Initial Biomass Ratios

The studies of Nan et al. (2003) show that the competition results between *U. pertusa* and *P. subcordiformis* under P restriction are not related to the initial population density (Fig. 7.10 and 7.11). However, Zhang (2006) showed that when initial biomass ratios were relatively low (13.5:1 and 6.7:1), the decrease in cell density of *S. trochoidea* in the co-culture system with *G. lemaneiformis* is due to competition between them for use of NO_3^- in water. When initial biomass ratio is relatively high (33.6:1), besides the competition for nutrients with *G. lemaneiformis*, the growth of *S. trochoidea* was mainly inhibited through direct cell contact.

High densities of *U. pertusa* (10 g/L) significantly inhibited the proliferation of *P. subcordiformis*. However, at lower densities of *U. pertusa* (0.25 g/L), the proliferation rate of *P. subcordiformis* increased with the increase of P concentration (Nan and Dong 2004). Under the high density of *U. pertusa*, the proliferation rate of *P. subcordiformis* and the maximum density it could reach were not significantly affected by P concentration. This experimental observation is not consistent with the results predicted by P uptake and growth kinetic parameters of both species, and it is speculated that there may be an allelopathic effect between *U. pertusa* and *P. subcordiformis*.

7.4.2 Seaweed Allelopathy on Microalgae

There are close linkages and complex interactions among various organisms in aquatic ecosystems, including competition for resources (nutrients, space, light, etc.), selective predation, and allelopathy (Nan and Dong 2004). Allelopathy is a biological phenomenon by which an organism produces one or more biochemicals that influence the growth, survival, and reproduction of other organisms. These biochemicals are known as allelochemicals and can have beneficial (positive allelopathy) or detrimental (negative allelopathy) effects on the target organisms.

Jin et al. (2003) have examined the effect of *U. pertusa* on *Heterosigma akashiwo* and *Alexandrium tamarense* using a co-culture system of seaweed and microalgae and find that the growth of *H. akashiwo* and *A. tamarense* is strongly inhibited by both fresh tissue and dry powder of *U. pertusa*. The allelochemicals are lethal to *H. akashiwo* at relatively higher concentrations. *U. pertusa* culture medium filtrate exhibits no significant growth inhibitory effect on the microalgae under initial or semicontinuous filtrate addition, which suggests that continuous release of small quantities of rapidly degradable allelochemicals from the fresh tissue of *U. pertusa* is essential to effectively inhibit the growth of *H. akashiwo* and *A. tamarense*.

Table 7.6 Inhibitory effects of the fresh tissue (g-wet/L) or the dry powder (g-dry/L) of two strains of *U. pertusa* on *H. akashiwo* or *A. tamarense* represented as the EC_{50} values (from Jin et al. 2003)

Treatments	*H. akashiwo*	*A. tamarense*
Fresh tissue of asexual strain of *U. pertusa*	0.3	2.0
Fresh tissue of sexual strain of *U. pertusa*	0.6	2.5
Dry powder of asexual strain of *U. pertusa*	0.4	0.6
Dry powder of sexual strain of *U. pertusa*	1.0	0.8

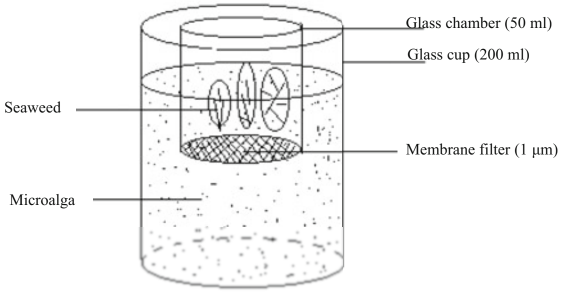


Fig. 7.12 Schematic picture of the isolation co-culture system of seaweed and microalga (from Jin et al. 2003)

The EC_{50} concentration indicates the concentration of seaweed at which normal growth of microalga is 50% inhibited. The EC_{50} concentrations of fresh *U. pertusa* tissue against *H. akashiwo* and *A. tamarense* are 0.6 g/L and 2.5 g/L, respectively (Table 7.6), indicating that fresh *U. pertusa* tissue can inhibit the former more significantly than the latter.

In order to exclude the inhibition to *H. akashiwo* and *A. tamarense* due to direct contact to *U. pertusa*, Jin et al. (2003) made an isolation co-culture system (Fig. 7.12) to separate the microalgae from *U. pertusa*, but the water was exchangeable in the system. The results of the experiment showed that by Day 8 almost all of *H. akashiwo* in isolated co-cultures with *U. pertusa* died (Fig. 7.13a, b), while the growth of *A. tamarense* in isolated co-cultures with *U. pertusa* was significantly inhibited (Fig. 7.13c, d). The results indicate that *U. pertusa* can secrete allelochemicals that inhibit the growth of both microalgae and even kill them.

Fresh tissues of *Ulva pertusa* and *Enteromorpha linza* can also strongly inhibit the growth of *Prorocentrum micans* and all *P. micans* are killed in the presence of higher concentrations of the seaweeds. In contrast, *P. micans* had no significant effect on the growth of these two seaweeds (Jin et al. 2005).

The growths of *H. akashiwo*, *A. tamarense,* and *P. micans* are significantly inhibited by the distilled water extract of *U. pertusa* at relatively higher concentration, and the methanol extract of *U. pertusa* can kill all microalgae at a relatively high concentration. The other three organic solvent (acetone, ether, and chloroform) extracts of *U. pertusa* have no apparent effect on the microalgae. The bioassays and HPLC analysis suggest that the inhibitory substances in *U. pertusa* to the microalgal growth have relatively high polarities. *H. akashiwo* is the most sensitive one while *A. tamarense* is the most tolerant one to the inhibitory substances (Jin et al. 2006).

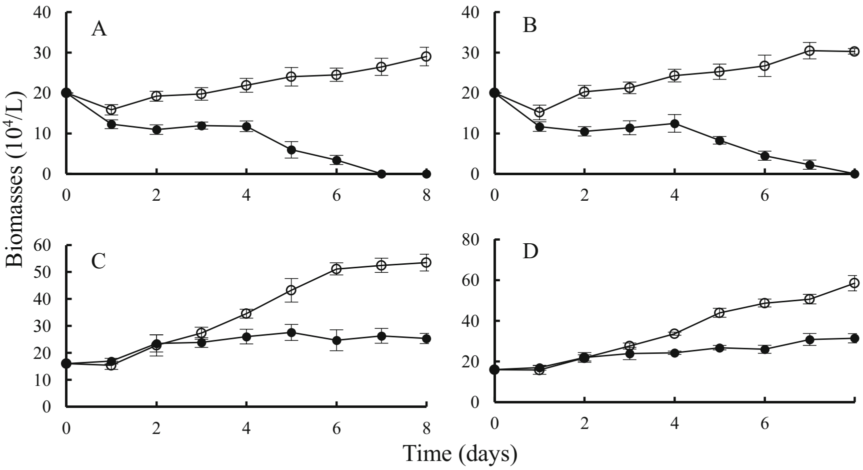


Fig. 7.13 Growth curves of *H. akashiwo* (**a**, **b**) or *A. tamarense* (**c**, **d**) coexisting with the asexual (**a**, **c**) or the sexual (**b**, **d**) strain of *U. pertusa* at the concentration of 2.5 g-wet/L in isolation co-culture assays (from Jin et al. 2003). ○ control; ● isolation co-culture with seaweeds

Further studies shows that the tissues of *U. pertusa* contain a variety of unsaturated fatty acids, some of which have strong algicidal effects on microalgae.

Appropriate temperature (25 °C), lower salinity (10 ppt), higher light intensity [400 μmol/(m^2·s)], and high pH (10) can enhance the allelochemical effect of *U. pertusa* in inhibiting *H. akashiwo*. Nutrient conditions can also significantly affect the allelochemical effect of *Ulva pertusa*. The allelochemical effect of *U. pertusa* in N and P limited environment is weakened.

7.5 Feeding of Filter-Feeding Fish and Bivalves

Co-culture of some filter feeders in aquaculture waters can regulate water quality by non-classical top-down effects. Filter-feeding bivalves, such as oysters and scallops, can filter phytoplankton as small as a few microns, which can significantly reduce phytoplankton biomass. Some fish can directly filter large phytoplankton and colonial phytoplankton (Dong et al. 1992; Dong et al. 1999; Xie 2003), while some others can affect phytoplankton communities indirectly by feeding on zooplankton (Dong 1994).

Filter-feeding bivalves used for water quality regulation in aquaculture waters mainly include oysters, scallops, clams, mussels, and razor clams, while filter-feeding fish used mainly include silver carp, bighead carp, and tilapia. The following introduces the feeding ecology of these bivalves and fishes.

7.5.1 Measurement of Filter Feeders' Feeding

Fish filter plankton by rhythmically stretching and compressing the oropharyngeal cavity to create a stream of water and by using structures such as gill rakers to filter food particles. In contrast, bivalves use gill filaments and cirri to filter food particles from continuously filtered water. In addition to the continuity nature, the plankton size that can be filtered by bivalve is much smaller than that of fish; therefore, the effects of bivalve on water quality regulation is often more obvious and direct than fish.

7.5.1.1 Measurement of Bivalve Feeding

Gills are not only the respiratory organ of bivalves, but also their most important feeding structure. Feeding habits of bivalves are closely related to gill filaments and movement of the cilia on the filaments. The gill filaments of Pacific oyster (*Crassostrea gigas*) and Philippine clam (*Ruditapes philippinarum*) have a denser water-filtering structure than those of bay scallop (*Argopecten irradians*) and Farrer's scallop (*Chlamys farreri*). The order of spacing between gill filaments is Philippine clam < bay scallop < Farrer's scallop < Pacific oyster. The spacing of the first three species are 20–30 μm, and the spacing of Pacific oyster is greater (Wang et al. 1998d).

There are two ways to feed or filter plankton in water for bivalves, i.e., hydrodynamic action and mucociliary action. Suspended particles passing through are mechanically trapped by rows of laterofrontal cilia or cirri and transferred onto the frontal ciliary tracts of the filaments. Particles are then carried in mucus by the frontal cilia to the dorsal or ventral margins of the ctenidia, where they are incorporated into compact mucus strings and transported to the mouth for ingestion via ciliated food tracts. Both mucociliary and hydrodynamic mechanisms function concurrently at different sites on the ctenidial filaments, thereby minimizing particle loss and optimizing particle transport efficiency (Ward et al. 1993). The ways of filter feeding depend on bivalve species, developmental stage, size and concentration of plankton, etc. Bay scallops have a high feeding rate on diatoms of medium size with a high specific gravity and are likely to have a predominant hydrodynamic feeding mechanism, whereas Pacific oysters have a predominantly mucociliary feeding mechanism and can feed and transport smaller-sized phytoplankton more efficiently (Wang et al. 2000).

The feeding of bivalves is often considered to be passive mechanical filter feeding. Some common concepts and mathematical expressions have been formed in bivalve researches. Filtration rate is the volume of water flowing through the gill in a unit of time. Filtering efficiency is the percentage of particles presented to the gill which are cleared from suspension when water flows through the gills once. Clearance rate (*CR*) is that volume of water completely cleared of particles per unit time. When all particles presented to the gill are cleared from suspension, then the *CR* is the same as the filtration rate. Grazing rate (*G*) is the number or weight of microalgal cells ingested by an animal per unit time. Feeding rate (*F*) is the weight or energy of food ingested by an animal as a percentage of the total weight or energy of food in the waters.

Clearance rates (*CR*, ml/ind.) of bivalves can be determined using the equation:

$$CR = v \cdot K = v \cdot \frac{\ln C_0 - \ln C_t}{t}$$

where C_0 and C_t are particle concentration at time 0 and t, v is the volume of water, n is the number of experimental animals, and K is the instantaneous filtration rate.

Feeding rate or ingestion rater (F) of the animal is as follows:

$$F = \frac{C_0 - C_t}{C_0} \times 100\%$$

Grazing rate (G) of the animal is as follows:

$$G = CR \cdot C = F\left(\frac{C_0 - C_t}{2}\right)$$

The average density of food particles can be calculated using the following equation when the food particle grows during an experiment, such as phytoplankton:

$$C = \frac{C_0\left[e^{\left(K_g - K_t\right)t} - 1\right]}{t\left(K_g - K\right)}$$

where Kg is the instantaneous growth rate of the living food particle. The grazing rate in this case is calculated as:

$$G = \frac{C_t K - C_0}{\left(K - K_g\right)t}$$

K_g of the food particle is calculated using the data from the control experiment. Where $K_g = (\ln C_0 – \ln C_t)/t$, C_0 and C_t are the density of food particles at the beginning and end of the control assay, respectively.

7.5.1.2 Measurement of Filter-Feeding Fish Feeding

Planktivorous fish can feed the food particles suspended in water by using either visual processes for identification or non-visual behavior such as filtration. The former feed on particulate matter by using visual cues. Many fishes at larvae stage are zooplanktivore that feed on zooplankton one at a time, or no more than a few at a time. Filtration is designed to trap the larger particles of the total size range by the structure of the gill rakers. Food particles will be trapped in the meshes of the gill rakers while the smaller particles pass through and are expelled through the opercular opening.

Filter feeders can be divided into ram or tow-net filterers and pump filterers. The former swims with mouth agape and opercles flaring. Water flows into the buccal cavity and out the opercular openings. The spaces between the gill rakers presumably behave like the pores of a sieve. Ram filtration is not a continuous process. For instance, herring (*Clupea harengus*) drives forward for 0.4 s and resumes 0.4 s later, when feeding heavily (Gerking 1994). The latter pumps water into the buccal cavity by a series of suctions while the fish is stationary. The buccal cavity expands quickly and the opercles flare to expel water after the cavity has filled.

Many farmed fishes such as silver carp, bighead carp, and tilapia are pump filter feeders. Some fish species such as tilapia can change their feeding habits according to the composition, size, and density of food particles. When there are abundant plankton and lack of other food source, tilapia can shift their feeding habits from particulate feeding to pump filter feeding (Gerking 1994).

Tow-net filter feeders swim fast, so the escape movement of zooplankton or nekton has little effect on their feeding. In contrast, the feeding of pump filter feeders is sensitive to the escape movement of zooplankton.

Grazing rate (G) of pump filter feeder on phytoplankton can be expressed by the following equation:

$$G = B \cdot f \cdot D \cdot E \cdot x$$

where B is suction volume, i.e., the water volume passing through the oropharyngeal cavity of the fish in one filtering or respiratory stroke or beat (ml/stroke); f is filtering frequency of the fish (times/min); D is the density of food particles (ind./ml); E is filtering efficiency, i.e., the percentage of particles presented to the gill are cleared from suspension when water flows through the gills; and x is the daily feeding rhythm factor, i.e., the time percentage of the day that is spent on feeding.

For filtering zooplankton:

$$G = B \cdot f \cdot D \cdot E \cdot x \cdot P$$

where P is the probability that the zooplankton will be sucked by the fish, which is related to evasion ability of zooplankton.

Clearance rate (F_C) and the filtration rate (F) of the fish can be calculated using the following equations:

$$F_C = V(\ln C_0 - \ln C_t)/t$$
$$F = V(\ln C_0 - \ln C_t)/(t \cdot E)$$

where C_0 and C_t are the densities of food particles at the beginning and end of the experiment, respectively; V is the volume of experimental water; and t is the duration of the experiment. The feeding and water filtration of pump filter feeder of fish can also be calculated as described below:

$$C_t = C_0(1 - B \cdot E/V)^n = C_0(1 - B \cdot E/V)^{f \cdot t}$$

where n is the filtration times of the fish during the experiment.

$$\text{Filtration rate}\ \ F = B \cdot n/t$$
$$\text{Grazing rate}\ \ G = F \cdot C \cdot E$$

where C is the density of food particle.

7.5.2 Feeding Capacity of Filter-Feeding Feeders

7.5.2.1 Feeding Capacity of Bivalves

Different species and sizes of bivalves filter different sizes of food particles with different clearance rates, and their impact on water quality of aquaculture waters vary also.

7.5.2.1.1 Selectivity and Clearance Rates of Food Particles by Bivalves

The clearance rates of small-size (imperfectly developed) bay scallops and small-size oysters increase with increasing algal size, while the clearance rates of large-size (well-developed) bay scallops and large-size oysters show significant differences (Wang et al. 2000). For example, large bay scallops are more selective for medium-sized [equivalent spherical diameter (ESD) = 5.55–5.79 μm] algae, while large Pacific oysters are more selective for small-sized (ESD = 4.35 μm) algae (Table 7.7).

Clearance rates of small size (0.23 ± 0.04 g) and medium size (0.40 ± 0.21 g) razor clams also increase with increasing size (ESD) of microalgae (from 4.46 to 8.83 μm). However, the clearance rate of large-size razor clam (2.35 ± 0.25 g) on microalga (*Chlorella* sp., 0.45 μm) is higher than that of small- and medium-size individuals (Fan et al. 2002b).

Morphological observations show that the outer sides of gill filaments of large bay scallops and Pacific oysters are covered with dense terminal and lateral cirri. The distance between these cilia is less than 1 μm, which determines their ability to filter food particles as small as 1 μm. Smaller size bay scallop and Pacific oyster exhibit less efficient filtering of smaller-sized algae due to underdeveloped and sparse gill filaments.

If bay scallop and Pacific oyster rely solely on gill filaments and cilia to passively and mechanically filter food, it is inevitable that the clearance rates will increase as

Table 7.7 Clearance rates (%) of *Argopecten irradians* and *Crassostrea gigas* on microalgae of different sizes (from Wang et al. 2000)

Bivalves and sizes (mm in shell length)		Algae sizes (μm, ESD)			
		4.35	5.55	5.79	11.6
A. irradians	14–15	4.21 ± 0.50	7.24 ± 1.23	11.9 ± 0.08	11.0 ± 0.34
	50–53	14.9 ± 1.50	31.6 ± 0.81	35.1 ± 3.40	25.5 ± 1.36
	61–63	23.3 ± 1.66	32.5 ± 1.29	28.8 ± 1.66	17.7 ± 1.50
C. gigas	16–25	0.81 ± 0.03	1.98 ± 0.56	3.04 ± 0.03	3.15 ± 0.09
	65–70	10.1 ± 1.87	31.3 ± 0.80	12.5 ± 1.94	11.1 ± 1.62
	77–90	97.3 ± 2.50	79.3 ± 3.62	67.7 ± 9.57	35.6 ± 3.40

Table 7.8 Effects of temperature on the clearance rates of *A. irradians* and *C. gigas* [mL/(g·min)] (from Wang et al. 2000)

Species and sizes		Temperatures (°C)			
		20	23	26	29
A. irradians	Small	71.8 ± 23.4	99.8 ± 12.1	128.9 ± 27.3	86.6 ± 24.7
	Medium	3.81 ± 0.42	8.94 ± 1.39	12.9 ± 4.54	14.8 ± 5.80
C. gigas	Small	50.3 ± 6.14	119.6 ± 25.8	159.5 ± 21.3	106.9 ± 11.8
	Medium	11.6 ± 0.20	12.7 ± 0.50	21.8 ± 0.88	18.0 ± 0.80

the size of the algae increases. The selectivity of the larger size bivalves (Table 7.7) suggests that there must be a feeding mechanism other than mechanical passive filter feeding for both species.

Clearance rates of bivalves are significanlty influenced by water temperature. When water temperature increases from 20 to 26 °C, the clearance rates of both small- and medium-size bay scallops and oysters increase. When water temperature further increases from 26 to 29 °C, the clearance rates is slightly increase for medium-size bay scallops and decrease for the others (Table 7.8).

Clearance rate (*CR*) versus water temperature (*T*) for bay scallop and Pacific oyster at temperature range of 20–29 °C can be expressed by the following equation:

Bay scallop

$$\text{Small}-\text{size}\quad \ln CR = 0.0483T + 3.319 \quad r = 0.60 \quad n = 16 \quad P < 0.01$$

$$\text{Medium}-\text{size}\quad \ln CR = 0.143T - 1.347 \quad r = 0.85 \quad n = 12 \quad P < 0.01$$

Pacific oyster:

$$\text{Small}-\text{size}\quad \ln CR = 0.081T + 2.262 \quad r = 0.64 \quad n = 16 \quad P < 0.01$$

$$\text{Medium}-\text{size}\quad \ln CR = 0.062T + 1.227 \quad r = 0.75 \quad n = 12 \quad P < 0.01$$

7.5.2.1.2 Effect of Microalgal Density on Clearance Rate of Bivalves

The clearance rates of small-size Pacific oysters (shell length of 17–33 mm) increase with increase of microalgal (*Nitzschia closterium*) density from 2.5 × 10^6 to 7.5 × 10^6 ind./L (Fig. 7.14). The clearance rates of small-size bay scallops (shell length of 15–18 mm) increase with increase of algal density from 0.5 × 10^6 to 5 × 10^6 ind./L (Wang et al. 1998f).

The response of large-size bay scallops and Pacific oysters to increased microalgal density is different. The clearance rates of large-size Pacific oyster (shell length of 60–75 mm) increase with the increase of microalgal density from 2.5 × 10^6 to 10 × 10^6 ind./L, and a decrease occurs at the algal density of 20 × 10^6 ind./L. The clearance rates of large-size bay scallops (shell length of 45–53 mm), on the other hand, exhibit an increase with the increase of algal density from 5 × 10^6 to 20 × 10^6 individuals/L (Wang et al. 1998f).

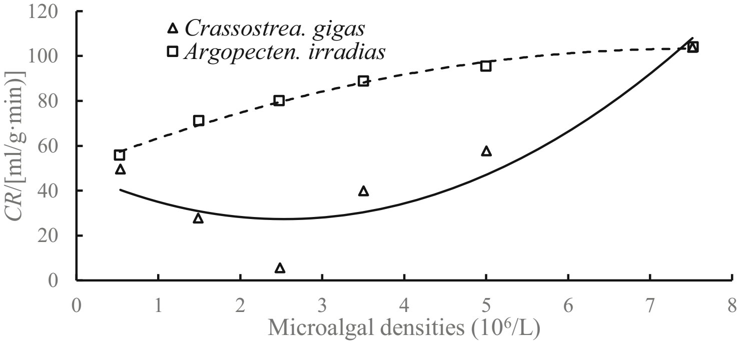


Fig. 7.14 Effect of microalgal densities on the clearance rates of *A. irradians* and *C. gigas* (from Wang et al. 1998f)

Table 7.9 Temperature with the maximum clearance rate (*CR*) in several bivalves

Species	Temperature (°C) with the maximum *CR*	References
Razor clam (*Sinonovacula constricta*)	20	Pan et al. (2002)
Philippine clam (*Ruditapes philippinarum*)	22	Dong et al. (2000a)
Farrer's scallop (*Chlamys farreri*)	24	Yuan et al. (2000)
Pacific oyster (*Crassostrea gigas*)	26	Wang et al. (2000)
Bay scallop (*Argopecten irradians*)	29	Wang et al. (2000)

7.5.2.1.3 Influence of Environmental Factors on Clearance Rates of Bivalves

The clearance rates of razor clams show a peak change from 15 °C to 30 °C, and the highest value is obtained at 20 °C. As the size of razor clams increases from 3.92 ± 0.27 cm to 6.25 ± 0.48 cm, the clearance rates of the clams increase (Pan et al. 2002).

Table 7.9 shows the temperature in which maximum clearance rate occurs for several farmed bivalves. As can be seen, bay scallop and Pacific oyster are more tolerant of high temperature, while razor clam, Philippine clam, and Farrer's scallop are slightly less tolerant of high temperature than other two species.

In the salinity range of 6–30 ppt, the clearance rate of razor clam gradually increases with increasing salinity, and the variation in clearance rate is greater in the salinity range of 14–22 ppt. The clearance rates of razor clam show a peak change from pH 6 to 9, with a maximum at pH 8 (Pan et al. 2002).

7.5.2.2 Feeding Capacity of Filter-Feeding Fish

The feeding capacity of filter-feeding fish on different food particles is a biological property of the fish themselves. Filter-feeding fish have three extremely important biological parameters of feeding, i.e., suction volume (*B*), filtering frequency (*f*), and filtering efficiency (E). The product of the three parameters is just an excellent indicator of feeding capacity (FC) of filter-feeding fishes (Dong and Li 1994b), i.e.

$$FC = B \cdot E \cdot f$$

Grazing rate (G) is the product feeding capacity and food particle density, i.e.

$$G = FC \cdot D$$

7.5.2.2.1 Suction Volume of Filter-Feeding Fishes

Suction volume (B) of pump filtering fishes is the water volume in one filtering stroke (ml/stroke). It can be measured or estimated by the methods of gypsum filling (Drenner et al. 1982), respiratory chamber (Yamamoto et al. 1988), and the changes of experimental food particle density (Dong et al. 1992).

Yamamoto et al. (1988) have measured the B of common carp by respiratory chamber method, and Dong et al. (1992) have determined the B of 1^+ age of silver carp and bighead carp (standard body lengths of 15.1–25.1 cm and 13.2–26.5 cm, respectively) by the respiratory chamber, with the following results:

$$B_\mathrm{h} = 0.561L - 8.94$$
$$B_\mathrm{a} = 0.627L - 7.48$$

where B_h and B_a are suction volumes of silver carp and bighead carp, respectively (ml/stroke); L is the body length (cm) of the fishes.

Chen et al. (1999) have measured the suction volume and filtration rate (F) of 1^+ age tilapia (standard body length 7.9–19.4 cm) by the respiratory chamber, and the results are as follows:

$$B_\mathrm{O} = 0.2633L - 2.147$$
$$F_\mathrm{O} = 4.232L - 11.00$$

The suction volumes of small-size silver carp and bighead carp (standard body lengths of 5.6–11.0 cm and 8.3–14.3 cm) are also determined by using the method of the changes of experimental food particle density (Dong et al. 1992):

$$B_\mathrm{h} = 0.107L - 0.837$$
$$B_\mathrm{a} = 0.157L - 0.418$$

The filtering frequency of silver carp (f_h) and bighead carp (f_a) is related to water temperature (T) and standard body length (L) as follows:

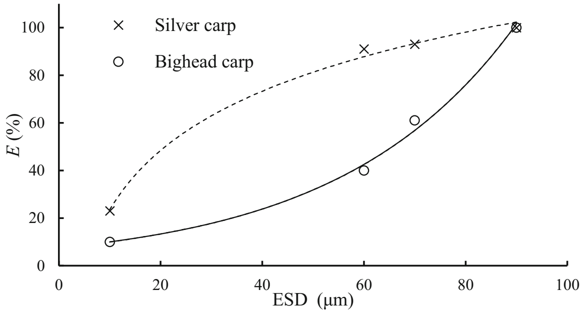


Fig. 7.15 Filtering efficiencies (*E*) of silver carp and bighead carp for different food particles. *ESD* equivalent spherical diameter (Dong and Li 1994a)

$$f_h = 2.15T - 2.37L + 52.99$$
$$f_a = 1.27T - 2.89L + 71.55$$

Above measurements show that the suction volume of bighead carp is larger than that of silver carp for the same size, while the filtering frequency of silver carp is greater than that bighead carp.

7.5.2.2.2 Filtering Efficiency of Silver Carp and Bighead Carp

The filtering efficiency of pump filer fish for a specific food particle can be determined by the methods of gill rake spacing, graphical calculation (Smith 1989), respiratory chamber (Dong et al. 1992), and changes of experimental food particle density (Dong and Li 1994a). Figure 7.15 shows the relationships between the filtering efficiencies and food particle sizes of silver carp and bighead carp (Dong and Li 1994a).

The filtering efficiencies of both silver carp and bighead carp on small-size food particles are low. The filtering efficiencies of silver carp on 10–60 μm food particles are significantly higher than those of bighead carp. The filtering efficiencies of both carps on 90 μm of rotifers are equal to 100%. The filtering efficiencies of silver carp (E_h) and bighead carp (E_a) are related to the equivalent spherical diameter of food particles (ESD, μm):

$$E_h = 35.85 \ \ln\mathrm{ESD} - 59.00 \ (R^2 = 0.9959)$$
$$E_a = 7.443\mathrm{e}^{0.029}\mathrm{ESD} \ (R^2 = 0.9969)$$

7.5.2.2.3 Evasion of Zooplankton from Fish Feeding

Active evasion of zooplankton often occurs when fish prey on them. The evasion can reduce the probability (*P*) of fish preying on the zooplankton. Drenner et al. (1986) use a suction tube to simulate fish pumping and determine the sucked probability for different zooplankton at different pumping distances. The followings are the sucked probabilities at a distance of 1 cm.

Ceriodaphnia reticulata	0.96
Daphnia galeata mendotae	0.92
Daphnia pulex	0.76
Diaphanosoma brachyurum	0.49
Mesocyclops spp.	0.28
Cyclops scutifer	0.24
Diaptomus pallidus	0.07
Chaoborus sp.	0.09

It can be seen that the probabilities for cladocerans are above 49%, and the probabilities for copepods are below 30%. Since rotifers and the larvae of cladocerans and copepods are weak in swimming, their probabilities being sucked by fish increase significantly to about 100%.

7.5.2.2.4 Feeding Capacity of Filter-Feeding Fish

The suction volume of bighead carp is larger than that of silver carp of the same size, while the filtering frequency of silver carp is greater than that of bighead carp (Table 7.10). Feeding capacity of bighead carp on large zooplankton (such as 90 μm of rotifer) is greater than that of silver carp; however, the opposite is true for food particles smaller than 70 μm. The two species of fish have similar feeding capacity on food particles of about 70 μm (Dong and Li 1994b).

Because the ratio of phytoplankton to zooplankton is less in large inland waters, such as large reservoirs (see Sect. 2.5.1, Dong et al. 1989b), than that in small waters, and the feeding capacity of bighead carp on zooplankton is greater than that of silver carp, more fingerlings of bighead carp than silver carp are usually stocked in large waters. On the contrary, silver carp should be stocked more in small waters, such as ponds.

Table 7.10 Comparison of feeding capacities (FC) between silver carp and bighead carp (body length = 8.0 cm at temperature of 25 °C) (from Dong and Li 1994b)

Species	f (Times/min)	B (ml/stroke)	$f \cdot B$	ESD (μm)	E (%)	FC
Silver carp	87.8	0.52	45.7	10	23	1050
				60	91	4160
				70	93	4250
				90	100	4570
Bighead carp	80.2	0.84	67.4	10	10	670
				60	40	2700
				70	61	4120
				90	100	6470

Note: B suction volume, E filtering efficiency, *ESD* equivalent spherical diameter of food particles, f filtering frequency

7.5.3 Feeding Rhythms and Food Selectivity of Filter-Feeding Fish

7.5.3.1 Feeding Rhythms of Silver Carp and Bighead Carp

Feeding rhythms, including diurnal and annual rhythms, are important parameters in feeding ecology of filter-feeding fish. As mentioned above, an accurate understanding of their feeding rhythms allows for precise setting of their feeding rhythm parameters (x) and thus better calculation of their daily or annual grazing rates. Annual rhythm of feeding is related to water temperature, while diurnal feeding rhythm of filter-feeding fish is related to biological clock and some environmental factors.

Methods for studying feeding rhythms of filter-feeding fish can be broadly classified into three categories: field analysis of fish intestinal food, flow-through chamber experiment, and hydrostatic experiment. Li et al. (1980), Xie (1989), and Wang (1989) have studied the feeding rhythms of silver carp in ponds using intestinal food analysis. They all proved that silver carp starts feeding after dawn, with a peak feeding period before dark and a period of non-feeding after midnight. By using flow-through chamber experiment, Herodek et al. (1989) found that silver carp was still feeding after midnight but relatively weak.

In ponds or lakes, light, water temperature, and dissolved oxygen all have their own daily rhythms of variation and are so intertwined to make it impossible to tell who is the dominant factor affecting the feeding rhythm of the fish. In contrast, controlled experiments indoors can achieve factor-by-factor analysis. Wang et al. (1993) studied the effects of water temperature and light on the feeding rhythm of silver carp using an indoor controlled hydrostatic experiment. The results showed that the feeding rhythm of silver carp was generally consistent regardless of temperature and light variation, which implies that the biological clock in the fish plays an important role in controlling the diurnal feeding rhythm.

7.5.3.2 Food Selectivity of Silver Carp and Bighead Carp

Food selectivity is a very important biological property of filter-feeding animals. The selectivity of filter-feeding fish for food can be divided into selectivity for specific food particles (food particle selectivity) and selectivity for specific feeding areas (feeding area selectivity).

Silver carp and bighead carp cannot selectively filter their ‘preferred’ species in the water with evenly distributed plankton. Their selectivity for food particles is only based on the size of food particles; i.e., the filtering efficiency of filter-feeding fish increases as the size of food particles increases (Fig. 7.15). Food particle selectivity of filter-feeding fish, therefore, is a passive selectivity based on the structure of their gill rakers in the water with evenly distributed plankton. However, when food organisms are unevenly distributed in the water, both silver carp and bighead have the ability to actively swim to zooplankton-rich areas to feed, i.e., feeding area selectivity (Dong and Li 1994a). Both carps are more selective for zooplankton than for phytoplankton, and bighead carp seems to have more feeding area selectivity than silver carp.

Observations on their feeding behavior also reveal that feeding area selectivity is the selectivity based on their gustatory abilities, which is also supported by histological studies; i.e., there are dense taste buds on the epidermis of filtering organs (Li and Dong 1996).

7.5.3.3 Effects of Food Organism Composition and Inorganic Particles in Water on the Feeding Habits of Silver Carp and Bighead Carp

Numerous studies have shown that the intestinal food compositions of silver carp and bighead carp vary greatly among waters, but it is clear that bighead carp consume more larger zooplankton than silver carp (Xie 2003). In addition, Kajak et al. (1975) and Chen (1982) have reported that intestinal food compositions of silver carp and bighead carp are generally consistent with the compositions of the phytoplankton community in their habitats; i.e., plankton composition in water column plays a decisive role in feeding habits of the fish, or the passive food particle selectivity is the main mechanism of their feeding.

After reviewing the studies about the foregut contents of silver carp and bighead carp in past 50 years, Xie (2003) and Liu and Huang (2008) conclude that both carps can feed on phytoplankton, zooplankton, and detritus. Silver carp feeds mainly on phytoplankton, while bighead carp feeds mainly on zooplankton. For a specific waters, the feeding habits of the fish are influenced by their feeding capacity, feeding selectivity, and food organism composition of the waters.

If passive food particle selectivity is the only mechanism, the particle size ingested by silver carp and bighead carp should be no less than 11 μm and 33 μm, respectively. This is because the spacing between the gill rakers or lateral protrusions of silver carp and bighead carp are 11–19 μm and 33.7–41.25 μm, respectively (Liu and Huang 2008). However, we often see phytoplankton smaller than 10 μm in the foregut of the fish caught in lakes, reservoirs, or ponds, suggesting that the two species should possess other feeding mechanisms.

Dong and Li (1994c) have ever conducted an experiment and found that the clearance rate of silver carp for *Chlorella pyrenoidosa* (3.2 ± 0.4 μm in ESD) alone is only 7.6 ± 1.65%/4 h, while the clearance rate for *C. pyrenoidosa* increases to 17.9 ± 6.46%/4 h after adding *Chlamydomonas reinhardtii* (10.0 ± 0.12 μm in ESD) and *Pandorina morum* (19.6 ± 4.78 μm in ESD) into the experimental waters. The clearance rate of the fish for *C. reinhardtii* alone is only 31.7 ± 3.96%/12 h, while it increases to 50.2 ± 11.8%/12 h after adding *P. morum* into the waters. Silver carp could feed on a certain amount of *Chlorella ellipsoidea* (6.8 ± 1.3 μm in ESD) when there is *Pandorina morum* co-existed in water (Zhao and Dong 2017). This feeding mechanism of filter-feeding fish can be called ‘crowding effect’ or ‘blocking effect’ (Dong and Li 1994c).

The presence of inorganic plankton, such as soil particles, in water can also cause a ‘crowding effect’ that increases the clearance rate of silver carp on small-size phytoplankton. For example, adding some fine soil particles into experimental water will significantly increase the clearance rate of silver carp on microalga *Scenedesmus obliquus* (Dong and Li 1994c).

Both silver carp and bighead carp have sacculus pharyngeals and palatal folds as well as abundant mucous cells. Therefore, it is believed that there is ‘sink feeding’ mechanism in those carps. The process is similar to the mucociliary action of bivalve feeding (Ward et al. 1993), to feed small-size phytoplankton (Li and Dong 1996).

7.5.4 Relationship between Feeding and Respiration of Filter-Feeding Fish

In general, fish respiration is independent of their feeding process, but filter-feeding fish combine respiration and feeding due to their special structure of filter-feeding organ. The feeding activity of filter-feeding fish can affect water quality by influencing the quantity and structure of plankton community in waters, while the respiration activity of the fish will consume dissolved oxygen and produce CO_2 to affect water quality.

7.5.4.1 Relationships between Feeding and Respiration of Silver at Low Dissolved Oxygen Levels

Silver carp and bighead carp are typical filter-feeding fish and are widely used as regulators of water quality in aquaculture waters. However, their relative respiratory surface area (total gill lamellae area/body weight) is about an order less than that of common carp, causing the carps less tolerant of low oxygen than common carp (Dong et al. 1989a; Wang and Dong 1990). In addition, there is a diurnal rhythm of dissolved oxygen (DO) fluctuation in aquaculture waters rich in planktonic biomass, so it is important to understand the relationship between respiration and feeding of filter-feeding fish under low DO conditions.

In the absence of phytoplankton, respiratory frequency (f), suction volume (B), gill ventilation (V_G, i.e., product of f and B), and oxygen extraction efficiency (EO_2, the percentage reduction of water DO content before and after respiration) of silver carp vary insignificantly in a DO range of 5.43–7.73 mg/L; when the DO level declines to 4.40 mg/L, the f, B, and V_G of the fish increase significantly, but EO_2 decreases significantly; and oxygen consumption rate (VO_2) of the fish reaches the highest value when DO level declines to 2.21 mg/L (Zhao et al. 2011b).

When phytoplankton is present in the water, and DO decreases from 7.73 mg/L to 3.37 mg/L, the f, B, V_G, and VO_2 of silver carp increase significantly, and EO_2 decreases; when DO decreases to 2.21 mg/L, V_G/VO_2 ratio increases significantly, and the fish starts to show hypoxic response.

When DO level is greater than 3 mg/L, hungry silver carp shows ‘active feeding and passive respiration’, i.e., higher V_G, higher clearance rate, and stable VO_2; when DO level is lower than 3 mg/L, the fish shows ‘passive feeding and active respiration’, i.e., a surge in V_G, a decrease in filtering efficiency (E), and an ‘anti-filtration response’ (the phytoplankton accumulated in the gill rakers of the fish are ejected from the oropharyngeal cavity by a violent coughing response) occurs sometime.

7.5.4.2 Effect of Phytoplankton Density on Feeding and Respiration of Silver Carp

When *P. morum* density in experimental water increases from 0 to 23.8 mg/L, the *f*, *B,* and V_G of silver carp increase only slightly, indicating that the fish is not sensitive to low density of phytoplankton. When the phytoplankton density increases to 63.3 mg/L, the *f* and V_G of the fish increase significantly and show a strong feeding response. Thereafter, with further increases in phytoplankton density, the feeding response of the fish begin to diminish gradually, indicating that the fish is able to reduce filter feeding by regulating V_G in higher phytoplankton density environment (Zhao et al. 2014).

However, with the further increase of phytoplankton density, the regulation of V_G is no longer sufficient to reduce the intake of phytoplankton, and the phytoplankton passively filtered into the oropharyngeal cavity increases gradually accompanied by respiratory movements. When the phytoplankton density increases to 138 mg/L, the anti-filtration response occurs. With further increase in phytoplankton density, the time interval of anti-filtration responses of the fish is gradually shortened.

Anti-filtration response of filter-feeding fish is an essential process of cleaning gill rakers and gill filaments, which can recover the normal feeding and respiratory functions of gill rakers and gill filaments of the fish. Thus, the ‘anti-filtration response’ is another adaptive strategy of filter-feeding fish in addition to regulating V_G to reduce feeding. The pseudofeces of bivalves may serve a similar function as the anti-filtration response of the fish.

The indicator of V_G/VO_2 can be used to characterize the transfer efficiency of DO by fish gills. As the phytoplankton density increases, the V_G/VO_2 of silver carp shows a trend of increase and then decrease, with a peak at about 63.3 mg/L of phytoplankton density (Fig. 7.16). The EO_2 of the fish shows the same trend as V_G/VO_2, but the V_G shows the opposite trend with increasing phytoplankton density. EO_2 increases significantly with phytoplankton density increasing from 138 to

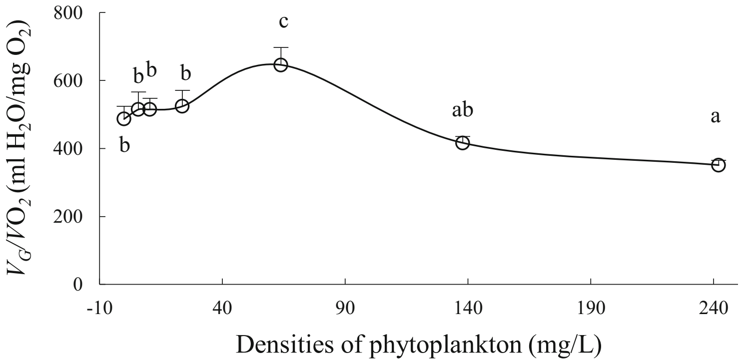


Fig. 7.16 Water convection requirement (V_G/VO_2) of silver carp at different phytoplankton densities (from Zhao et al. 2014)

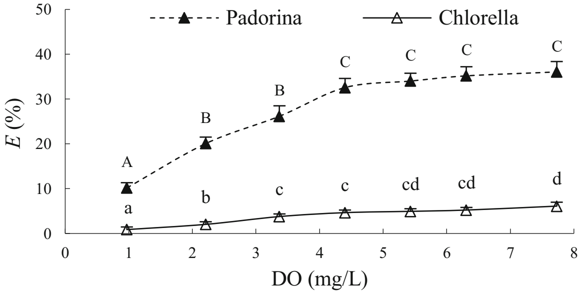


Fig. 7.17 Filtering efficiencies (*E*) of silver carp on different size of phytoplankton at different DO levels (from Zhao and Dong 2017)

242 mg/L, indicating that silver carp can meet normal DO demand by increasing EO_2 while reducing filter feeding in the waters with high-density phytoplankton.

7.5.4.3 Effects of Phytoplankton Sizes on Feeding and Respiration of Silver Carp

When DO level decreases from 7.49 to 0.98 mg/L, the *f* of silver carp fed with *P. morum* (20.1 ± 4.6 μm in ESD) or *C. ellipsoidea* (6.8 ± 1.3 μm in ESD) increases from 59 to 66 times/min or from 68 to 80 times/min, respectively. And the increase of the latter is higher than the former (Zhao and Dong 2017). The grazing rates of the fish for both sizes of phytoplankton decrease significantly with decreasing of DO; however, the grazing rate of the fish for *P. morum* is significantly higher than that for *C. ellipsoidea* at each DO level due to the higher filtering efficiency (*E*) of the fish for *P. morum* (Fig. 7.17).

7.5.4.4 Effects of Starvation on Feeding and Respiration of Filter-Feeding Fish

Starvation as a physiological state is prevalent in natural fish and also occurs often in aquaculture. Usually, filter-feeding fish exhibit active feeding when hunger. In non-starvation conditions, however, filter-feeding fish may breathe while engaging in passive filter feeding. Under low DO conditions, fish usually adjust their physiological functions to cope with DO deficiency, and their feeding strategies may also change accordingly. Tsadik and Kutty (1987) have proved that the utilization of artificial pellet feed by filter-feeding tilapia is significantly reduced during low DO period in water. Zhao et al. (2018) have also proved that under the conditions of 5.28–7.43 mg/L DO hungry silver carp are very sensitive to the presence of *C. ellipsoidea*, and its *f*, V_G, and V_G/VO_2 are all significantly higher than those of non-starved individuals.

The V_G of silver carp is greater during active feeding and the energy cost will be higher. Therefore, the VO_2 of hungry silver carp is significantly higher than that of non-starved fish under normoxic conditions. When DO level drops below 3.17 mg/L, the *B*, V_G, V_G/VO_2, and EO_2 of both hungry and non-starved individuals increase significantly and show a hypoxic response. When DO level further decreases to 1.90 mg/L, the VO_2 of the fish reaches the highest value, indicating that the potential

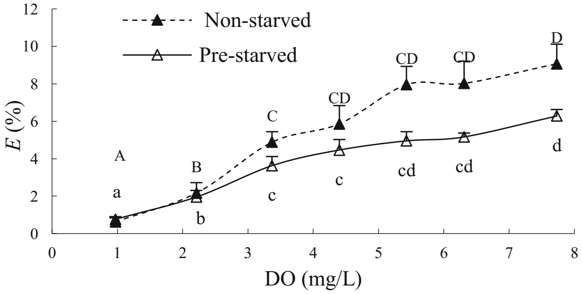


Fig. 7.18 Filtering efficiencies (E) of silver carp at different DO levels under pre-starved and non-starved condition (from Zhao et al. 2018)

of the fish to obtain oxygen through its own regulation is maximized at this point. When DO level continues to decrease to 0.89 mg/L, although the f and B of the fish are still increasing, the fish can no longer obtain more oxygen from the water due to the reduced respiratory efficiency, and the DO level at this point is close to the critical DO value of the fish.

In the normoxic state, the EO_2 of hungry silver carp is significantly lower than that of non-starving one, indicating that under adequate DO conditions the fish increases V_G to ensure more filtered food rather than respiratory requirements. EO_2 begins to decrease significantly in non-starved fish when DO levels drop below 3.17 mg/L, at which point the V_G of the fish increases significantly due to DO deficiency. The filtering efficiency (E) of hungry silver carp for *C. ellipsoidea* is significantly lower than that of non-starved fish in the normoxic state (Fig. 7.18) because of the greater V_G during active feeding.

7.6 Proliferation of Phytoplankton by Bivalve Metabolites

The impacts of farmed bivalves on water quality are mainly through feeding on plankton, consumption of oxygen, exhalation of carbon dioxide, and excretion of nitrogenous compounds in farming waters.

7.6.1 Respiration and Excretion of Filter-Feeding Bivalves

The oxygen consumption rate [Q_O, mg/(g·h)] and ammonia excretion rate [Q_N, mg/(g·h)] of bay scallop as a function of temperature (T, °C) and wet weight (W, g) are as follows:

$$Q_O = 0.046W^{-0.272}1.08^T$$
$$Q_N = 6.79W^{-0.327}1.03^T$$

There is a significant interaction of body weight and temperature on the oxygen consumption rate of bay scallop (Wang et al. 1998g).

Table 7.11 The Q_{10} values of *A. irradians* and *C. gigas* at different temperatures (from Wang et al. 1998g)

Species	Temperature (°C)		
	16–20	20–24	24–28
Pacific oyster *C. gigas*	1.61	4.72	1.13
Bay scallop *A. irradians*	/	2.28	2.03

The relationship between oxygen consumption rate and ammonia excretion rate of Pacific oyster as a function of temperature (T, °C) and wet weight (W, g) is as follows:

$$Q_{\mathrm{O}} = 0.085W^{-0.130}1.06^{T}$$
$$Q_{\mathrm{N}} = 2.66W^{-0.236}1.01^{T}$$

There is also a significant interaction of body weight and temperature on the ammonia excretion rate of Pacific oysters.

The equations above show that the oxygen consumption rates and ammonia excretion rates per unit body weight of bivalves decrease with increasing body weight, while the oxygen consumption rates and ammonia excretion per unit body weight increase with increasing temperature in certain range.

Pacific oyster has a greater variation in respiration quotient (Q_{10}) than bay scallop (Table 7.11), indicating that Pacific oyster is more sensitivity to temperature changes than bay scallop.

The oxygen consumption rates [Q_{O}, mg/(g·h)] and ammonia excretion rates [Q_{N}, μg/(g·h)] of razor clam (*S. constricta*) are related to temperature (T, °C) and dry weight (W, g) of soft tissues as follows (Fan et al. 2002a):

$$Q_{\mathrm{O}} = 0.320W + 0.0298T - 0.370$$
$$Q_{\mathrm{N}} = 69.75W + 7.93T - 154.1$$

The effects of temperature and body weight on oxygen consumption rate and ammonia excretion rate of Philippine clam (*R. philippinarum*) and Farrer's scallop (*C. farreri*) are also significant (Wang et al. 1997), and there is an interaction between temperature and body weight. The oxygen consumption rates [Q_{O}, mg/(g·h)] and ammonia excretion rates [Q_{N}, μg/(g·h)] of Philippine clam are related to temperature (T, °C) and body wet weight (W, g) as follows:

$$Q_{\mathrm{O}} = 0.307W^{-0.738}1.004^{T}$$
$$Q_{\mathrm{N}} = 7.841W^{-0.910}0.990^{T}$$

The oxygen consumption rates [Q_{O}, mg/(g·h)] and ammonia excretion rates [Q_{N}, μg/(g·h)] of Farrer's scallop are related to temperature (T, °C) and body wet weight (W, g) as follows:

$$Q_{\mathrm{O}} = 0.040W^{-0.349}1.079^{T}$$
$$Q_{\mathrm{N}} = 57.40W^{-0.561}0.992^{T}$$

Philippine clam is distributed in low and middle tide zones, and Farrer's scallop is distributed below the subtidal zone. Therefore, Philippine clam lives in an environment with greater temperature variation and has a stronger adaptive capacity to daily temperature variation than Farrer's scallop, which is proved by smaller Q_{10} values of Philippine clam (Wang et al. 1997). The daily temperature variation in ponds is large and the Philippine clam is a better pond culture species than Farrer's scallop in terms of temperature adaptation.

The Philippine clam is a buried bivalve species, preferring to inhabit in sands of low and middle tide zones with freshwater runoff inflow. In a sandy environment, the respiration and excretion of the Philippine clam are under normal conditions. When the habitat conditions change, such as when it is in a state of non-buried, its oxygen consumption rate and ammonia excretion rate will change (Wang et al. 1998e):

$$\text{Sand-free}\ \ Q_{\mathrm{O}} = 0.0430W^{-0.672}1.10^{T}$$
$$\text{Sand-free}\ \ Q_{\mathrm{N}} = 28.3W^{-0.520}0.97^{T}$$
$$\text{Sandy}\ \ Q_{O} = 0.0269W^{-0.612}1.10^{T}$$
$$\text{Sandy}\ \ Q_{N} = 6.50W^{-0.978}1.02^{T}$$

The oxygen consumption rates and ammonia excretion rates of Philippine clams under sandy condition are lower than the values under sand-free condition, which implies that the experimental environment should simulate their natural ecological environment as much as possible in studying the physio-ecology of buried bivalves. In this way, the results obtained will be more realistic and meaningful.

7.6.2 Proliferation of Phytoplankton by Bivalve Metabolites

Bivalves not only have the side of feeding on phytoplankton and inhibiting their development in aquaculture waters, but they also have the other side of promoting phytoplankton growth by excreting metabolites.

Wang et al. (2001b) conducted experiments using seawater that had ever temporarily cultured with bivalves to examine the effect of bivalve metabolites on algal growth, and found that algal growth rates were accelerated with increasing bivalve density (Fig. 7.19).

The growth-promoting effect of the bivalves on *Chlorella* sp., *Nitzschia closterium,* and *Isochrysis galbana* showed some species-specific. For examples, the growth-promoting effect of Farrer's scallop on *Isochrysis galbana* is significantly stronger than that of Philippine clam. These results suggest that both direct feeding pressure and indirect growth promotion should be considered when estimating carrying capacity and productivity of bivalve farming waters. The

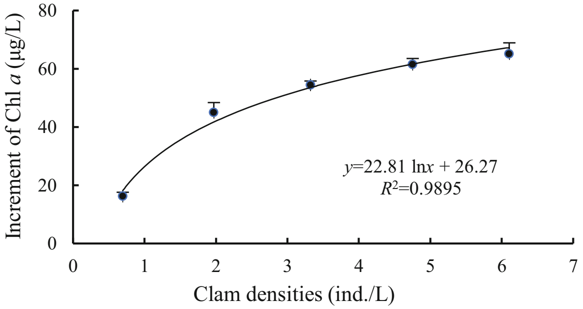


Fig. 7.19 Effects of clam *Ruditapes philippinarum* densities in experimental water on growth of phytoplankton *Chlorella* sp. (from Wang et al. 2001b)

increase in algal reproductive rates caused by nitrogen regeneration from herbivorous zooplankton approximately equals the zooplankton-caused mortality (Sterner 1986).

7.7 Effects of Bivalves on Water and Sediment Quality

Numerous reports on the effects of oyster and mussel farming on water quality and sediment quality have shown that these bivalves can effectively reduce the concentration of suspended particulate matter, TN, and TP in water (e.g., Shumway 2011). However, it is difficult to implement experimental studies with replicates and controls in field investigation. The results of several experimental studies using pond enclosures to simulate aquaculture ecosystems are presented below.

7.7.1 Effects of Bivalves on Water Quality of Farming Ponds

Mu (2002) studied the water quality regulation of Pacific oyster (92 ± 10 mm in length) in shrimp ponds using 5 m × 5 m × 1.2 m enclosures. Stocking densities of oyster were 0 (control), 9.6, 16.8, and 28.8 ind./m^2 in three replicates, denoted as I, II, III, and IV, respectively. Throughout the experimental period, the transparency of three treatments remained on the rise in general, except for the control treatment, which was decreasing. The transparency of treatments III and IV increased rapidly, and after 15 days of oyster stocking the water is clear to see the pond bottom (120 cm). The studies prove that oyster stocking can improve the transparency of aquaculture waters, and the higher the density of oyster stocking, the more rapid the increase in transparency.

Chlorophyll *a* concentration in the water of Treatment I remained relatively high and was on the rise until 20 September and then declined slightly (Fig. 7.20). The chlorophyll *a* of the other three treatments ended their upward trend after 11 September and did not rebound until late in the experiment. Overall, the stocking of oysters can reduce the chlorophyll *a* level in the waters.

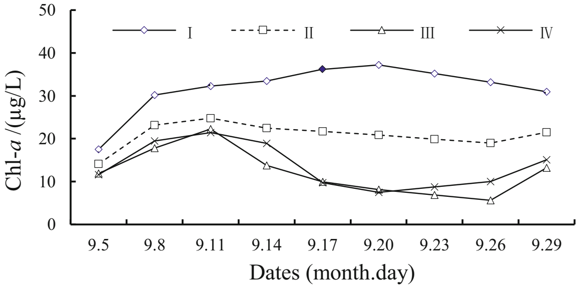


Fig. 7.20 Changes of chlorophyll *a* in each treatment with different stocking density of oyster (from Mu 2002)

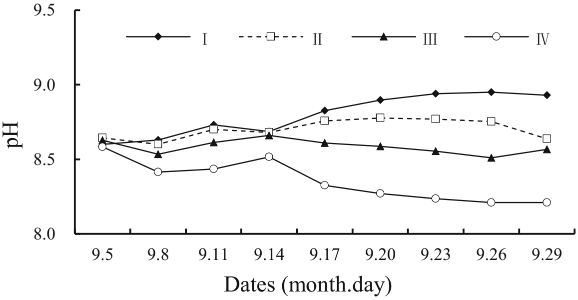


Fig. 7.21 Variation of pH in each treatment with different stocking density of oyster (from Mu 2002)

The water pH variation in Treatments I and IV was significant but in opposite directions (Fig. 7.21). In general, Treatment I showed an upward trend, while Treatment IV showed a downward trend. The studies prove that oyster stocking can reduce water pH, and the higher the density of oysters, the more rapidly the pH decreases.

The water COD in Treatment I was essentially on an increasing trend. The COD in Treatment II was slightly elevated overall. The COD in Treatment III basically showed a decreasing trend and was relatively slow to change. The COD in Treatment IV showed a decreasing trend in general, but variation was much more drastic than that of Treatment III. Overall, oyster stocking can reduce COD levels in the water.

Dong et al. (1999) studied the water quality regulation of bay scallop (49.6 ± 4.5 mm in length) in ponds using 5 m × 5 m × 1.1 m enclosures and found that the primary productivity of waters without scallop stocking increased by 272%, while others stocking with scallop decreased by 4.5%–94%. Bay scallop stocking could alter the structure of the plankton community. The phytoplankton diversity index decreased by 4.4% in waters without bay scallop stocking, while it decreased by 35.4%–84.2% in waters stocked with bay scallop. Rotifers accounted for a certain proportion in zooplankton of each treatment in the early period of the experiment, but were rarely seen in the late period. The average individual number of zooplankton, especially protozoa and rotifers, decreased with the increase of scallop stocking in the experiment.

Table 7.12 Water quality of each treatment with different density of Philippine clam in shrimp ponds (from Su et al. 2003)

Water quality	FS	FB1	FB2	FB3	FB4
Stocking density (10^4 ind./hm^2)	0	20	40	50	120
Clam productions [g/(m^2·d)]	0	0.67	0.83	0.53	0.36
TN (mg/L)	3.56 ± 0.32	3.59 ± 0.07	3.51 ± 0.39	3.32 ± 0.22	3.26 ± 0.13
TP (μg/L)	190 ± 126	201 ± 94	192 ± 100	140 ± 71	165 ± 76
COD (mg/L)	4.86 ± 0.48	4.84 ± 0.53	5.01 ± 0.88	4.49 ± 0.59	4.22 ± 0.40
Bacterioplankton (10^9 ind./L)	17.64 ± 11.06	5.83 ± 6.49	16.88 ± 5.47	12.19 ± 5.10	10.35 ± 4.77
Zoobenthos (dwg/m^2)	4.12 ± 7.39	4.12 ± 7.39	4.12 ± 7.39	4.12 ± 7.39	4.12 ± 7.39

Lu et al. (1997) studied the effects of Philippine clam stocking on water quality of shrimp farming ponds using 5 m × 5 m × 1.4 m enclosures. The results show that there was no significant difference in TN, TP, and COD among the treatments during the 3 months of experimental period, but the number of bacterioplankton in the waters decreased significantly with increasing stocking density of the clam (Table 7.12). The stocking of Philippine clam had a great impact on the plankton community structure and primary productivity. Stocking small amounts of Philippine clam, such as FB2 treatment, could increase the biomass of phytoplankton and zooplankton, but higher stocking densities would reduce the biomass of zooplankton.

7.7.2 Effects of Bivalves on Sediment of Aquaculture Ponds

Su et al. (2003) studied the effect of Pacific oyster on the sediment quality of shrimp farming ponds using enclosures (10 m × 10 m × 1.5 m). In Treatment IV, for example, after 30 days' culture of oyster the TN, TP, and total sulfur (TS) in pond sediments increased from 1.15 ± 0.17, 5.48 ± 0.66, and 0.22 ± 0.14 mg/g to 1.99 ± 0.17, 6.28 ± 0.92, and 0.46 ± 0.19 mg/g, respectively. The integrated pollution index of Treatments IV and V was less than that of the control (Fig. 7.22), indicating that the organic pollution of the sediment could be reduced by co-culture of oyster at appropriate densities in shrimp ponds, such as Treatments IV and V. From Table 7.12 you can see that the weight (biomass) of benthos decreased with increasing stocking densities of Philippine clam.

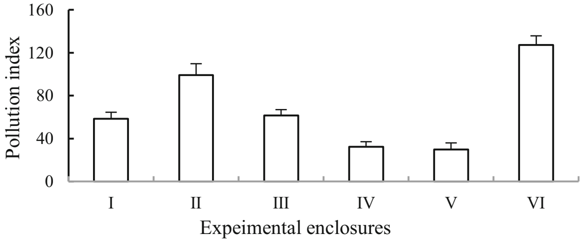


Fig. 7.22 Integrated pollution indexes of TN, TP, and TS in the sediments of shrimp-oyster co-culture systems (from Su et al. 2003). Stocking densities of the oyster were 0, 127, 253, 496, 1003, and 1246 g/m^3, marked as I, II, III, IV, V, and VI, respectively. Pollution index = C_i/S_i, where C_i is the product of measured values of TN, TP, and TS concentrations, and S_i is the product of standard values of TN, TP, and TS concentrations

7.8 Effects of Filter-Feeding Fish Stocking on Water Quality

Silver carp, bighead carp, and tilapia are cultured worldwide because of their excellent biological characteristics and their capacity in regulating water quality. The effects of silver carp and bighead carp on water quality have drawn wide attention (Dong 1994), and some scholars have even suggested banning the stocking of silver carp in reservoirs because of the concerns that it could promote phytoplankton blooms (Spataru and Gophen 1985). Therefore, it is of theoretical and practical significance to elucidate the effects of silver carp, bighead carp, and tilapia stocking on water quality.

7.8.1 Effects of Filter-Feeding Fish on Water Quality

Many tilapia species are omnivores. When there are abundant plankton and lack of other food source, tilapia can shift their feeding habits from articulate feeding to pump filter feeding (Gerking 1994). Silver carp and bighead carp are typical pump filter feeders relying on gill rakers to filter plankton, but they also have other feeding mechanisms, such as ‘sink feeding’ (Li and Dong 1996) and ‘blocking effect’ (Dong and Li 1994c), to feed on smaller size of phytoplankton. However, in general the latter two feeding mechanisms of the carps are only complementary to the first one. In China and Eastern Europe, silver carp and bighead carp are often co-cultured with common carp in ponds to improve pond water quality or/and to increase total production. In practice, it has been found that co-culturing silver carp with common carp can increase common carp production, while co-culturing bighead carp may reduce the production of common carp. Silver carp and bighead carp differ in their impact on the plankton community in ponds.

7.8.1.1 Effects of Stocking Silver Carp and Bighead Carp on Water Quality

Li et al. (1993) have studied the effects of silver carp stocking on water quality of common carp farming systems by using suspending enclosures (14.3 m^3) in a reservoir. The results showed that after stocking of silver carp, zooplankton, phytoplankton, chlorophyll *a,* and primary productivity decreased by 58.7%, 63.6%, 52.5%, and 65.0% on average, respectively, transparency and phytoplankton community diversity indices increased by 18.2% and 32.5%, respectively, the quantity of *Microcystis aeruginosa* decreased by 90.6%. The phytoplankton blooms in the water were significantly suppressed; however, the quantity of small green algae (<20 μm in diameter) did not show significant changes; thus, its proportion in the phytoplankton biomass increased by 82.3%. Although ammonia nitrogen concentration in water increased after stocking of silver carp, TP concentration of in water decreased significantly. In addition, silver carp stocking also significantly reduced COD and pH of the water. In brief, silver carp stocking has purifying effect on aquaculture waters.

After 4 year's studies in East Lake of Wuhan, Hubei Province, using enclosure, Xie (2003) proves that (1) water quality of East Lake is still suitable for the blooming of *Microcystis* spp., and zooplankton cannot control cyanobacterial blooms in the lake; the increase of stocking density of silver carp and bighead carp is the root cause of the disappearance of cyanobacterial blooms in the lake in the mid-1980s. (2) The effective density of silver carp and bighead carp to control cyanobacterial blooms is 46–50 g/m^3 at current nutrient loading of East Lake. (3) Silver carp and bighead carp can eliminate cyanobacterial blooms through food chain (direct filtering).

There are also some cases of plankton reduction after stocking of silver carp and bighead carp. For example, Kajak et al. (1975) found in a small lake using enclosures that silver carp stocking not only led to a sharp reduction in plankton biomass, but also a significant decrease in the proportion of cyanobacteria. In another case, Opuszynski and Shireman (1995) found that total phytoplankton, cyanobacteria, and green algae densities were lower in bighead carp stocking ponds, and all types of zooplankton were significantly reduced, especially cladocerans, which were less than half the density in the fish-free ponds.

Burke et al. (1986) found that co-culture of silver carp and bighead carp with other fish in ponds could quickly reduce the density of all types of zooplankton, but phytoplankton in chlorophyll *a* increased more than 100%. The experimental results of Zhao et al. (2001d) also showed that phytoplankton was promoted and zooplankton was inhibited after stocking of silver carp in ponds.

Smith (1989) reviewed 14 experimental studies and found that in 11 of these experiments, phytoplankton abundance increased after stocking silver carp. Of the 9 experimental studies conducted afterward, 3 cases showed an increase in phytoplankton, 5 cases showed a decrease (Dong 1994). Thus, it is no longer necessary to debate whether stocking of silver carp will reduce or promote phytoplankton, but to study the condition dependence and mechanism of the ecological effects.

It is now clear that silver carp can directly filter phytoplankton and small zooplankton, such as rotifers, small cladocerans, and copepod nauplius. Although

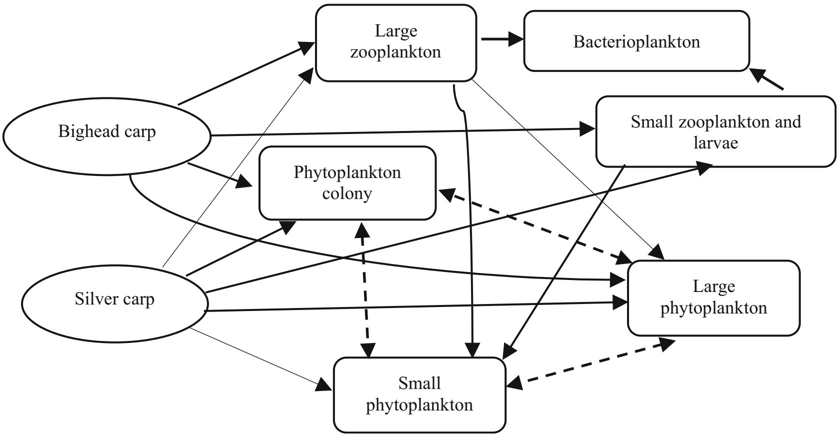


Fig. 7.23 Influence paths of silver carp and bighead carp on the structure of plankton community

the feeding success rates of silver carp for large zooplankton are lower due to their escape or evasion response (Drenner et al. 1986), the zooplankton populations can also be reduced as the fish could feed on the larvae of zooplankton. Bighead carp can directly filter on larger phytoplankton, phytoplankton colony, and zooplankton (Fig. 7.23).

The indirect effects of silver carp and bighead carp on phytoplankton include two ways. First, when herbivorous zooplankton are suppressed by fish, the grazing pressure on phytoplankton, especially on small phytoplankton, is reduced, and the quantity of phytoplankton increases (Smith 1985). Experiments in some larger waters have also demonstrated this way of effects. Bighead carp may have a greater indirectly effect on phytoplankton than directly effects (Januszko 1974; Burke et al. 1986).

Second, large phytoplankton are filtered in large quantities by fish, reducing the nutritional competitors of small phytoplankton, leading to an increase in biomass of small phytoplankton. Small phytoplankton generally have higher reproductive capacity; therefore, sometimes total phytoplankton biomass increases after stocking of the fish.

Differences in stocking density of the fish may also have different effects on phytoplankton. Januszko (1974) found that phytoplankton quantity increased by 10% when the stocking density of silver carp was 1500 ind./hm^2, while it decreased by 10% when the stocking density was 3000 ind./hm^2. Domaizon and Devaux (1999) also found that when the stocking densities of silver carp were 0 and 8 g/m^3, the chlorophyll *a* concentration in experimental water was low, while they were higher when the fish was stocked at densities of 16, 20, and 32 g/m^3. The highest chlorophyll *a* concentration occurred when the fish was stocked at 16 g/m^3.

Silver carp and bighead carp will have different effects on phytoplankton with different phytoplankton community structures. Differences in nutrient loading, hydrological condition, and season will result in different phytoplankton community

Table 7.13 Dissolved oxygen concentrations, transparencies, primary productivities, and community respiration in different treatments after stocking tilapia (from Jie 2006)

Treatments	CO	P1	P2	P3
Stocking densities (ind./m^3)	0	7	22	48
DO (mg/L)	9.36 ± 0.62^a	8.82 ± 0.30^b	8.33 ± 0.40^b	8.02 ± 0.70^b
Transparencies (cm)	38 ± 6^a	42 ± 6^b	45 ± 3^b	42 ± 8^b
Primary productivities [gO_2/(m^2·d)]	4.05 ± 0.64^a	4.10 ± 0.38^a	4.32 ± 0.50^a	4.77 ± 0.39^a
Community respiration [gO_2/(m^2·d)]	3.84 ± 1.27^a	3.28 ± 0.15^a	3.21 ± 0.64^a	3.32 ± 0.48^a
P/*R*	1.06 ± 0.24^a	1.25 ± 0.10^{ab}	1.34 ± 0.18^{ab}	1.44 ± 0.11^b

structures, so these factors will also indirectly or directly affect the ecological role of the fish.

7.8.1.2 Effects of Tilapia on Plankton Community

Some tilapias are filter-feeding fish, which can play a role in regulating water quality in polyculture waters. Nile tilapia (*Oreochromis niloticus*) stocking can lead to significant changes in the plankton community of aquaculture waters, such as an increase in phytoplankton density, primary productivity, a shift in the phytoplankton community from diatom dominance to small green algae (<10 μm) dominance (Zhao et al. 2000a). As stocking density of tilapia increases, the quantities of rotifers, cladocerans and copepods, and water pH decrease; while on the contrary, protozoa, water turbidity, total alkalinity, electrical conductivity, TN, and TP increase (Zhao et al. 2000b).

The water transparencies of ponds with tilapia are significantly greater than that without tilapia (Table 7.13). Dissolved oxygen and the ratio of primary productivity to respiration (*P*/*R*) show a tendency to decrease with increasing fish stocking density. The transparency and *P*/*R* of the waters at medium fish stocking density are 18.4% and 26.4% of higher than those without fish (Jie 2006).

7.8.2 Effect of Filter-Feeding Fish on Bacterioplankton

The role of bacteria is very important for maintaining a good water quality and ecological balance in aquaculture waters. The respiration rates of micro- (20–200 μm), nano- (3–20 μm), and pico-plankton (<3 μm, mainly bacterioplankton) in shrimp ponds are on average 0.07, 0.38, and 0.31 mgO_2/(L·d), respectively, accounting for 9%, 50%, and 41%, respectively, of the total plankton respiration rate (Liu et al. 2001a).

Silver carp can directly filter the bacteria attached to planktonic detritus and may also contribute to the growth of the bacterioplankton by inhibiting zooplankton which are the feeders of bacterioplankton. Feeding rates of zooplankton on bacterioplankton in shrimp ponds are 262 ± 167 μgC/(L·d) (Liu et al. 2001b).

Therefore, the feeding of the fish on macro-zooplankton can have a significant effect on the quantity of bacterioplankton in aquaculture waters. Opuszynski (1979) reported an increase of bacterioplankton quantity in ponds after silver carp stocking.

The tilapia (*O. mossambicus* × *O. niloticus*) in shrimp ponds can reduce bacterioplankton biomass, particulate organic carbon, and dissolved organic carbon concentrations of the water, but the *P/B* ratio of bacterioplankton is greatly increased, which suggests that tilapia can improve the water quality of aquaculture ponds (Liu et al. 1999a, 2000a).

The impacts of filter-feeding fish on water quality are mainly through five ways, i.e., (1) direct filtering phytoplankton and zooplankton; (2) indirectly reducing the grazing pressure of zooplankton on phytoplankton by feeding the zooplankton; (3) direct filtering the bacteria attached to planktonic detritus; (4) indirectly reducing the grazing pressure on bacterioplankton by feeding zooplankton; and (5) indirectly reducing the nutritional competitors of small phytoplankton by filtering large phytoplankton (Fig. 7.23).

7.8.3 Effects of Silver Carp Stocking on Pattern of Nutrient Cycling

Silver carp and bighead carp are pelagic fish, the disturbance of bottom sediments by the fish activity in shallow waters may accelerate nutrient replenishment to overlying water from sediment interstitial water, thereby affecting the growth of plankton (Laws and Weisburd 1990). However, when water body is too shallow and the bottom sediments are fine silt or clay, the sediment may be stirred up by the fish and the turbidity may increase, which in turn affects phytoplankton photosynthesis.

During summer, the growth of planktonic communities in many temperate deeper waters are often restricted by the uneven vertical distribution of nutrients due to the thermocline. Silver carp and bighead carp are active in pelagic zone (layer) of the waters and cause little disturbance to the uneven distribution. In contrast, the feces excreted by the fishes after feeding on plankton in the pelagic zone partially sink to the bottom, out of euphotic zone, which will exacerbate the degree of uneven vertical distribution of nutrients (Kajak et al. 1975). The reason for the inhibition of plankton community by the fish in some deep waters is likely to be related to the above reasons in addition to higher stocking density.

Silver carp is a filter feeder on phytoplankton and small zooplankton. After the introduction of the fish into a water body, the structure and flux of food web of the waters will change greatly. Before introduction of the fish, phytoplankton are partially consumed by zooplankton, which in turn may be consumed by other higher trophic level animals. The assimilation of phytoplankton by zooplankton is much higher than that by the fish (He 1985), so a proportion of the secondary production is passed backward along the food chain. After introduction of the fish, small-size zooplankton are suppressed by the fish, and the fish can digest and utilize only a small fraction of filtered phytoplankton, while its feces will enter the detritus chain or are re-filtered by the fish or other animals.

However, Chen and Liu (1989) found that when silver carp filters and digests the feces formed by *Microcystis*, the digest rate will significantly exceed the rate of digesting fresh *Microcystis*. When silver carp digests the phytoplankton, a portion of the food material is directly excreted in the chemical form (e.g., NH_4^+-N) available to the phytoplankton in water. Therefore, the introduction of silver carp into the waters results in so-called 'short-circuiting' (Liu and Huang 1997). As a result of this 'short-circuiting' effect, the material cycling in the waters is accelerated. The increased circulation of nutrients in the lower trophic levels will facilitate the compensation of phytoplankton production. In East Lake, Wuhan, China, feeding process of silver carp and bighead carp accelerate the release of nutrients and promote the primary productivity of the waters (Liu and Huang 1997).

Brief Summary

1. Instrumental species in aquaculture are the integrated organisms with main target organism. They not only play a role in regulating and improving the water quality or/and sediment quality of aquaculture waters, but also normally possess high commercial value.
2. Biomanipulation is the management of aquatic communities by controlling natural populations of organisms aimed at water quality improvement. Biomanipulation includes the methods of bottom-up effect and top-down effect.
3. Bottom-up effects regulate the phytoplankton mainly by controlling the amount of inorganic nutrients input (increase or decrease) and/or the proportion of nutrient elements, such as N/P ratio, and in turn influence on the biomass of higher trophic levels. The pathway of the action is as follows: inorganic nutrients → phytoplankton → zooplankton → zooplanktivorous fish → piscivorous fish. The bottom-up effect is characterized by a time lag in the backward food chain and by a gradual decrease in the intensity of the effect.
4. The top-down effects regulate phytoplankton mainly through controlling the amount of zooplanktivorous fish. The pathway of the action is as follows: piscivorous fish → zooplanktivorous fish → zooplankton → phytoplankton. There is also a time lag in the top-down transmission of the effects, but the intensity of the effects may be gradually amplified along the food chain.
5. The key factor on which the classical biomanipulation theory relies is zooplankton, but some scholars have also proposed a non-classical biomanipulation theory, i.e., the use of filter-feeding fish or bivalve to directly manipulate phytoplankton.
6. Primary productivity is usually constrained by the availability of one or two key elements (referred to as limiting elements) that are in shortest supply relative to the requirements of the organism. Although most of aquaculture waters exhibit dual limitation of N and P, more freshwater bodies have P as the first limiting element, while the opposite is true for high salinity of waters.
7. Because the concentration of phosphorus and iron in natural seawater is very low and the two elements are easy to be adsorbed and chelated, they are the potential tools to regulate water quality in aquaculture.

8. Seaweeds can be used for improving water quality or directly treating tailwater in aquaculture. In addition, seaweeds can also improve water quality through interactions with microalgae. The function of seaweeds in regulating water quality is achieved by influencing microalgae: (1) by shading the photosynthesis of microalgae; (2) by competing for nutrients; and (3) by allelopathy.
9. Co-culture of some filter feeders in aquaculture waters can regulate water quality by non-classical top-down effects. Filter-feeding bivalves, such as oysters and scallops, can filter phytoplankton as small as a few microns, which can significantly reduce phytoplankton biomass.
10. Grazing rate (G) of pump filter feeder on phytoplankton can be expressed by $G = B \cdot f \cdot D \cdot E \cdot x \cdot P$, where B is suction volume, i.e., the water volume passing through the oropharyngeal cavity of the fish in one filtering or respiratory stroke or beat (ml/stroke); f is filtering frequency of the fish (times/min); D is the density of food particles (ind./ml); E is filtering efficiency, i.e., the percentage of particles presented to the gill that are cleared from suspension when water flows through the gills; x is the daily feeding rhythm factor, i.e., the time percentage of the day that is spent on feeding; P is the probability that the zooplankton will be sucked by the fish, which is related to evasion ability of zooplankton. The product of the three parameters is just an excellent indicator of feeding capacity (FC) of filter-feeding fishes, i.e., $FC = B{\cdot}E{\cdot}f$.
11. The selectivity of filter-feeding fish for food can be divided into selectivity for specific food particles (food particle selectivity) and selectivity for specific feeding areas (feeding area selectivity). Food particle selectivity of filter-feeding fish is a passive selectivity based on the structure of their gill rakers in the water with evenly distributed plankton. However, when food organisms are unevenly distributed in the water, both silver carp and bighead carp have the ability to actively swim to zooplankton-rich areas to feed, i.e., feeding area selectivity. The presence of large size of microalgae or inorganic plankton in water can cause a ‘crowding effect’ that increases the filtering efficiencies of silver carp for small-size microalgae.
12. Silver carp can directly filter phytoplankton and small zooplankton. Although the feeding success rates of silver carp for large zooplankton are lower due to their escape response, the zooplankton populations can also be reduced as the fish could feed on the larvae of zooplankton. Bighead carp can filter directly on larger phytoplankton, phytoplankton colony, and zooplankton.
13. The indirect effects of silver carp and bighead carp on phytoplankton include two ways. First, when herbivorous zooplankton are suppressed by the fishes, the grazing pressure on phytoplankton is reduced, and the quantity of phytoplankton increases. Second, large phytoplankton are filtered in large quantities by the fish, reducing the nutritional competitors of small phytoplankton, leading to an increase in biomass of small phytoplankton.
14. The disturbance of bottom sediments by fish activity in shallow waters may accelerate nutrient replenishment to overlying water from sediment interstitial water, thereby affecting the growth of plankton. However, in temperate deeper waters with thermocline, the feces excreted by the fish after feeding on plankton

in the pelagic zone partially sink to the bottom, out of euphotic zone, which will exacerbate the degree of uneven vertical distribution of nutrients.

15. When silver carp digests the phytoplankton, a portion of the food material is directly excreted in the chemical form (e.g., NH_4^+-N) available to the phytoplankton in water. Therefore, the introduction of silver carp into the waters results in so-called ‘short-circuiting’. As a result of this ‘short-circuiting’ effect, the material cycling in the waters is accelerated. The increased circulation of nutrients in the lower trophic levels will facilitate the compensation of phytoplankton production.

Sediment and Remediation of Aquaculture Ponds

8

Shuang-Lin Dong and Li Li

The soil carries the water of the pond. The sediment or bottom mud of an aquaculture pond is an important part of the pond ecosystem. The nutrient exchange takes place between the sediment and bottom water, which has a great influence on the water quality in the pond. Aquaculture activities will change the properties of the surface sediment, and then affect the growth of farmed animals and the yield of the pond system. When the pond sediment is altered to adversely affect farming activities, attempts should be made to remediate the pond sediment. Physical, chemical, and biological methods are used in pond sediment remediations.

8.1 Sediment of Aquaculture Ponds

The materials that form the pond bottom are called sediment or mud. The bottom of the pond is originally made up of terrestrial soil. When the pond is filled with water, the soil's properties are changed by the natural deposition process. The pond sediment is the reservoir of a variety of chemicals and also the habitat for many animals. The nutrient exchange between sediment and overlying water is complex. Pond sediment usually has high organic matter concentrations, which consume a lot of oxygen. The sediment is also a source of some harmful chemicals.

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8.1.1 Characteristics of Pond Soil

Soil types vary widely around the world. The marine soils in China show a latitudinal zonal distribution from south to north, i.e., north-south variation of moist forest soils influenced by warm and humid air currents of the Pacific subtropical high pressure in the east. From the east to the west of China, continental soils show a longitudinal zonal distribution, that is, from the coast to the hinterland of the continent, the influence of the warm and humid air currents of the Pacific subtropical high pressure gradually weakens, the coverage of temperate steppe vegetation, the height of grasses and the organic matter content become lower and lower, and alkaline earth metals and alkali metal salts increase gradually in the soils (Zhang 2002).

Soil formation in a specific geographic space is the result of the joint action of historical and modern natural processes and human activities, and the formation process is affected by climate, geomorphology, geology, hydrology, and biology factors (Zhang 2002). The characteristics such as particle size structure, organic matter content, and pH of pond soil have great influence on water quality.

The soil used to build the pond comes from the top or near the top of the local terrestrial soil. The deeper the soil, the lower the weathering degree. Some tiny or soluble substances will move downward and accumulate at a specific layer due to the leaching process.

Soil texture is very important for aquaculture ponds. The soil with a particle size of 0.05–2 mm is called sand, 0.002–0.05 mm is silt, and less than 0.002 mm is clay. The soil used for pond construction should contain at least more than 20% of clay (clay particles $\geq$50%), and the soil in most ponds generally contain 30–40% of clay (Boyd 1995). If there is not enough clay, the soil is prone to “leak”. When there is too much clay, the soil is too sticky, and easy to harden when gets dry.

The surface soil of woodlands and grasslands contains a lot of organic matter, while the soil in agricultural land rarely contains more than 6% of organic matter, and the value is even lower in the tropics and subtropics regions. The soils in most ponds are mineral but contain a certain amount of organic matter. Those organic matters contain a large percentage of humus which is hard to decompose. As the pond ages, the percentage of organic matter in the soil increases as well.

Dissolved oxygen (DO) is found in the interstitial water of water-immersed soil or sediment. But due to biological consumption, the oxygen content in the soil is often lower than that in the water. And the content gradient will drive oxygen from the water to the soil. The opposite is true for carbon dioxide.

The color of pond soil is determined by what it contains. Soils contain iron oxides that are yellow or bright red. The color of the soil with high organic matter concentration is dark and even black. Sandy soils tend to be light brown. The water-immersed soil or bottom mud is usually in reducing condition and contains ferrous compounds, the color of which is gray and black. The surface layer of typical pond soil is yellow gray due to ferric compounds, but the deep layer is black due to the reduction of ferric to ferrous compounds.

In the pond soil, there are a large number of colloidal particles (1–100 nm in diameter) such as layered silicate, ferric oxide, alumina, and some humus particles. These colloidal particles carry electric charges and have a large surface area, which can adsorb ions as well as other dissolved substances in water. Thus, the colloidal particles can be regarded as active soil components.

Different types of soils have different pH. Some highly organic soils may have $\mathrm{pH} < 3$, most highly leached mineral soils have $\mathrm{pH} \geq 4$, soils rich in calcium and alkali have $\mathrm{pH} < 8.5$, and alkaline soils have pH between 8.5 and 10. There is also a wide range of pH variations in pond sediments. According to Boyd (1995), the pH of sediments in 358 freshwater ponds varied from 3.9 to 8.0, with an average of 6.69, and that of 346 brackish ponds ranged from 1.2 to 9.8, with an average of 6.5. The pH of pond sediment has a great influence on the ion exchange between the soil and the overlying water.

The soils used to build aquaculture ponds are mostly non-sulfate types of soil, and most sulfur in the soil exists in organic matter. In general, pond soils contain more organic matter than terrestrial soil, having a higher percentage of sulfur. The sulfur content of freshwater pond soils is generally lower than that of seawater ponds (including brackish waters). The former is rarely above 0.1%, while the latter is often above 0.5% (Boyd 1995). This is because the sulfate concentration in seawater is higher than in freshwater.

8.1.2 Ion Exchange Between Pond Sediment and Water

Ion exchange between pond sediment and overlying water has a great impact on water quality and sediment quality (Boyd 1995). Most clay particles have negative charges and a minority of them have positive charges. The substitution of Al^{3+} for Si^{4+} or Mg^{2+} for Al^{3+} in a clay micelle produces an unsaturated negative charge, while the substitution of Al^{3+} for Mg^{2+} produces an unsaturated positive charge.

Some charges on the clay particles are not produced by the substitution process described above; they are generated by hydroxy groups on the surface of colloids. The charge resulting from hydroxy groups increases as the pH increases:

$$\text{Micelle–OH} + \mathrm{OH^-} = \text{Micelle–O}^- + \mathrm{H_2O}$$

The hydroxyl group may produce a positive charge at a low pH

$$\text{Micelle–OH} + \mathrm{H^+} = \text{Micelle–OH}_2^+$$

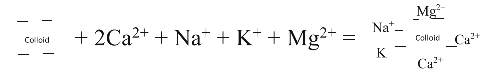
Humus has negative charges because of the hydroxy, carboxy, and phenolic groups on it. Those groups can be taken as organic acids, and the dissociation of a small fraction of those groups will produce one charge even at a low pH. As the pH increases, the humus will carry more electric charges due to the dissociation of more groups:

$$(\text{Hydroxy})\text{–}OH + OH^{-} = O^{-} + H_2O$$

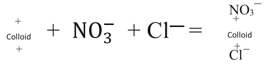
$$(\text{Carboxyl})\text{–}COOH + OH^{-} = COO^{-} + H_2O$$

$$(\text{Phenol})\text{–}OH + OH^{-} = \text{Benzene ring–}O^{-} + H_2O$$

Negative charges in sediment colloids attract cations, while positive charges attract anions:

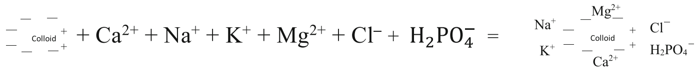


$$\overset{-\;-}{\underset{-\;-}{{}^{-}_{-}\text{Colloid}{}^{-}_{-}}} + 2Ca^{2+} + Na^{+} + K^{+} + Mg^{2+} = {}^{Na^{+}-}_{K^{+}-}\overset{Mg^{2+}}{\underset{Ca^{2+}}{\text{Colloid}}}{}^{-}Ca^{2+}$$



$$\overset{+}{\underset{+}{\text{Colloid}}} + NO_3^{-} + Cl^{-} = \overset{NO_3^{-}}{\underset{Cl^{-}}{\text{Colloid}}}$$

Most colloids carry net negative charges, but some sites may have positive charges. This makes the colloids possible to attract both positive and negative ions:



$$\overset{-\;-}{\underset{-\;-}{{}^{-}_{-}\text{Colloid}{}^{+}_{+}}} + Ca^{2+} + Na^{+} + K^{+} + Mg^{2+} + Cl^{-} + H_2PO_4^{-} = {}^{Na^{+}-}_{K^{+}-}\overset{Mg^{2+}}{\underset{Ca^{2+}}{\text{Colloid}}}{}^{+\,Cl^{-}}_{+\,H_2PO_4^{-}}$$

The negative charges on the colloid attracted the cations with different strength. The order of the cations being attracted is as follows:

$$Fe^{3+} > Al^{3+} > Ca^{2+} > Mg^{2+} > K^{+} \geq NH_4^{+} > Na^{+}$$

The possibility of the cations being attracted decreases with the decrease of valence. For the cations with the same valence, cations with smaller ion radii have higher charge density, thus are more easily to be attracted. In addition, the concentration of ions in the water will also affect the actual attraction process. For example, if Ca^{2+} is added to the solution, more Ca^{2+} will be adsorbed in the sediment colloid. Some component in soil has special adsorption on some materials, for example, organic matter has a strong attraction on the bivalent metal ions.

The anions easily attracted by sediment colloids carrying positive charges include phosphate, silicate, and some organic acid ions. The order in which anions are being attracted is as follows:

Oxalic acid ion > citric acid ion > phosphoric acid ion > sulfuric acid ion > chloride ion > nitrate ion

8.1.3 Acidity of Pond Sediment

The pH, the negative logarithm of H^+, is a measure of the concentration of H^+ in a solution, while the acidity is a measure of a substance's ability to provide H^+. The pH of pond sediment is related to its acidity. The sediment pH is an important variable as it can affect the solubility of sediment minerals. When alkaline substances are applied to remediate acidified pond soil, the acidity of the sediment must be measured first.

The change of pH and acidity of most pond sediments are mainly caused by the exchangeable aluminum in the sediment (Boyd 1995), the process can be expressed as the following:

$$\text{Colloid–}Al^{3+} \rightarrow Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$$

The concentration of H^+ and pH depend on the equilibrium concentration of Al^{3+} in the solution. And the equilibrium concentration of Al^{3+} is related to the proportion of the total amount of exchangeable cations and Al^{3+} attracted by sediment colloid. The acidity is mainly determined by the amount of Al^{3+} attracted by sediment colloids. In addition, the amount of Fe^{3+} attracted by the colloid can also affect sediment acidity as Fe^{3+} can hydrolyze in the same way as Al^{3+}.

Some sediments contain iron pyrite (FeS_2) or other sulfides. Accumulation of iron pyrite in the soil of the coastal areas is common. Sulfates are abundant in seawater and brackish water of coastal wetlands. The sulfate can be reduced to produce sulfide by microbial activities under anaerobic conditions. FeS_2 can be formed by the reaction of iron and sulfide, and then deposited in sediments. The simplified equation is as follows:

$$\underset{\text{in sediment}}{Fe_2O_3} + \underset{\text{in seawater}}{4SO_4^{2-}} + \underset{\text{organic matter}}{8CH_2O} + 1/2O_2 \rightarrow 2FeS_2 + 8HCO_3^- + 4H_2O$$

The FeS_2 is stable under anaerobic conditions, but when exposed to the air, it can be oxidized to produce sulfuric acid. Soil with more than 0.75% total sulfur is called potential acid-sulfate soil. When it is exposed to the air and oxidized, it becomes acid-sulfate soil. As calcium carbonate can neutralize acidity, soil with a large amount of calcium carbonate deposited will not develop into acid-sulfate soil (Boyd 1995).

The oxidation of iron pyrite involves many reactions:

$$FeS_2 + H_2O + 3.5O_2 \rightarrow FeSO_4 + H_2SO_4$$

$$2FeSO_4 + ½O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O$$

$$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O \rightarrow 15FeSO_4 + 8H_2SO_4$$

In addition, $Fe_2(SO_4)_3$ can be hydrolyzed in the following reactions:

$$Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4$$

$$Fe_2(SO_4)_3 + 2H_2O \rightarrow 2Fe(OH)(SO_4) + H_2SO_4$$

$Fe_2(SO_4)_3$ can react with iron pyrite to produce S, which can be oxidized to produce sulfuric acid by microorganisms:

$$Fe_2(SO_4)_3 + FeS_2 \rightarrow 3FeSO_4 + 2S$$

$$S + 1.5O_2 \rightarrow H_2O + H_2SO_4$$

Ferrous hydroxide can react with the adsorbed bases, such as potassium in acidic sulfate soil to form jarosite:

$$3Fe(OH)_3 + 2SO_4^{2-} + K^+ + 3H^+ \rightarrow KFe_3(SO_4)_2(OH)_6 \cdot 2H_2O + H_2O$$

Jarosite is relatively stable, but tends to hydrolyze in older acid-sulfate soil:

$$KFe_3(SO_4)_2(OH)_6 \cdot 2H_2O + 3H_2O \rightarrow 3Fe(OH)_3 + K^+ + 2SO_4^{2-} + 3H^+ + 2H_2O$$

Because deep pond sediments are often anoxic and the microorganisms are not active, the above oxidation reactions are not likely to happen. However, when the pond is drained, these reactions can lead to acidification of the pond soil. During the rainy season, sulfuric acid from the embankments can make the pH of the pond water drop dramatically, affecting the growth of farmed animals. The cases used to occur in the Iloilo Province of the Philippines and southern China (Boyd 1995; Zhou and Wang 2011).

8.2 Sedimentation in Aquaculture Ponds

The sediments of the aquaculture pond include exogenous and endogenous sources. The exogenous sources are mainly the particulate matter that comes into the pond when the pond is filled with water. The particulate matter will settle to the bottom in relatively static pond water. Exogenous sediments are mainly composed of silt and debris of animals and plants, and also include some large phytoplankton, such as diatoms. Endogenous sediments are mainly residual feeds and feces, biological debris, sand, and so on. In some ponds, there is lots of water exchange or strong currents formed by aerators to badly erode the embankments. In this case, there is lots of soil in the sediment from the collapse of the embankments. For intensive and semi-intensive aquaculture ponds, the residual feeds and feces are important sources of pond sediment. The sediment of ponds used for many years usually has high organic matter content, which has a great influence on water quality and aquaculture production.

Sedimentation of suspended solids in the ocean mainly occurs in the euphotic zone, and the plankton is the main component of the sediment. As the depth of ocean water increases, the amount of suspended solid decreases sharply and tends to be stable at the depth of more than 100 m (Bishop et al. 1977). The sedimentation rates in the ocean range from 1 to 1000 mgC/(m^2·d) and the quantity is mainly related to the primary productivity and distance to the land. The sedimentation rates in the nutrient-rich coastal waters range from 30 to 600 mgC/(m^2·d) and show obvious seasonal variations (Valiela 1995).

The sediment under the cages usually has high organic loading from residual feeds and feces. A study on salmon farming cages in European indicated that only about 10% of organic matter in the sediment can be decomposed each year (Gowen 1992).

In nearshore bivalve farming areas, the biodeposition from filter-feeding bivalve is strong. The sedimentation rates in the areas with the bivalve are 3–7 times more than those without bivalves (Zhou et al. 2003a, b; Dahlbäck and Gunnarsson 1981; Haven and Morales-Alamo 1966). There is 30 cm thick sediment deposited every year in the Scherda estuary, the Netherlands (Haven and Morales-Alamo 1966). The sedimentation rate of the *Choromytilus chorus* in the southern gulf of Chile was 271 g/(m^2.d) (Jamillo et al. 1992). There are 59,200 tons of sediments produced every year in the bivalve farming area of Sishili Bay, Yantai, China (Zhou et al. 2001b).

Aquaculture ponds are shallower and usually have high phytoplankton biomass. The sedimentation in the pond is usually stronger than in larger inland waters and the ocean. Ren et al. (2010) indicated that the total particulate matter (TPM) sedimentation rates varied from 10.2 to 38.3 g/(m^2·d) with an average of 22.1 g/(m^2·d) in the extensive sea cucumber farming ponds without feeding. The fluxes of TPM are higher in spring and autumn than in the other seasons because of the stronger wind in spring and autumn. The maximum flux occurred in May, and the lowest occurred in January (Table 8.1).

As the sea cucumber farming ponds are shallow, the resuspension of the sediment cannot be ignored. The sediment resuspension rates ranged from 59.6% to 95.5% with an average of 81.7% in the pond. The resuspension rates in summer and winter were significantly lower than that in spring and autumn. Their sediment resuspension rates are comparable to those of some open, wind-affected lakes and nearshore areas.

The organic carbon sedimentation rates ranged from 377.0 to 1201.0 mg/(m^2·d) with an average of 756.1 mg/(m^2·d) in the ponds. The organic nitrogen sedimentation rates varied from 45.5 to 174.8 mg/(m^2·d) with an average of 92.1 mg/(m^2·d). The total phosphorus sedimentation rates varied from 9.2 to 22.7 mg/(m^2·d) with an average of 15.6 mg/(m^2·d).

Feed is usually not used in extensive farming ponds of sea cucumber. The sediments are mainly carried in with the tide and the plankton growing in the pond. The sediments in the pond where feed is used also include residual feed and feces. Boyd et al. (2010) have studied the sediment of 233 aquaculture ponds (164 ponds in Thailand) in the world with the age of 1–52 years (average 14.9 ± 10.4 years). The sediment thickness of these ponds ranged from 4 to 36 cm, with an average of 16.8 ± 11 cm. The increment of sediment thickness was 1.44 ± 0.79 cm/year, which was equivalent to 6840 g/(m^2.year). The dry weight density of the

Table 8.1 Annual sediment fluxes of total particulate matter (TPM), particulate organic carbon (POC), particulate organic nitrogen (PON), total phosphorus (TP), chlorophyll *a* (Chl *a*), and resuspension rate (ReS) in sea cucumber farming ponds (from Ren et al. 2010)

Months	TPM g/(m^2·d)	POC mg/(m^2·d)	PON mg/(m^2·d)	TP mg/(m^2·d)	Chl *a* mg/(m^2·d)	ReS %
7 Apr	24.8 ± 1.2	782.5 ± 72.6	87.0 ± 5.8	17.3 ± 1.4	2.5 ± 0.1	89.6
7 May	38.3 ± 2.7	1104.3 ± 22.1	113.4 ± 13.4	21.6 ± 2.1	4.4 ± 0.4	95.5
7 Jun	14.6 ± 1.8	512.9 ± 71.6	58.9 ± 7.0	11.6 ± 0.6	1.2 ± 0.3	89.6
7 July	18.0 ± 2.6	626.7 ± 79.8	57.7 ± 19.4	19.4 ± 2.3	0.9 ± 0.2	66.5
7 Aug	23.6 ± 3.8	484.8 ± 28.1	74.2 ± 7.4	16.6 ± 3.4	3.7 ± 0.9	67.1
7 Sept	29.3 ± 3.2	1084.5 ± 73.9	146.7 ± 12.7	22.7 ± 2.5	3.6 ± 0.5	83.8
7 Oct	28.8 ± 0.7	1200.6 ± 75.9	155.5 ± 1.4	16.6 ± 0.5	4.0 ± 0.8	90.5
7 Nov	31.8 ± 1.8	1142.4 ± 88.0	174.8 ± 12.3	16.2 ± 1.6	2.6 ± 0.3	92.1
7 Dec	14.5 ± 2.5	465.3 ± 65.2	52.2 ± 6.6	10.8 ± 1.6	1.2 ± 0.2	79.3
8 Jan	10.2 ± 1.2	377.0 ± 38.9	45.5 ± 5.7	9.4 ± 1.1	1.0 ± 0.1	59.6
8 Feb	11.9 ± 0.5	419.8 ± 26.2	50.8 ± 1.5	9.2 ± 0.4	1.4 ± 0.4	69.8
8 Mar	19.1 ± 1.5	754.6 ± 86.5	80.6 ± 14.4	16.6 ± 0.3	2.8 ± 0.5	87.9
8 Apr	22.1 ± 1.3	874.3 ± 244.0	99.9 ± 22.2	15.1 ± 1.1	2.8 ± 0.2	91.0
Mean	22.1	756.1	92.1	15.6	2.5	81.7

sediment was 0.176 ± 0.760 g/cm^3, with an average of 0.475 ± 0.187 g/cm^3. The organic matter content of sediment was 1.08 ± 7.01%, with an average of 2.46 ± 1.21%.

Soil bacterial dry matter generally contains 10% of nitrogen and 50% of carbon. The organic matter with a carbon and nitrogen ratio (C/N) of 5 is easy to be decomposed by bacteria. According to Boyd's (1995) survey of 346 freshwater and seawater (including brackish) ponds, the C/N of the former is 6.4, while the C/N of the latter is 6.0. Both are much lower than the C/N of the terrestrial soil (10–12). The reason for this is the difference in sources of organic matter and their composition between terrestrial soil and pond sediment. The N content in phytoplankton and residual feed in the pond is 5–10% and 5–6%, respectively, on a dry matter basis. However, the N content in terrestrial plants is generally less than 4%.

Farming scallop and sea cucumber without feeding can have a significant impact on the sediment of the pond. The C/N in the sediment of scallop ponds, sea cucumber ponds, the ponds with no scallop, and sea cucumber and adjacent nearshore areas are 13.2, 24.0, 18.4, and 23.7, respectively (Zheng 2009), which are all much higher than 5. This indicates that organic carbon is more abundant than organic nitrogen in the surface sediment. The high C/N in the sea cucumber ponds and adjacent nearshore areas indicates more biologically unavailable organic carbon in the sediment.

8.3 Respiration of Aquaculture Pond Sediment

The respiration of pond sediment includes aerobic respiration and anaerobic respiration. Heterotrophic microorganisms can obtain nutrients and energy from the decomposition and transformation of organic or inorganic substances. The final electron and hydrogen acceptor of aerobic respiration is dissolved oxygen, while those for anaerobic respiration are organic metabolites and inorganic substances. The formula is as follows:

$$\text{Oxidation}\ \ NH_4^+ + 2O_2 = NO_3^- + 2H^+ + H_2O$$
$$\text{Reduction}\ \ SO_4^{2-} + 4H_2 = S^{2-} + 4H_2O$$

Under aerobic conditions, microorganisms in the sediment can decompose organic matter to produce CO_2 and water. However, in anaerobic conditions, the soluble organic matter, methane and hydrogen sulfide, etc. could be produced. Sediment respiration has a great influence on the water quality and nutrient cycling of the pond.

8.3.1 Aerobic Respiration of Pond Sediment

The respiration of pond sediment is mainly composed of the respiration of benthic animals, benthic algae, and microorganisms. The metabolic activities of benthic animals consume organic matter and dissolved oxygen, and release CO_2. The respiration of benthic algae in the dark consumes dissolved oxygen and releases CO_2. Aerobic respiration of microorganisms is an oxidation reaction process, in which the C in organic matter is oxidized to CO_2 and energy is released.

The organic matter in the pond sediment mainly consists of carbohydrates, proteins, and fats. Because of the different proportions of C, H, and O in these organic matters, the ratio (respiration quotient, *RQ*) of CO_2 produced to O_2 consumed when the organic matter is decomposed is also different. Carbohydrates with 40% C have an *RQ* of 1.0, while proteins and fats have *RQ* of 0.8 and 0.7, respectively. The higher the degree of oxidation of organic matter, the higher the *RQ*. The higher the degree of reduction of organic matter, the lower the *RQ*. More

Table 8.2 Major electron donors, acceptors, and end products for several types of bacteria (from Valiela 1995)

Bacterium types	Electron donor	Electron acceptor	Oxidized end products
Nitrifying bacteria	NO_2^- ,NH_4^+,NH_2OH	O_2,NO_3^-	NO_3^- ,NO_2^-
Sulfur bacteria	H_2S, S^0, $S_2O_3^-$	O_2	S^0,SO_4^{2-}
Hydrogen bacteria	H_2	O, SO_4	H_2O
Methane bacteria	CH_4	O_2	CO_2
Iron bacteria	Fe^{2+}	O_2	Fe^{3+}
CO bacteria	CO	H_2	CH_4

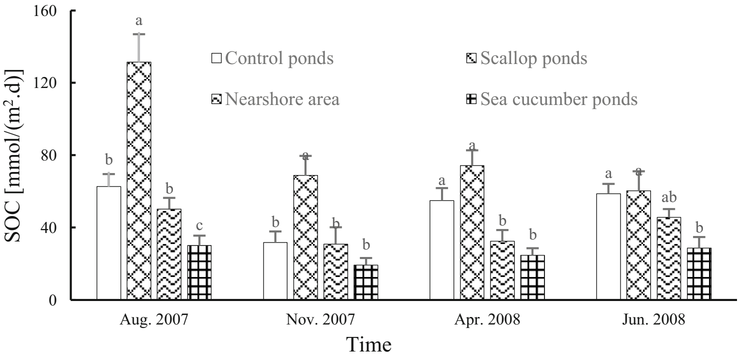


Fig. 8.1 Oxygen consumption (SOC) of sediment (0–5 cm) in the studied ponds (from Zheng 2009). Scallop was cultured during Aug. 2007 and Nov. 2007; no scallop was cultured during Apr. 2008 and Jun. 2008

dissolved oxygen will be consumed when the organic matter with low *RQ* is oxidized.

Under aerobic conditions, heterotrophic microorganisms can oxidize inorganic compounds (Table 8.2).

The main factors affecting the aerobic respiration of microorganisms in pond sediment are DO, temperature, pH, and organic matter. Aerobic respiration requires a continuous supply of oxygen, and anaerobic respiration occurs when all the oxygen is used up. The sediment may be anaerobic due to a poor supply of oxygen even when the pond water is saturated with oxygen. In this case, the sediment will have a black color because of the reductive ferrous compounds.

In the optimal temperature range, the respiration intensity of microorganisms will double if the temperature rises by 10 °C. Each microorganism has its optimal pH range. Fungi thrive better in acidic soils, while bacteria prefer neutral or alkaline soils. Therefore, neutral or alkaline pond sediment is more beneficial to the growth and respiration of bacteria.

Aerobic microorganisms need to decompose organic matter for growth and respiration, so sediments with higher organic matter content will have more microorganisms and higher intensity of respiration. Zheng (2009) reported that the oxygen consumption of 0–5 cm sediment in aquaculture ponds was related to its total organic carbon (TOC) content. As the sedimentation rates of scallop farming ponds were high [293.2 ± 40.8 gdw/(m^2·d)], the TOC content of the scallop farming pond sediment (1.841 ± 0.116%) was higher than those of sea cucumber farming ponds (0.495 ± 0.050%), control ponds without sea cucumber and scallop cultured (1.362 ± 0.180%) and nearshore area (1.210 ± 0.115%). As a result, the oxygen consumption of the sediment in the scallop pond was significantly higher than that of the other waters (Fig. 8.1). After the harvest of the scallop, the oxygen consumption rates of the sediment decreased gradually to the levels similar to the control ponds. Because sea cucumbers can feed on the organic matter in the sediment, the TOC of the sediment in the sea cucumber pond was low, and the oxygen consumption rate was also low in November.

The oxygen consumption rate of surface sediment in freshwater grass carp culture pond in Guangdong, China was 0.76–1.09 gO_2/(m^2·d) (Zhang 2012a), and that of semi-intensive shrimp pond in Shandong Province, China was 0.25–1.74 gO_2/(m^2·d) (Xu et al. 1999). The oxygen consumption rate in the surface sediment of an intensive *Ictalunes punctatus* culture pond in Alabama, USA was 0.19–2.74 gO_2/(m^2·d) (Mezainis 1977), and the oxygen consumption in Israel's intensive aquaculture pond was 3–4 gO_2/(m^2·d) (Schroeder 1987). It can be seen that the oxygen consumption rate of the pond sediment is related to the type of aquaculture systems and stocking density.

The oxygen consumption rate of sediment is also related to various factors such as water temperature. Sediment oxygen consumption (SOC) of seawater ponds under different temperatures and dissolved oxygen conditions is shown in Fig. 8.2 (Zheng 2009). As can be seen from the figure, the oxygen consumption rate of pond sediment varied between 155 mg/(m^2·d) and 1668 mg/(m^2·d). With the increase in temperature and DO, SOC exhibited an increasing trend. The oxygen consumption rate of pond sediment in winter in northern China is relatively low. For example, the oxygen consumption rate of surface sediment in overwintering fish ponds in Jilin Province is 0.18–0.65 gO_2/(m^2·d) (Yang and Lei 1998).

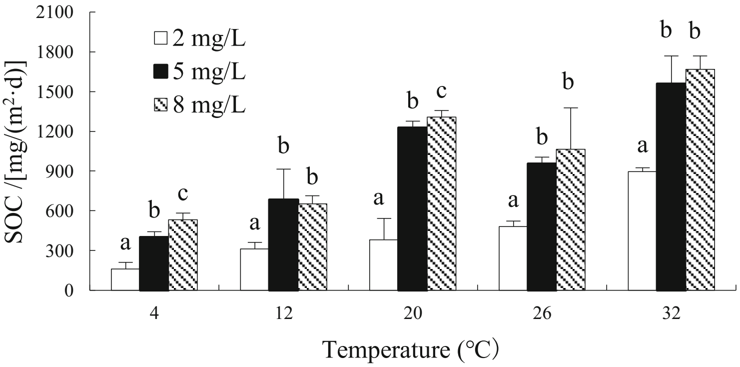


Fig. 8.2 Sediment oxygen consumption (SOC) of seawater pond under different temperatures and dissolved oxygen conditions (from Zheng 2009)

When the pond is aerobic, the aerobic decomposition rate of organic matter increases, and the accumulation rate of organic matter in the sediment slows down. The study of Ghosh and Mohanty (1981) showed that aeration could promote the mineralization rate of organic nitrogen in sediment by 20–41%.

8.3.2 Anaerobic Respiration of Pond Sediment

When the pond water is anoxic, the sediment will be also anoxic. Even though the water is aerobic, only a very thin layer of the sediment is aerobic and most part is anoxic. Under the aerobic condition, the microorganisms in the pond sediment will carry out aerobic respiration. When the oxygen is used up, anaerobic respiration by microorganisms, or reduction reactions of relatively oxidized inorganic or organic compounds will occur automatically. Fermentation is a type of anaerobic respiration in which microorganisms decompose complex organic compounds into simpler ones.

Many microorganisms can use relatively oxidized inorganic substances as electron acceptors instead of oxygen. Bacteria using nitric acid as an electron acceptor can hydrolyze complex compounds and produce CO_2, while nitric acid is reduced to nitrite, ammonia, nitrogen, or nitrogen oxides. In the zone where nitric acid reduction occurs, part of the organic carbon is completely oxidized to CO_2, and others are converted to organic fermentation products.

$$HNO_3^- + H^+ \rightarrow HNO_2 + H_2O$$

$$2HNO_2 + 4H^+ \rightarrow H_2N_2O_2 + 2H_2O$$

$$H_2N_2O_2 + 4H^+ \rightarrow 2NH_2OH$$

$$NH_2OH + 2H^+ \rightarrow NH_3 + 2H_2O$$

$$H_2N_2O_2 \rightarrow N_2O + H_2O$$

$$H_2N_2O_2 + 2H^+ \rightarrow N_2 + 2H_2O$$

$$N_2O + 2H^+ \rightarrow N_2 + H_2O$$

Iron and manganese reducing bacteria decompose organic matter using iron oxide and manganese oxide as oxidants to produce ferrous iron (Fe^{2+}) and reduced manganese (Mn^{2+}). Sulfate acid-reducing bacteria and methane-producing bacteria cannot hydrolyze complex organic matter, simple carbohydrates, and amino acids. They can only use short-chain fatty acids and simple ethanol produced by fermentation bacteria as organic carbon sources, and produce hydrogen sulfide and methane (Boyd 1995).

In general, the deeper the pond sediment, the lower the redox potential. Each layer of the pond sediment has its own unique redox reactions. When

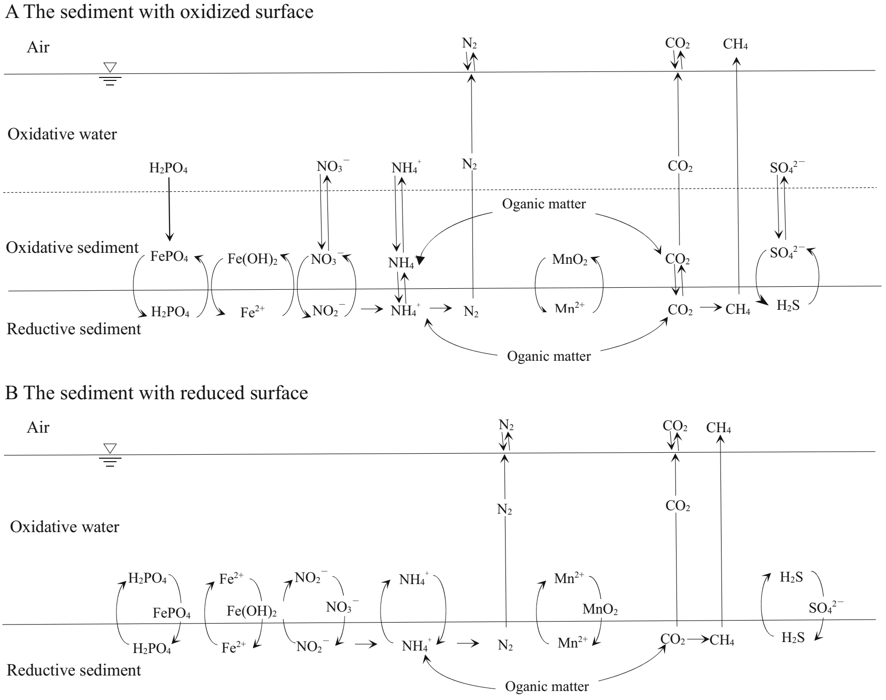


Fig. 8.3 Matter exchanges between sediment and water in the pond (from Boyd 1995)

microorganisms consume oxygen, the redox potential of sediments will decrease. With the decrease of redox potential, the electron acceptors of microbial respiration change to nitric acid, nitrite, ferric iron, oxide manganese, sulfuric acid, and carbon dioxide. The by-products of anaerobic respiration are soluble organic compounds, CO_2, ammonia, nitrite, nitrogen, ferrous iron, reduced manganese, hydrogen sulfide, hydrogen, methane, and so on (Boyd 1995).

Mortimer (1942) measured the redox potential of indoor closed (without oxygen supplementation) and open (with oxygen supplementation) sediment-water systems. The results showed that the redox potential of the sediment in the closed system is lower, and there are higher concentrations of iron, manganese, phosphoric acid, ammonia, and nitrite in the water. The concentration of sulfuric acid is low because it is reduced to hydrogen sulfide. All these changes in water quality are caused by the anaerobic respiration of sediments.

When the pond water is aerobic, there will be a layer of oxidative sediment, which will hinder the diffusion of reducing substances from the sediment into the overlying water (Fig. 8.3a). However, when the bottom water is anoxic or the surface sediment is in reduction condition, the reducing substances in sediment are easier to diffuse into water (Fig. 8.3b).

The bioturbation of benthic fish (carp, crucian carp, channel catfish, etc.) raised in the pond or aeration can disturb the layer of oxidative sediment. Such disturbance will cause the reducing substances such as nitrite in the sediment to enter the water.

Some reducing compounds, such as H_2S, are highly toxic to cultured animals and have certain effects on benthic fish or crustaceans (see Sect. 2.3.3).

8.4 N and P Exchange Between Sediment and Overlying Water

Sediment is the main reservoir of dissolved nutrients and ions from pond water. Some ions exchanged between water and sediment and reached equilibrium. The residual feed, feces, and biogenic deposits in sediment could come back to water through decomposition, mineralization, and diffusion processes. These processes directly affect the water and sediment quality and the yield of aquaculture.

8.4.1 Nitrogen Exchange Between Sediment and Overlying Water

Lots of nutrients come into the aquaculture system through feeding or fertilization. As the system has limited utilization rates of these nutrients, a large amount of organic matter will be settled and accumulated at the bottom of the pond. Most N and P accumulates in the sediment due to their low unitization rates (11–36%) in semi-intensive fish ponds (Schroeder 1990). The N and P deposition to harvest product account for 70 and 35.4%, respectively, of the total N and P input in tilapia ponds with organic fertilizer used (Green 1995). Funge and Briggs (1998) found that only 10% of N and 7% of P were utilized in intensive shrimp ponds and others were accumulated in the sediment.

The N in the pond sediment mainly exists as organic N, which accounts for 70–90% of the total N. In the sediment, organic N is transformed into inorganic N by microorganisms. At the same time, due to other abiotic factors, complex dynamic equilibrium is formed among various forms of N.

Nitrogen transformation can be divided into three processes: ammonification, nitrification, and denitrification. Unlike the sediments of natural water, the organic matter accumulated in the pond sediments usually has low C/N, which is easier to be decomposed by microorganisms. Ammonia produced by the ammonification of organic matter will first enter the interstitial water of sediment, and then diffuse into the overlying water due to concentration gradient. The concentration of ammonia in the interstitial water of sediment is 10–25 times than that in the overlying water in a grass carp polyculture pond. However, the concentrations of nitrate and nitrite are lower in the interstitial water compared with the overlying water (Zhao et al. 2011a).

Ammonia produced by the ammonification process in sediments may be further oxidized to nitrate or nitrite before entering the overlying water. This nitrification process consumes oxygen. Nitrate produced by nitrification can be reduced to N_2O or N_2 (denitrification) under anoxic conditions, resulting in nitrogen loss in the form

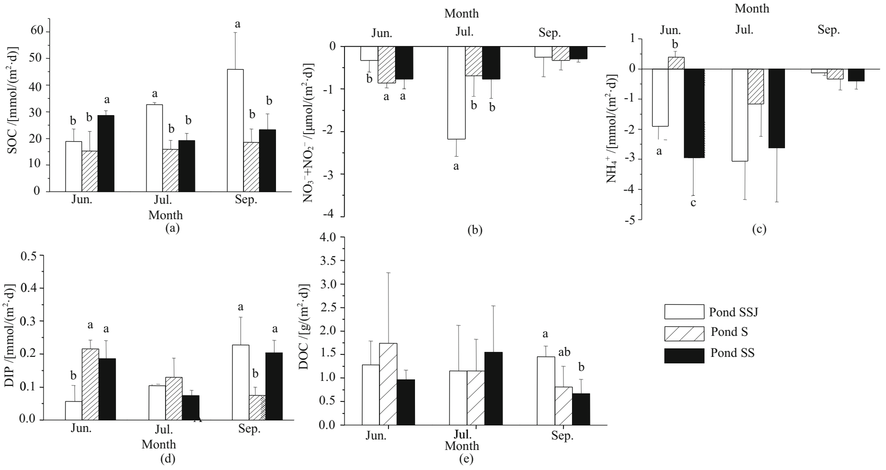


Fig. 8.4 Comparisons on benthic fluxes of experimental ponds in three months (from Zheng et al. 2009). (**a**) *SOC* sediment oxygen consumption; (**b**) Sediment nitrate + nitrite fluxes; (**c**) Sediment ammonium fluxes; (**d**) Sediment phosphate fluxes; (**e**) Sediment dissolved organic carbon (DOC) fluxes. Negative values indicate sediment uptake. *SS* polyculture ponds of sea cucumber with shrimp, *SSJ* polyculture ponds of sea cucumber with shrimp and jellyfish

of N_2 in sediment. Most denitrifying bacteria are facultatively anaerobic, and denitrification is more likely to occur when the sediment-water interface is anoxic.

The nitrification rates in grass carp polyculture ponds range from 0 to 12.9 mmol/(m^2·d) (Guo 2011), which are higher than those in the sediments of the Pearl River estuary [0.32–2.43 mmol/(m^2·d)] and the sediments of Daya Bay [0–4.68 μmol/(m^2·d)] (Xu et al. 2005b, 2007a). The ammonization rates in the grass carp polyculture pond range from 0 to 41.25 mmol/(m^2·d), which are higher than those in the sediments of the Pearl River estuary [4.17–13.06 mmol/(m^2·d)] and the sea cucumber culture pond [0–21.916 mg/(m^2·d)] (Zheng 2009). The denitrification rates of the grass carp polyculture pond range from 0 to 734.15 μmol/(m^2·d), which are much higher than that of sea cucumber ponds, and much lower than that of the shrimp pond, and similar to the denitrification rate of many estuaries and lakes.

The sediments absorbed nitrate in monoculture and polyculture ponds of sea cucumber, and the benthic fluxes are significantly different in different months (Fig. 8.4). The absorption rates are higher in July. There is a trend of ammonia uptake in all the pond sediments except the monoculture pond in June (Zheng et al. 2009). In grass carp culture pond ammonia is sometimes released and sometimes absorbed by the sediment from June to October; nitrate and nitrite are absorbed by the sediment in July and August, and released in the rest time of the year (Guo 2011).

The factors affecting the nitrogen flux between the sediment and overlying water mainly include temperature, DO, redox potential, organic matter content, and biodisturbance. Therefore, the nitrogen flux at the sediment-water interface varies greatly in different culture systems and seasons.

8.4.2 Phosphorus Exchange Between Sediment and Overlying Water

Phosphorus in sediments exists in a variety of complex bound forms. It can be divided into particulate and dissolved phosphorus. It can also be divided into inorganic and organic phosphorus based on its properties. Others divide phosphorus into organically bound and unstable or weakly bound phosphorus, Fe or Al bound phosphorus, Ca bound phosphorus, etc. based on its morphology.

The organic phosphorus in pond sediment can be decomposed by microorganisms and produces inorganic phosphorus, which diffuses into the overlying water to participate in the phosphorus cycling in the water. Sediment is a large reservoir of soluble reactive phosphorus (SRP) in the overlying water. The concentration of SRP in the interstitial water of the surface sediment is higher than that in the overlying water (Zhao et al. 2011a), and SRP will gradually diffuse into the overlying water due to the concentration gradient. However, when the concentration of SRP in the overlying water is higher, the sediment will absorb SRP.

Fe^{3+}, Ca^{2+}, and Al^{3+} can precipitate SRP by forming insoluble phosphate. In addition, colloidal or clay particles in the overlying water may adsorb large amounts of SRP. Under certain conditions, the adsorbed phosphorus can be released into the water through ion exchange.

The sediment in monoculture and polyculture ponds of sea cucumber absorbs dissolved inorganic phosphorus (DIP) from water during the culture seasons, and there are significant differences among different culture systems (Fig. 8.4). The DIP in the sediment of grass carp culture ponds is released to overlying water in June, July, and October with the minimum flux of 0.06–0.93 mmol/(m^2·d) in June. While the DIP is mainly absorbed by the sediment in August and September, and the maximum flux is -500 mmol/(m^2·d) (Guo 2011).

8.4.3 Factors Affecting Exchange of N and P Between Sediment and Water

Nutrients are exchanged between sediment and overlying water by the processes of diffusion, adsorption-desorption, precipitation-dissolution, and decomposition of organic matter. The direct factor affecting the rate and direction of nutrient exchange at the sediment-water interface is the difference in nutrient concentration between the interstitial water of sediment and the overlying water. Other influencing factors include temperature, DO, redox potential, organic matter content, and the physical properties of the sediment. The disturbance of benthic animals can also affect the exchange processes.

8.4.3.1 Temperature and Dissolved Oxygen

The adsorption reaction between sediment and the overlying water is usually a heat-generating process. When the temperature rises, the adsorption capacity of sediment decreases. The ions absorbed on the surface of solid particles are easily desorbed and

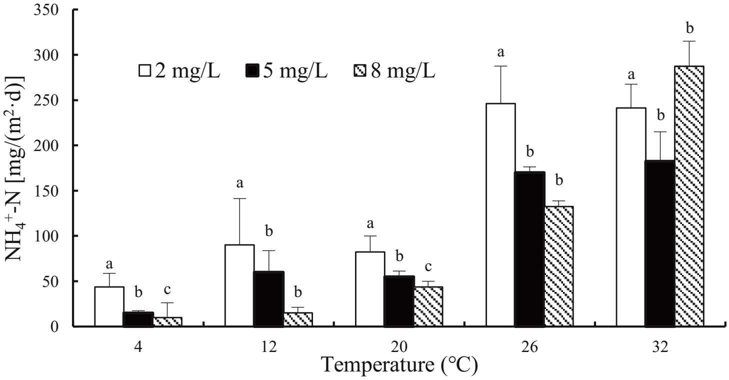


Fig. 8.5 Fluxes of ammonium across sediment-water of seawater pond in different temperatures and dissolved oxygen conditions (from Zheng 2009)

enter the interstitial water of sediment and the overlying water. Moreover, the solubility and the diffusion rate of nutrients increase as temperature increases.

PO_4^{3-} can be adsorbed by binding to the hydroxyl on the surface of sediment soil. When the DO concentration in the sediment increases, the desorption of PO_4^{3-} is inhibited. On the contrary, the reductive environment is in favor of the desorption of PO_4^{3-}. The DO concentration affects the nitrification-denitrification processes, and thus affects the conversion rate and flux of different nitrogen forms. Nitrification consumes oxygen. When the oxygen concentration in the sediment increases, the nitrification rate increases. At the same time, the exchange rate of NH_4^+ decreases, while the exchange rates of NO_3^- and NO_2^- increase. As the sediment is in reduction condition in summer, the flux of ammonium across the sediment-water interface is three times more than that of spring and winter (Sundby et al. 1992). Statistical analysis shows that the DO change and oxygen consumption in sediment can explain 68% of the NH_4^+ exchange rate; the DO change in overlying water and the NO_2^- exchange rate can explain 73% of the NO_3^- exchange rate; the NO_3^- exchange rate and temperature can explain 74% of the NO_2^- exchange rate.

The NH_4^+ diffuses from the sediment to the overlying water in seawater sea cucumber culture ponds under different temperatures and DO conditions, however, the variations are large (Zheng 2009). The NH_4^+ flux increases as temperature increases, but decreases as dissolved oxygen increases (Fig. 8.5).

The PO_4^{3-} fluxes between sediment and overlying water are also affected by temperature and DO. At 4 °C, PO_4^{3-} diffused from the overlying water to sediment under different DO concentrations; however, the difference among different DO treatments was not significant. At the other temperature treatments, the sediment released PO_4^{3-} to overlying water. When the dissolved oxygen was 5 and 8 mg/L, the PO_4^{3-} fluxes tended to increase with the increase of temperature.

8.4.3.2 pH and Redox Potential

The pH, as an important factor affecting the redox condition and chemical equilibrium state at the sediment-water interface, has a significant impact on nutrient biogeochemical processes by indirectly affecting microbial activities (Liu et al. 2002b). Jin et al. (2004) reported that pH was a major factor influencing the release of phosphorus in the sediment of Taihu Lake.

8.4.3.3 Properties and Organic Matters of Sediments

The surface sediment of aquaculture ponds is mainly composed of oxides, clays, and organic matter. Both the clay particles with electric charge and large surface area, and the organic matter with biological availability and high chemical activity have a great influence on the nutrient exchange between sediment and water. The adsorption and release of PO_4^{3-} by ferric oxide determine the concentration of PO_4^{3-} in interstitial water, which in turn directly affects the exchange of PO_4^{3-} at the sediment-water interface.

The nutrients in the interstitial water of the pond sediment are mainly generated by the decomposition of organic matter. The nutrients could diffuse and transfer to the overlying water. Therefore, the content and replenishment of organic matter in sediment have an important effect on the exchange of nutrients.

8.4.3.4 Bioturbation

Bioturbation refers to the mixing and structural change of sediment particles caused by the activities of benthic animals. Bioturbation can change the physical and chemical properties of sediment and affect the biogeochemical process of the sediment-water interface. In addition, bioturbation can change the physical structure, stability, and erosion rate of sediments, and accelerate the nutrient exchange between interstitial water and overlying water. The activities of benthos can destroy the original surface structure and the vertical structure of sediment, and promote the release of inorganic nitrogenous nutrients. The presence of benthic bivalve can greatly accelerate the sediment resuspension and biosedimentation rate. The disturbance of benthic burrowing animals can promote the coupling of nitrification and denitrification in sediment, thus promoting the denitrogenating of water. The bioturbation of benthos also affects the acidity, alkalinity, and redox potential of sediments. Meanwhile, it could also change the forms of phosphorus, promote the oxidation of phosphorus, and inhibit the release of soluble reactive phosphorus.

Bioturbation can change the structure and succession of benthic communities, and affect the abundance and diversity of microorganisms and meiofauna. The burrowing and pipe-building behaviors of benthos have a great influence on the microbial community in the sediment and thus improve the utilization of organic matter, exacerbate chemical reactions and fluctuations in redox conditions, and affect the metabolic activities of the microbial community on the pipe wall.

8.5 Remediation of Aquaculture Pond Sediment

In aquaculture, the pond sediment often changes to a condition that is not beneficial for production due to natural or man-made reasons, and it is necessary to remediate the sediment in order to sustain production. Pond sediment could be improved by physical, chemical, and biological methods, and each method has its advantages and disadvantages.

8.5.1 Physical Remediation

The physical remediation methods of aquaculture ponds include exposure, freezing, and dredging. The pond can be drained after the harvest of cultured organisms, then the sediment can be exposed to the sun or frozen in winter to improve the sediment quality. Exposure and freezing can not only kill pests, parasites, and pathogens but also increase the redox potential and the decomposition rate of organic matter in the sediment. Those measures would result in more nutrients releasing into the water after the pond is refilled with water.

After the pond is drained, the removal of excessive silt can reduce the organic matter in the sediment, improve the sediment quality, and reduce the oxygen consumption when the pond is refilled. Silt from freshwater ponds can be directly used as fertilizer for crops. Silt from seawater ponds should be washed by rain first to grow the salt-tolerant crops or be used as fertilizer for crops. According to Boyd (1995), after being placed outdoors for 6–8 months, the salt content of the silt from marine shrimp pond in Southeast Asian countries is not different from that of the silt from freshwater ponds.

In the past, fish farmers in Jiangsu and Zhejiang provinces, China, stirred the pond sediment with iron chains to improve the quality of the sediment. At present, the “water ploughs” are used to improve the water and sediment quality by mixing the upper layer of oxygen-saturated water with the lower layer of oxygen-deficient water.

Line the bottom with water-proof mulch is also a common way to prevent the deterioration of sediment in the shrimp farming ponds of the supratidal zone. Line the whole pond or the bottom can completely or partially separate the pond soil from pond water, which facilitates dredging and disinfection and also helps to prevent the spread of pathogens in the sediments (see related content in Chap. 13).

The heat released during the dissolution of the quicklime can kill some harmful organisms in the sediment. Quicklime is also used to increase hardness and alkalinity in the pond.

8.5.2 Chemical Remediation

The chemical remediation of aquaculture pond sediment is to change the contaminants into harmless forms through the application of chemical reagents. Commonly used methods include alkalization and oxidation.

8.5.2.1 Alkalization of Pond Sediment

Accumulation of residual feed and feces in the sediment of the aquaculture pond will reduce the pH of the sediment. When the pH of the surface sediment is below 6.5, alkalization should be considered.

Pond sediment in acid-soil areas often has low pH. In rainy and humid inland areas, the soils tend to be highly leached to contain a high proportion of exchangeable aluminum and iron compounds. Salt concentrations of the pond water in these areas are not high. The pond water and sediment are acidic and need to be alkalized frequently. Ponds that have high organic matter or acidic sulfate soil at the coast also need to be alkalized frequently (Boyd 1995).

The organic colloid in the sediment is often negatively charged and can attract cations; carboxy groups on humus can dissociate to generate H^+ and then negatively charged, and clay particles generally dissociate more H^+ than OH^-, and thus have negative charges. Therefore, there is an ion exchange between sediment and overlying water or interstitial water. Take the reaction of Al^{3+} for example:

$$\text{Al–clay particles} \leftrightarrow Al^{3+} + 3H_2O \leftrightarrow Al(OH)_3 + 3H^+$$

In soil chemistry, exchangeable acidity refers to the amount of standard sodium hydroxide solution used to exchange H^+ and Al^{3+} adsorbed on the soil colloids. The exchangeable acidity of the soil depends on pH and cation exchange capacity. If the exchangeable acidity of the sediment is too high for aquaculture animals, alkaline substances should be applied to remediate it.

Quicklime is commonly used in the alkalization of pond sediment. The reaction that happened in sediment after usage of quicklime is as follows:

$$2H^+ + CaCO_3 \rightarrow Ca^{2+} + CO_2 + H_2O$$

As a result, Al^{3+} leaves the colloidal particles to precipitate in $Al(OH)_3$. The H^+ in water is neutralized, the pH rises, and the exchangeable Al^{3+} in sediment is replaced by Ca^{2+}.

Pyrite (FeS_2) accumulation is common in the soils of brackish water ponds in a coastal wetland. Total sulfur in some coastal soils can be as high as 5%. The soil on the pond embankment above the water surface is exposed to air and the pyrite in it will be oxidized to sulfuric acid:

$$FeS_2 + H_2O + 3.5O_2 \rightarrow FeSO_4 + H_2SO_4$$

$$2FeSO_4 + ½O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O$$

$$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O \rightarrow 15FeSO_4 + 8H_2SO_4$$

In rainy days, these sulfuric acids will enter the pond with rainwater, lowering the pH of pond water. The low pH might sometimes affect or even kill farmed organisms.

When such ponds are drained, the pond soil is exposed to air again, and the sulfur compounds in the soil will be oxidized to sulfuric acid. Therefore, a high water level should be kept for this kind of pond. The pond should be refilled as soon as possible after drainage. Frequent water exchange can effectively prevent the acidification of the sediment in seawater ponds.

Regular alkalization of such ponds with quicklime is the most effective way to maintain a good quality of water or sediment. The application of quicklime could increase the alkalinity, hardness, and pH of both pond water and sediment, and promote the accumulation of humus in the ponds. The amount of quicklime used is related to the exchangeable acidity of the sediment and can be calculated based on the method suggested by Boyd (1995) and Chen (1996). It is important to note that inorganic fertilizers should not be applied until a few weeks after the application of quicklime, otherwise the effectiveness of the application will be affected.

8.5.2.2 Oxidation of Pond Sediment

Increasing the DO concentration and redox potential in the interstitial water of surface sediment and overlying water can reduce the diffusion of toxic compounds from pond sediment into the water. The measures to increase DO and redox potential are named sediment oxidation technology and include the use of aerators and chemicals.

The functions of using an aerator in an aquaculture pond are to oxygenate the water, break the water temperature stratification, and promote the water flow. The water in semi-intensive and intensive aquaculture ponds is often hypoxic after midnight, and it is necessary to turn on the aerators.

During midday with high temperatures and weak wind, the water in the pond is easy to be stratified, which hinders the vertical circulation of water. Due to intense photosynthesis, the upper water layers may be hypersaturated with oxygen, but the lower water layers and surface sediment may be hypoxic due to respiration. At this time turning on the aerator can promote the mixing of upper and lower water layers, reduce the escape of oxygen from the upper layer of water to the air, and increase the DO of the lower layer water.

Using of aerator can avoid the hypoxia of surface sediment. However, ordinary aerators can create strong water currents and erode the embankment of a pond sometimes, therefore, the micropore aerator will be better.

Bleach (calcium hypochlorite) is a strong oxidant commonly used in aquaculture to improve sediment quality. When it meets water, it generates HClO and O_2:

$$Ca(ClO)_2 + CO_2 + H_2O = CaCO_3 + 2HClO$$

$$2HClO = 2HCl + O_2$$

Sprinkling bleach on pond sediment can not only kill pathogens but also oxidize the reduced compounds in sediment.

Potassium permanganate ($KMnO_4$) is also a strong oxidant, which can release oxygen in water:

$$2KMnO_4 + H_2O \rightarrow 2KOH + 2MnO_2 + 1.5O_2$$

Therefore, application of $KmnO_4$ can reduce chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in water and sediment, and can also oxidize the reduced H_2S and Fe^{2+}:

$$3H_2S + 4KMnO_4 \rightarrow 2K_2SO_4 + S + 3MnO + MnO_2 + 3H_2O$$

$$3Fe(HCO_3)_2 + KMnO_4 + 7H_2O \rightarrow MnO_2 + 3Fe(OH)_3 \downarrow + KHCO_3 + 5H_2CO_3$$

$KMnO_4$ is commonly used as a bactericide, which can oxidize the surface membranes of bacterial cells and kill aquatic ectoparasites. However, high concentrations of $KMnO_4$ are also toxic to aquaculture organisms.

In addition, H_2O_2 is also a strong oxidant that can be decomposed in water to produce oxygen. It can be used as a disinfectant as well as a sediment ameliorant to reduce the concentration of organic matter in water.

Some scholars suggested using $NaNO_3$ and CaO_2 to improve pond sediment. The chemicals could oxygenate surface sediment (Chamberlain 1988), and prevent the formation of reductive sediment (Avnimelech and Zohar 1986). $NaNO_3$ is cheaper than CaO_2 and easy to use, but it could be reduced to nitrite by bacteria in a hypoxic environment. When a high concentration of nitrite diffuses into water, it can harm farmed animals.

Shigeno (1978) recommended the use of ferrous oxide powder in ponds to prevent the release of H_2S from sediment. The reaction is:

$$Fe^{2+} + S^{2-} = FeS \downarrow$$

Although this method can temporarily eliminate H_2S, it is more feasible to avoid H_2S generation by increasing the redox potential of sediment.

8.5.3 Bioremediation

Bioremediation is a technology that utilizes plants, animals, and microorganisms to absorb, degrade, and transform pollutants in the sediment, thus reducing the concentration of toxic and harmful substances in the environment or making them completely harmless. It can be divided into in-situ and ex-situ bioremediation based on the location of implementation. It can also be divided into microbial remediation, phytoremediation, and animal remediation. In general, bioremediation methods are cheap, safe, and easy to operate.

8.5.3.1 Microbial Remediation

Microbial remediation is to use indigenous microorganisms and selected exogenous microorganisms to improve the metabolic characteristics of microorganisms in a system, enhance the degradation rate of organic matter in sediment, and inhibit the reproduction of harmful bacteria. Microorganisms have been used to improve water and sediment quality in shrimp farming ponds. For example, photosynthetic bacteria, *Bacillus subtilis*, and compound microbial preparation can improve water and sediment quality. The application of *Bacillus subtilis* can change the composition of the bacterial community and increase the quantity of aerobic bacteria in the sediment of shrimp farming ponds (Lin et al. 2005). Immobilized microorganisms can effectively degrade organic matter in the sediment of shrimp farming ponds (Jin et al. 2010).

In recent years, various probiotics are used to improve water and sediment quality in aquaculture ponds. Some probiotics work well but others do not work as expected. The effectiveness and function of probiotics in water and sediment quality improvement still need to be further studied (Boyd 1995; Schryver and Vadstein 2014).

8.5.3.2 Phytoremediation

Phytoremediation is a technique that uses the absorption and metabolism of plants or co-existing microorganisms to reduce or eliminate pollutants. There are three main mechanisms used by plants to improve sediment: direct absorption of pollutants by plants; plant and rhizosphere microorganism working together to promote the absorption, transformation and degradation of pollutants; enzymes secreted by plant roots degrading organic pollutants (Sriprapat et al. 2011).

Plants can directly absorb the organic pollutants in sediment and then store the non-toxic intermediate metabolites in their body. *Phoenopsis crastii* is used to remediate the organic contaminated sediments and the nitrogen content in plant tissues increases by 2.9–6.7% (Bramwell and Devi Parsad 1995). After the plantation of lotus roots, the organic matter contents in the 0–5 and 5–10 cm sediments decrease by 11.45% and 19.12%, respectively (Zhang 2013a).

The degradation rate of organic pollutants in rhizosphere is greater than that of other regions (Xia et al. 2002). The quantity of microorganisms in the rhizosphere is about 10 times of that in the non-rhizosphere. Plants can provide oxygen to microorganisms; thus, the aerobic transformation process takes place in the rhizosphere (Yin et al. 2007). Zhang (2013a) found that planting lotus root in the intensive fish farming pond could promote the degradation capacity of organic matter by microorganisms, and accelerate the degradation of organic matter in the rhizosphere.

Aquatic plants can effectively reduce the pollutants from uneaten feed and feces in aquaculture, but the plants must be harvested in time. Otherwise, the plants will be decomposed to produce secondary pollution. Therefore, it is better to grow economical plants.

The fresh diatoms (*Cylindrotheca fusiformis*) applied to sea cucumber farming ponds are not good food sources for the sea cucumber, but also can effectively improve the sediment quality when there is light in the system (Shi et al. 2013; Li et al. 2015). Some of the diatom cells are active and can photosynthesize and absorb nutrients in the water. Compared with the control ponds without applying the diatom, the utilization of organic carbon, nitrogen, and total phosphorus in the ponds applying the diatoms increase by 16.8%, 23.4%, and 8%, respectively. In addition, the economic benefits of the ponds also increase by 5.1% compared with the control ponds.

8.5.3.3 Animal Remediation

Some benthos can feed on residual feed and feces, detritus of dead plants, and animals in the sediment. Therefore, farmed animals are co-cultured with benthos, such as polychaete (*Neanhtes japonica*) and sea cucumber, in ponds somewhere in China to improve the sediment quality and the yield of the pond (Zhou and Liu 2000; Zhang et al. 1994). The polychaetes (*N. japonica*) are artificially cultured or introduced naturally by tidewater in shrimp farming ponds to improve sediment quality. Plenty of fertilized eggs and larvae of *N. japonica* can be introduced into ponds with tidewater during the spawning days of the animal. *N. japonica* is a good food source for shrimp. In addition, as typical sedimental-feeding benthos, they can feed on the residual feed, feces, and dead organisms in sediments. The feeding activities of *N. japonica* can affect the physical and chemical properties of sediments (Sayama and Kurihara 1983; Zhou and Liu 2000).

Sea cucumber is also an important sediment improver. As typical sedimental-feeding benthos, sea cucumber mainly feeds on organic matter in the sediment. After one year of feeding by sea cucumber, the contents of total organic carbon (TOC), total organic nitrogen (TON), and total phosphorus (TP) in the sediment of the pond are all less than those of the control pond sediments without sea cucumber (Ren et al. 2012) (Fig. 8.6).

As the organic matter content of the sediment decreases due to the feeding of sea cucumbers, the nitrification, denitrification, and ammonification rates of the substrate are all reduced accordingly (Zheng 2009). As shown in Table 8.3, the nitrification rates in the sediment of sea cucumber monoculture pond are significantly lower than those

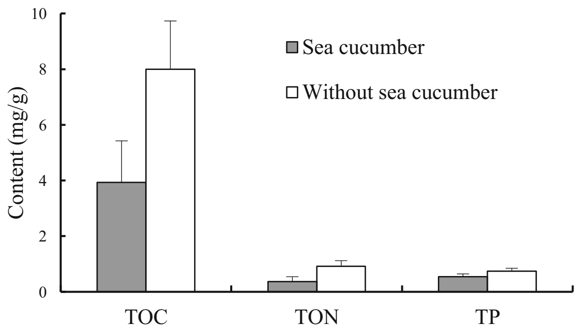


Fig. 8.6 Total organic carbon (TOC), total organic nitrogen (TON), and total phosphorus (TP) contents in the sediment of sea cucumber culture ponds and the pond without sea cucumber (from Ren et al. 2012)

Table 8.3 Nitrification rates of the sediments of sea cucumber monoculture pond, polyculture pond with scallop, control pond, and nearshore sediment (from Zheng 2009)

	Rates of nitrification [mmol/(m^2·d)]				
Sampling sites	Aug., 2007	Nov., 2007	Apr., 2008	Jun., 2008	Average
Sea cucumber monoculture	2.45 ± 0.39^{ab}	1.78 ± 0.40^{b}	1.29 ± 0.55^{a}	2.08 ± 0.35^{a}	1.72
Sea cucumber polyculture with scallop	3.24 ± 0.64^{a}	3.75 ± 0.41^{a}	1.95 ± 0.38^{a}	2.29 ± 0.43^{a}	2.67
Adjacent nearshore	1.24 ± 0.25^{b}	0	0.47 ± 0.09^{b}	0.45 ± 0.22^{b}	0.31
Control pond without sea cucumber	0.45 ± 0.11^{c}	0	0.15 ± 0.03^{c}	0	0.05

Note: The values with different letters in the same column are significantly different from each other ($P < 0.05$)

in the control pond without sea cucumber and the sediment of adjacent nearshore. Similarly, the denitrification and ammonification rates also show the same trend.

Sea cucumbers are also co-cultured with scallop, oyster, abalone, and fish to improve the sediment. It is worth noting that some buried filter-feeding bivalves, such as razor clam (*Sinonovacula constricta*) and short-necked clam (*Ruditapes philippinarum*) in shrimp farming ponds, can improve water quality and increase shrimp production, but these shellfish do not improve sediment quality of the ponds.

Brief Summary

1. The soil texture of aquaculture pond is very important. Moreover, the particle size, organic matter content, pH etc. of pond sediment have a great impact on the water quality of ponds.
2. The materials that form the pond bottom are called sediment or mud. The sediment of the pond included exogenous and endogenous sources. The exogenous sources are mainly particulate matter that comes into the pond when it is filled with water. Endogenous sediments are mainly residual feeds and feces, biological debris, sand, and so on. In some ponds, there is lots of soil in the sediment from the collapse of the embankments. In offshore fish cage areas, the sedimentation of residual feed and the feces from fish are important sources of the sediments, and in bivalve culture areas the biodeposition of feces and pseudofeces from bivalves is an important source of the sediments.
3. There is both aerobic and anaerobic respiration in the sediment of the aquaculture pond. Microorganisms can decompose organic matter under aerobic conditions and produce CO_2 and water. Under anaerobic conditions, soluble organic matter, methane, hydrogen sulfide, and other reducing substances are produced. When the pond water is aerobic, there will be a layer of oxidative sediment, which will hinder the diffusion of reducing substances from the sediment into the overlying water. However, when the bottom water is anoxic or the surface sediment is in

reduction condition, the reducing substances in sediment are easier to diffuse into the water.

4. The direct factor affecting the exchange rate and direction of nutrients is the gradient distributions of nutrients between sediment and the overlying water. Other influencing factors include temperature, dissolved oxygen, redox potential, organic matter content, and the physical properties of the sediment. Bioturbation of benthic animals could also affect the exchange processes.
5. The aquaculture pond sediment can be remediated by physical, chemical, and biological methods. The physical remediation methods of aquaculture ponds include exposure, freezing, and dredging. The chemical remediation of aquaculture pond sediment is to change the contaminants into harmless forms through the application of chemical reagents. Commonly used methods include alkalization and oxidation. Bioremediation is a technology to absorb, degrade, and transform pollutants in the sediment, thus reducing the concentration of toxic and harmful substances in the environment or making them completely harmless. It can be divided into in-situ and ex-situ bioremediation based on the location of implementation. It can also be divided into microbial remediation, phytoremediation, and animal remediation. In general, bioremediation methods are cheap, safe, and easy to operate.
6. The pyrite (FeS_2) accumulation is common in the soils of seawater and brackish water pond in a coastal wetland. FeS_2 is stable under anaerobic conditions, but when the sediments or soil on the pond embankment above the water surface is exposed to air and the pyrite in it will be oxidized to sulfuric acid. For ponds with high sulfur content in the soil, the pH of water can decrease dramatically on rainy days by washing the sulfuric acid on the pond embankment into the pond. High water levels should be kept in this type of pond and water should be refilled as soon as possible after drainage to reduce the formation of sulfuric acid. The application of quicklime can alleviate the decrease of pH in such ponds.

Integrated Aquaculture and Structure Optimization

9

Shuang-Lin Dong

Compared with monoculture, integrated aquaculture (IA) is a multi-species or multi-systems aquaculture model, and has the advantages of high resource utilization, environmental protection, diversified products, disease prevention, and so on. Therefore, IA is generally regarded as a model of sustainable production systems of aquaculture. Structural optimization refers to the optimization of species composition and stocking quantities of each species within a specific IA system.

China has a long history and rich experiences of IA, and has the greatest variety of farmed aquatic species in the world. This chapter will focus on the historical evolution, basic rationales, classification, and structure optimization of the IA in China.

9.1 History of Integrated Aquaculture in China

9.1.1 Definition of Integrated Aquaculture

Muir (1981) defined IA as the techniques of aquaculture which are integrated with conventional agricultural or industrial activities by using their wastes, or which provide useful by-products. Li (1986) defined integrated fish farming in reservoirs as culture of a fish species together harmoniously with other production activities. One of the IA models he cited was that fed common carp in net cage integrated with filter-feeder silver carp outside of the net cages. The feces and feed residual of the common carp can be filtered by the silver carp, and can promote the growth of

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phytoplankton as organic fertilizers. The phytoplankton in turn can be filtered by the silver carp as food.

Edwards et al. (1988) defined integrated farming as ‘an output from one subsystem in an integrated farming system, which otherwise may have been wasted, becomes an input to another subsystem resulting in a greater efficiency of output of desired products from the land/water area under a farmer’s control’. Later, a much broad definition was given by Edwards (1998) as: concurrent or sequential linkages between two or more human activity systems (one or more of which is aquaculture), directly on-side, or indirectly through off-site needs and opportunities, or both.

Tan et al. (1992) defined integrated fish farming as a production method that is mainly aquaculture with multiple operations and integrated use of aquatic and terrestrial ecosystems. Liu and Huang (2008) had a similar definition of IA to Tan’s.

Chopin and Taylor merged multi-trophic aquaculture and integrated aquaculture, and formed the popular term—integrated multi-trophic aquaculture (IMTA) (Chopin and Robinson 2004). Western scholars like to use the term IMTA to describe integrated aquaculture of fed species and extractive species in water (Soto 2009). In China, integrated aquaculture of different feeding habits of aquatic organisms is conventionally called polyculture or co-culture.

The IA is described by the Agriculture Organization of the United Nations (FAO 2008) as: aquaculture system sharing resources, water, feeds, management, etc., with other activities; commonly agricultural, agro-industrial, infrastructural (waste waters, power stations, etc.). Later, the IA is defined by Soto (2009) as the culture of aquatic species within, or together with, the undertaking of other productive activities.

So, IA has both narrowly defined and broadly defined definitions. The broad-defined IA refers to the simultaneous farming of several aquatic organisms or farming aquatic organisms together with other productive activities, which includes the following three forms:

1. The co-culture of aquatic organisms in a pond, such as fish polyculture in a pond.
2. The culture of aquatic organisms with other agro-industrial activities in the same waters, such as fish farming together with duck farming in a pond.
3. The culture of aquatic organisms together with other industrial activities, such as mulberry fish ponds. In addition, aquaculture and ecological tourism, science popularization, and power generation can also be included in the category.

9.1.2 Historical Evolution of Integrated Aquaculture in China

Aquaculture and IA in China have the longest history in the world. Chinese have carried out fish farming activities for about 8000 years at the Jiahu Site, Henan, China. Rice-fish farming probably began at that time. However, until the Three Kingdoms Period (220–265 AD) the rice-fish (common carp) farming was recorded in the book ‘The Seasonal Food’ (Liu and He 1992). It was not until the Tang Zhaozong Dynasty (889–907 AD) that rice-grass carp farming, an ecological aquaculture model, was recorded in the book ‘The Curious in Lingbiao Region’, and the principle of mutual benefit between grass carp and rice in the model was described (see Sect. 1.2.1).

Emperor Li of the Tang Dynasty (618–907 AD) banned common carp farming since the word pronunciation for common carp was ‘Li’. Emperors were considered sacred. Apparently, anything that shared the emperor’s name was sacred and should not be eaten. This ban led the Chinese to develop the culture of other fish species. The culture of grass carp, black carp, silver carp, and bighead carp was developed then. In the book ‘Jiatai Huiji Notes’ (1201–1204 AD) it was recorded that ‘In early spring fingerlings were bought and stocked into ponds…, most of them were bighead carp, silver carp, common carp, grass carp and black carp’. This is the evidence of polyculture of different fish species in a pond (Liu and He 1992).

In the ‘Complete Book on Agriculture’ written by XU Guang-qi (1639 AD) it was recorded that ‘In early spring fingerlings were bought, 600 silver carp and 200 grass carp were stocked into a pond, only the grass carp was fed with grass’. The proverb ‘one grass carp feeds three silver carp’ is still prevalent in China now. Grass carp in this farming model is fed species, its faces and feed residual can be filtered by the silver carp, or can promote the growth of phytoplankton as organic fertilizers (Liu and He 1992). This is the conclusive evidence of trophic integration of different fish species, in which the optimized ratio for stocking silver carp and grass carp is provided and trophic relationship between them is clarified. In the book, the integrated farming of sheep and grass carp and silver carp was also recorded: ‘Every morning the feces of the sheep were swept into the pond as feed or fertilizer’. This is a reliable record of fish-livestock integration in China.

According to ‘The New Story of Canton’ written by QU Da-jun of Qing Dynasty (about 1700 AD), the integration of dike-pond was very popular in seventeenth century in the Pearl River Delta region. Fish farming integrated with plantation of lichee, tea plant, mulberry, forage crops, vegetables, silk worm breeding, and pig raising. Crops and animal feces were fed directly to carps in ponds (Liu and Huang 2008).

Mariculture starts much later than freshwater aquaculture in China. In Song Dynasty (960–1279 AD) the farmers at Jinmen of Fujian Province began culturing seaweeds (*Gloiopeltis* sp.) on rocky reefs. Then the farmers at Pingtan of Fujian Province created the method of porphyria culture. In the ‘Cultivation of Oyster’ written by ZHENG Hong-tu of Ming Dynasty (1368–1644 AD), the cultivation of oyster was systematically described in detail.

In 1975, large-scale integrated mariculture of kelp and bivalve was done in Penglai, Shandong Province (Xie 1981). At the same time intercrop of kelp and mussel in Fuding, Fujian Province, also occurred (Fu 1979). Currently, the integrated mariculture of kelp, scallop, abalone, sea cucumber, and so on are applied in nearshore areas widely.

In the pond the integrated mariculture of Chinese shrimp (*Fenneropenaeus chinesis*) and mullet (*Mugil soiuy*) was recorded at Ganyu, Jiangsu Province, in 1979 (Wu et al. 1980). Currently, integrated mariculture has become common practice in China, and is widely praised by the international academic community (Sorgeloos 2013).

9.2 Rationales of Integrated Aquaculture

IA has been widely practiced in Asia, and has drawn much attention of the western world since Chopin and Taylor (Chopin and Robinson 2004) created the term integrated multi-trophic aquaculture system (IMTA). From the definition of IMTA and IA given by Edwards et al. (1988) and Chopin and Robinson (2004), the rationale of them is waste utilization; however, benefits from IA practices can be more than just waste utilization, such as additional products, improve cultural environment for recirculation, habitat preservation, prevention of harmful bacteria, removal of pest species or seed from unwanted spawning, and improving the growth of target species (Troell 2009).

Currently, there are several dozen practices of IA in China. Although the waste utilization is the most important consideration in those IA practices, other IA practices based on other considerations are also popular and important. The main ecological rationales of IA are: (1) waste reclamation through trophic relationship, (2) water quality maintenance through complementary functions between species or systems, (3) water quality regulation through non-classical top-down effect, (4) full utilization of the resources of aquaculture waters through different ecological niche species, (5) diseases prevention ecologically, (6) benefit multiplication through integration of aquaculture and other industrial activities (Dong 2011b). Therefore, IA is the aquaculture model that rationally integrates anthropogenic inputs with aquaculture ecosystem services or integration of multiple industrial activities.

9.2.1 Waste Reclamation Through Trophic Relationship

It is the most important rationale to realize the reclamation of aquaculture waste through the trophic relationship between farmed organisms. The rice-grass carp farming occurred in the Tang Dynasty (889–907 AD) of China, which is an example of waste reclamation. In addition, there are other mutual benefits between rice shoots and grass carp in the rice-grass carp farming systems (Liu and Cai 1998).

Li (1986) considers that efficient utilization of input materials (feeds and fertilizers) is an important ecological function of integrated fish farming. He took the polyculture of common carp, silver carp, and bighead carp in a small size reservoir as an example, in which common carp were cultured in net cages with artificial pellet, and silver carp and bighead carp were cultured outside of the cages. The feces and residual feeds of the common carp became the diets of the filter-feeders, or became manure to promote the growth of phytoplankton that in turn became the food resource of the filter-feeders.

Polyculture of shrimp (*Litopenaeus vannamei*) with clam (*Meretrix meretrix*) and seaweed (*Gracilaria* spp.) in seawater pond is also based on such rationale (Dong

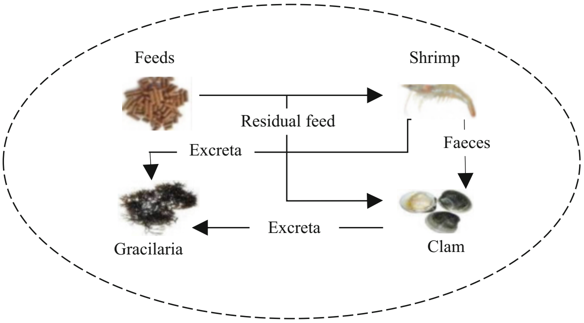


Fig. 9.1 Conceptual diagram of an integrated mariculture operation including shrimp, clam, and seaweeds (from Dong 2015b)

et al. 2007). In the pond system the pelleted feeds are first used by the shrimp; then the feed residuals and feces of the shrimp are filtered by the clam; finally, the inorganic nutrients excreted by the farmed animals (shrimp and clam) and released from the decomposition of feed residuals and feces are absorbed by the seaweed (Fig. 9.1).

In China, there are many other kinds of IA models with the function of waste reclamation, such as partitioned aquaculture of tilapia + shrimp + oyster + *Gracilaria* in ponds (Shen et al. 2007), aquaponics, kelp + fish + oyster in nearshore areas, and so on. This kind of IA is also called IMTA (Troell 2009).

9.2.2 Water Quality Maintenance Through Complementary Mechanism

It is also an important function of IA to stabilize and improve water quality through complementary functions between species or systems. The silver carp cultured outside the net cage of common carp can reduce the content of COD, total phosphorus, chlorophyll *a*, and particulate matter in the water, reduce the quantity of bacteria, phytoplankton, and zooplankton, and increase the dissolved oxygen and transparency, thus improving the carrying capacity of the aquaculture waters (Xiong et al. 1993). The seaweed (*Ulva* sp.) cultured with red sea bream (*Pagrus major*) can affect dissolved oxygen, pH, and CO_2 levels in the water (Hirata et al. 1994). There are two ways to maintain or improve the water quality in IA: one is through the complementary metabolic functions between farming systems or farmed species, another is through chemically complementary functions between the two systems.

9.2.2.1 Complementary Metabolic Functions

Aquaculture systems can be divided into ‘autotrophic’ and ‘heterotrophic’ systems based on the metabolic characteristics of the systems (Table 2.2). In the production process the autotrophic system, such as kelp cultivation system, will produce O_2, uptake CO_2, absorb ammonia, and thus delay the eutrophication of the waters. On the contrary, the heterotrophic system, such as the fed fish farming system, will uptake O_2, produce CO_2, release ammonia, and accelerate the eutrophication of the waters. These two types of systems have many ecological complementarities, and the integration of the two systems can increase the carrying capacity of the integrated system (Fig. 1.7).

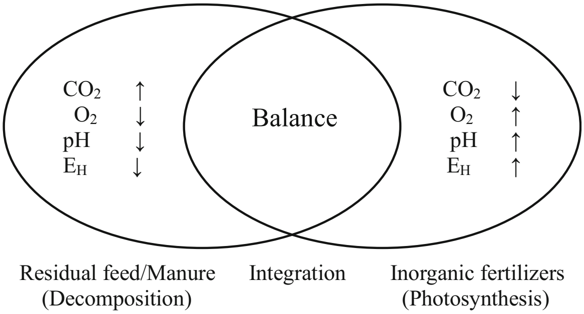
Aquaculture species can also be divided into fed species such as shrimp, and extractive species, such as oyster and kelp (Chopin et al. 2001). The aquaculture systems that farming fed or extractive species can also be named as fed aquaculture systems or extractive aquaculture systems. In general, the integration of these two types of species can reduce pollution and improve resource utilization efficiency. However, both the fed fish species and the extractive bivalves are animals, co-culture of them will still cause some problem (see Sect. 2.1.5). If macroalgae are added into the system to form an IMTA system, the problem will be solved (Chopin 2012). The fed fish, bivalve, and macroalgae are successfully cultured in a large scale in Sanggou Bay, Shandong Province (Fang et al. 1996, 2016).

9.2.2.2 Chemically Complementary Functions

In the 1980s, common carp in net cages and silver carp outside the cages were cultured in small reservoirs in China. In the farming process pellets were delivered to the common carp, and small amount of chemical fertilizer was applied outside the cages (Li 1986). Boyd and Tucker (1998) also reported that tilapia farming with organic fertilizer plus chemical fertilizer can achieve better results in ponds. The integrated use of pellets or organic fertilizer and chemical fertilizer can effectively exploit the chemically complementary functions to achieve stable water quality and improve harvest.

As shown in Fig. 9.2, a portion of the pellet feeds put into the waters is ingested by common carp, and the rest is dispersed in the water. The ecological effects of the feed residuals and fish feces are similar to the application of organic fertilizer. Decomposition of the feeds and feces decreases the pH, DO, and redox potential (E_H) and increases the CO_2 of the aquatic system. The application of chemical fertilizers has exactly the opposite effect of the application of organic matters. The application of chemical fertilizers into the water increases pH, DO, E_H and decreases CO_2 due to photosynthesis improvement.

Fig. 9.2 Ecological effects of integration of pellet feeding and chemical fertilizer application (modified from Dong 2015b)



Imbalance in the water environment can occur in both fed aquaculture system and chemically fertilized system, but in opposite ways. The former is characterized by the weak photosynthesis and active decomposition, which can lead to anoxic dead of farmed fish. In the latter case, the intense photosynthesis and weak decomposition often lead to fish bubble disease or alkaline disease due to high DO and/or high pH (Shi 1998; Zhang 2008a).

In 1988, an experiment of feed delivering and chemical fertilizer application to culture silver carp and bighead was carried out in Yeyuan Reservoir, Shandong Province, and desired results were obtained (Sun et al. 1990). The reservoir has a water area of 688 hm^2 and an average water depth of 4.3 m. Seventy-five experimental net cages (56 m^3 each) were set up with three treatments: no feeding and no fertilizer (NN), no feeding and fertilizer (NY), and feeding and fertilizer (YY). The average fish yields after 3 months of trial were 1.21 kg/m^3 for NN treatment, 1.31 kg/m^3 for NY treatment, and 2.42 kg/m^3 for YY treatment. The integrated use of feeding and fertilizer application can effectively play a role of chemically complementary effects to improve water quality and increase yields. In recent years, fertilizer application in large inland waters is restricted due to water quality protection in China.

9.2.3 Water Quality Regulation Through Top-down Effect

Filter-feeding fish and bivalve can directly filter the phytoplankton in the water and thus indirectly affect the water quality. The polyculture of fed fish or crustacea with filter-feeding fish or bivalves in China are the IA models based on the rationale of non-classic top-down effect (see Chap. 7 for details).

Filter-feeding fish can sometimes filter out almost all the zooplankton (rotifers, cladocerans, and copepods) in pond water, which cuts off the energy flows along the food chain through phytoplankton → zooplankton → farmed animals. When the filter-feeding tilapia are stocked in the net cage in shrimp farming ponds, called ‘Net Partitioned Polyculture’ (see Sect. 11.5.3), the regulation effect of the fish on water quality can be exerted, and the food chain can be maintained unblocked. The IA practice of shrimp and tilapia with the model can also avoid the fish from competing for high-quality pellet feeds of the shrimp, and improve both shrimp and tilapia yields (Sun and Dong 2010; Jie 2006).

9.2.4 Full Utilization of the Resources of Aquaculture Waters

The resources of aquaculture waters mainly include diet organisms, space, and time. IA is an important initiative to make full use of the resources of aquaculture waters through different ecological niche species.

9.2.4.1 Full Utilization of Space and Diet Organisms

Full utilization of the space resources of farming waters means stocking organisms that live in different water layers or areas, so that the vertical and horizontal spaces of the waters can be effectively used, and the physical carrying capacity of the waters can be well exploited.

The main fish species in freshwater ponds in China are silver carp, bighead carp, grass carp, common carp, crucian carp, black carp (*Mylopharyngodon piceus*), mud carp (*Cirrhinus molitorella*), etc. According to their live habitat, they can be divided relatively into pelagic and benthic fish. Bighead carp and silver carp are upper pelagic fish, grass carp is lower middle pelagic fish, and common carp, crucian carp, black carp, and mud carp are benthic fish. Grass carp usually prefer to inhabit near-shore areas with abundant aquatic plants, while bighead carp and silver carp are often found in open pelagic areas. Unlike monoculture, a reasonable stocking of the fishes inhabiting different locations can make full use of the carrying capacity of farming waters.

The natural diet organisms in aquaculture waters mainly consist of macrophytes, nekton, phytoplankton, zooplankton, detritus with bacteria, benthos, etc. By co-culture of fishes with different feeding habits the fishes can make full use of the various natural diet resources in aquaculture waters. From the feeding habits point of view, silver carp and bighead carp filter plankton; grass carp mainly grazes aquatic plants; black carp feeds zoobenthos; mud carp feeds a lot of organic debris and benthic algae; common carp and crucian carp mainly feed zoobenthos and organic debris. By co-culturing these fishes in a pond or stocking them in an inland large waters simultaneously, it is possible to make full use of the various natural diet resources and space of the waters and increase the fish production of the waters (Shi 1991; Freshwater Fish Farming Experience Summary Committee of China 1961). Also, some fishes have certain trophic relationships with each other in the polyculture systems, such as the relationship between grass carp and silver carp.

In 1984, a ‘stereo-culture’ model in a seawater bay was developed in Changdao County, Shandong Province (Luo and Wang 1984). The model is to culture kelp and wakame in the upper layer, scallops and mussels in the middle layer, and sea cucumbers and abalone are on the bottom of the waters. The seaweeds make full use of light resources in the upper layer, filter-feeding bivalves in the middle layer use planktonic resources, and abalone and sea cucumbers use benthos and non-living organic matter resources on the water bottom. This culture model also considers the use of space and diet resources, while taking advantage of interspecific trophic relationships.

More than 400 years ago, Chinese farmers invented an IA of rotary stocking and harvesting in ponds, which is still very popular nowadays in China, such as the rotary harvesting of shrimp (*L. vannamei*) and swimming crab (*Portunus trituberculatus*) in seawater ponds or mitten crab (*Eriocheir sinensis*) in freshwater ponds (Fig. 9.3). In this model shrimp and crab seedlings are stocked in the spring; all or some of the shrimps are harvested in the summer when the shrimp grow to a saleable size; and finally, the crab is harvested at late autumn. Before harvesting the

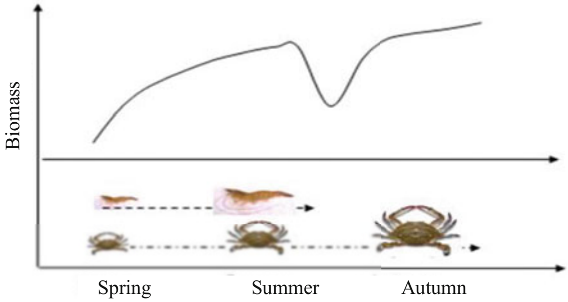


Fig. 9.3 Rotary harvesting of shrimp and crab in an integrated aquaculture pond (from Dong 2015b)

shrimp, the total biomass of the shrimp and crab in the pond is so high that the growth of the shrimp and crab are affected each other. The biomass drops sharply after the shrimps are harvested and the crab growth accelerates. The major purpose of the rotary stocking and harvesting is also the full use of water space and diet resources by maintaining a stable and high biomass in the farmed waters.

9.2.4.2 Full Utilization of Time or Seasons

Full utilization of the temporal resources of farming waters is to extend the use time of the waters for as long as possible during the year. Rotational farming is a model of IA that makes full use of the time resources of ponds. For example, in Jiangsu Province, vannamei shrimp are cultured in ponds from May to October during the warm season, while Mandarin fish (*Siniperca chuatsi*), which still feed and grow in winter, are farmed from October to next May after harvesting the shrimp (Shen and Zhang 2004). By this way, the pond is used all year-round.

9.2.5 Diseases Prevention Ecologically

The IA of disease prevention ecologically is also very popular in China. In the models, some diseases are prevented by using the commensalism of farmed organisms, in which one of the farmed organisms has a preventive effect on a certain disease of the other farmed organisms. One example of the models is the co-culture of shrimp and puffer fish (*Takifugu rubripes*), which objectively has the effect of preventing the spread of shrimp white spot disease (Liu et al. 2007). The carnivorous puffer fish can prey on infected and slow-swimming shrimps without being infected with the pathogenic virus. If healthy shrimps preyed on the infected shrimp, they would probably be infected. Through this model the white spot disease of the cultured shrimp is prevented efficiently.

In addition, ‘clean fish’, such as *Ctenolabrus rupestris*, in Atlantic salmon net cages can reduce sea lice disease by feeding on the parasitic sea lice on the surface of salmon body (Treasurer 2002).

9.2.6 Benefit Multiplication Through Integration with Other Activities

The integration of aquaculture with agriculture, sea ranching, game fishing, tourism, wind turbine, and so on also fall under the category of IA. Such inter-industry integration can not only expand the development space of aquaculture, but also increase or amplify the economic and/or ecological benefits of aquaculture and other industries.

The integration of aquaculture and agriculture is significant in China, including mainly paddy field aquaculture and waterlogged salt-alkali land aquaculture. Paddy field aquaculture is a conventional household integrated aquaculture system in many countries, which allows fish and rice shoots to share water and land space, increases both aquaculture and agriculture yields, and reduces environmental loads through mutually beneficial effects between fish and rice seedlings. The paddy field aquaculture system is favorable to the growth of the both, because: (1) grass carp fingerlings graze small size of wild weeds but leave the large size of rice shoots intact, therefore reducing the competition between the weeds and the rice shoots for space, light, and nutrient; (2) insect pests are controlled by the fish in the field; (3) aquatic organisms and organic detritus in the field serve as the natural diet organisms of the fish; (4) ammonia from fish excretion in the field serves as manure for the rice; (5) CO_2 from fish respiration promotes photosynthesis of aquatic plants; (6) fish movement loosens the texture of the soil, and thus favoring the rice; (7) the rice can shade the fish from the sunlight, which is beneficial to the survival and growth of the fish (Liu and Cai 1998).

China consists of 35 million hectares of salt–alkali lands, and more than 3 million hectares of waterlogged salt-alkali land can be reclaimed to pond-terrace systems. Aquaculture activity in the waterlogged salt-alkali land has not only formed a mutually beneficial development pattern of ponds and terraces but also exploited the vast deserted land resources (see Chap. 11 for detail).

The above mentioned are the main ecological rationales of IA in China. Of course, there are some IA that are based on other ecological considerations. For example, fish that prey on live bait fish are co-cultured with bait fish in the same pond. Mandarin fish (*Siniperca chuatsi*) is a highly valuable fish that mainly feeds on live fish, therefore, it is co-cultured with the small size of silver carp and bighead carp. In terms of operation, after stocking the mandarin fish farmers only cultivate the plankton in pond water for the live bait fish. Polyculture of broodstock of carps with carnivorous fish, such as mandarin fish, is another additional example. In the broodstock pond, the mandarin fish can eliminate those small ‘waste’ fishes which compete feeds with the broodstock. The IA models established on the above rationales are characterized by high utilization of various resources, low side effects on the environment, and high economic benefits.

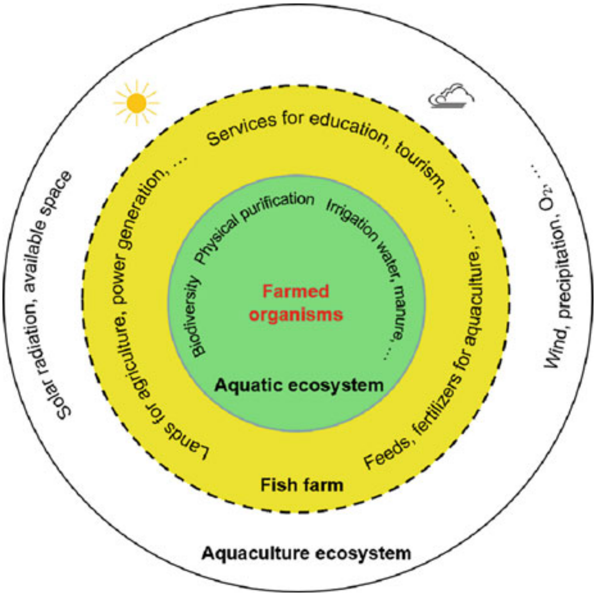
9.2.7 Making Full Use of Other Services of Aquaculture Ecosystem

The boundary of an aquaculture ecosystem is the extent of a farm, including aquaculture waters, ancillary land, and the available space above them, in which there are provision, regulation, support, and culture functions for humans directly and indirectly (Table 2.12). Because of the high diversity of aquaculture ecosystems, various ecosystem services can be used to improve their comprehensive benefit, outputs, and sustainability of aquaculture systems (Fig. 9.4).

As far as an aquatic ecosystem is concerned, the diversity of farmed organisms is the basis of ecosystem service functions for constructing reasonable trophic relationship and complementary function between farmed organisms, making full use of resources (natural feed organisms, space, time) of aquaculture waters, and realizing ecological prevention of diseases. As far as the land-based and water-based ecosystems of an aquaculture farm are concerned, the key to realize the multiplication of aquaculture and ecological benefits is to make full use of the provision service functions of the waters for agriculture and agriculture for aquaculture farmed aquatic organisms. In terms of aquaculture ecosystem including available space above the waters and land, it is important to make full use of ecological services such as solar radiation, wind power, ecotourism, popular science education, and game fishing in order to maximize its comprehensive benefits.

The development of human aquaculture activities is actually a process from single species farming (monoculture) to multi-species farming (polyculture), from pond to land-pond combination (integration of aquaculture and agriculture), from sole food production to comprehensive utilization of ecosystem resources (broadly defined IA). Human's understanding of aquaculture ecosystem services is

Fig. 9.4 Ecosystem services of aquaculture ecosystem



also a process from simple provision services (such as aquatic food products) to support and regulation services (such as water self-purification capacity, ecological prevention of diseases), and then to culture services (such as game fishing, ecotourism). Therefore, the utilization levels of ecological service functions of the aquaculture ecosystem are also important indicators of IA levels.

9.2.8 Dialectical Way of Thinking in Integrated Aquaculture

Two major attitudes to the nature in ecology emerged in the eighteenth century. One was an 'arcadian' stance toward nature epitomized by Gilbert White (1720–1793), the parson-naturalist of Selborne, UK. This arcadian view advocated a simple, humble life for a man with the aim of restoring him to peaceful coexistence with other organisms. Another, 'imperial' tradition, is best represented in the work of Carolus Linnaeus (1707–1778). His ambition was to establish, through the exercise of reason and hard work, man's dominion over nature (Worster 1994). These two extreme thoughts can also be found in modern ecology. Similar extremes of opposition still exist in modern activity.

The world view of ancient Chinese was affected by Lao Tzu (about 600–500 BC), a great ancient Chinese philosopher. His theory includes 'Reversal is the movement of Tao', namely when the development of anything brings it to one extreme, a reversal to the other extreme takes place. This is one of the main theories of Lao Tzu's philosophy and also that of the Book of Changes as interpreted by the Confucianists. This theory has also provided the principal argument for the doctrine of the golden mean, favored by Confucianist and Taoist alike. 'Never too much' has been the maxim of both (Feng 2008).

Affected by this thinking mode ancient Chinese invented the grass carp-rice integration in Tang Dynasty (889–904 AD). The grass carp grazes aquatic plants, so it is a little weird to keep the grass carp in the rice field. But the grass carp can't graze the big size of aquatic plants! If the grass carp fingerling is released to the rice field after the rice shoots grow up to a certain size, there is only a mutually beneficial relationship between them. In this integration, the relationships of both opposite and complementary between grass carp and rice-shoots exhibit thoroughly (Fig. 1.7).

The grass carp–rice integration is the practice of the Chinese traditional dialectical way of thinking, and an apotheosis of ecosystem approach to aquaculture. The ecological rationales of IA are mainly that water quality maintenance through complementary mechanisms between species or systems, waste reclamation through trophic relationship, in which Chinese traditional dialectical way of thinking, such as 'reversal is the movement of Tao' and 'the doctrine of the golden mean', are inherited. In aquaculture 'fed species and extractive species', 'heterotrophic and autotrophic', 'decomposition and photosynthesis', 'oxidation and deoxidation', 'source and sink', and so on are all the unity of opposites (Fig. 1.7, Table 2.2 and Fig. 9.2); the balance or golden mean can be reached through integration of these opposites in an appropriate proportion.

In the development path of aquaculture neither the arcadian view nor the imperial view is practical; harmonious or balance is the only way to go. The extensive aquaculture with low carbon (emission) & low productivity and the super-intensive monoculture with high productivity & high carbon are also a unity of opposites, the ecological intensification in some way might exert their advantages, overcome their disadvantages, and reach the goals of high productivity and low carbon to some extent (see Chap. 15).

9.3 Classification of Integrated Aquaculture Systems

Chien and Tsai (1985) classified pond farming into (a) monoculture systems, (b) crop rotation culture systems, (c) polyculture systems, and (d) integrated culture. Troell (2009) classified integrated mariculture systems into four main groups: (a) polyculture; (b) sequential integration (partitioned aquaculture systems); (c) temporal integration; and (d) mangrove integration (aquasilviculture).

China has the greatest variety of farmed aquatic species and production systems in the world. From an ecological limiting factor point of view, IA is one of six major aquaculture systems (Table 2.3). IA models in China can be summarized into two groups, namely the species integration and the systems integration, and the latter group can be further divided into the integration of aquatic systems, the integration of aquatic and land systems, and so on (Table 9.1).

9.3.1 Species Integration

Species integration is the rational co-culture of two or more aquatic species possessing different trophic level, feeding habits, living space, and culture time in the same waters. This group includes the following seven types.

9.3.1.1 Integrated Multi-trophic Aquaculture or Trophic Integration

Trophic integration refers to the polyculture of aquatic species from different trophic levels in the same aquatic system, in which an output from one species, which otherwise may have been wasted, becomes a food or nutrient to another species. This type of IA has a long history and many models in China and some Asian countries. The longest and most useful example is the polyculture of several Chinese carps, which had been recorded in China 1000 years ago. The IA models of the 80% fed fish and 20% filter-feeding fish in freshwater ponds (Xi and Liu 2002), the co-culture of shrimp and bivalve in seawater ponds (Wang and Cui 2009), and the interculture of scallops and kelp at open seas (Fang et al. 1996) are now very popular in China.

In 2004 Chopin and Taylor started using IMTA for this type of IA model. Some scholars also simply refer to this type of IA, especially including seaweeds, as modern integrated aquaculture (Neori et al. 2004). Within the IMTA context, Chopin (2006) presented a conceptual model of fed species integrated with inorganic extractive species and organic extractive species (Fig. 9.5). This type of IA has

Table 9.1 Classification of integrated aquaculture systems (modified from Dong 2011b)

Groups		Types	Cases
1 Species integration		1-1 Integrated multi-trophic aquaculture or trophic integration	Grass carp–silver carp, shrimp–razor clam in ponds, fed fish–bivalve–seaweed at open sea
		1-2 Spatial integration	Polyculture of carps in pond or reservoir
		1-3 Rotary stocking and harvesting	Shrimp–crab in pond
		1-4 Temporal integration	Shrimp in warm season and mandarin fish in cool season in pond
		1-5 Disease prevention integration	Shrimp–puffer fish in pond
		1-6 Multi-function integration	Sea cucumber–jellyfish–shrimp–scallop in pond
		1-7 Other integration	mandarin fish–live bait fish in pond
2 Systems integration	2-1 Integration of aquatic systems	2-1-1 Partitioned aquaculture systems	Tilapia + shrimp + oyster + *Gracilaria*
		2-1-2 Aquaculture and aquatic agriculture integration	Fish–rice
		2-1-3 Aquaponics	Carp–lettuce (*Lactuca sativa*)
		2-1-4 Aquaculture and waterfowl integration	Fish–duck
		2-1-5 Fish and amphibian integration	Fish–turtle, fish–frog
		2-1-6 Aquasilviculture	Fish (*Sciaenops ocellatus*)–mangrove
		2-1-7 Other integration	Inner net partitioned polyculture
	2-2 Integration of aquatic and land systems	2-2-1 Integration of pond and livestock or poultry breeding	Pond–sheep, pond–chicken
		2-2-2 Integration of pond and plantation	Pond–grain, pond–fruit tree
		2-2-3 Other integration	Shrimp culture with cooling water from power plant
	2-3 Integration of aquaculture with the services provided by the space above the farm		Fish farming – photovoltaic power generation, fish farming – wind turbine
	2-4 Integration of aquaculture with the culture services of the farm		Game fishing, aquaculture ecotourism

been promoted in dozens of countries, especially in freshwater ponds. IA of fed fish, bivalve, and seaweed at open seas is more favored by Western countries. Experiments have shown that bivalves in IA grow 50% faster and can remove 54% of the particulate organic matter in the water; seaweeds in IA grow 46% faster

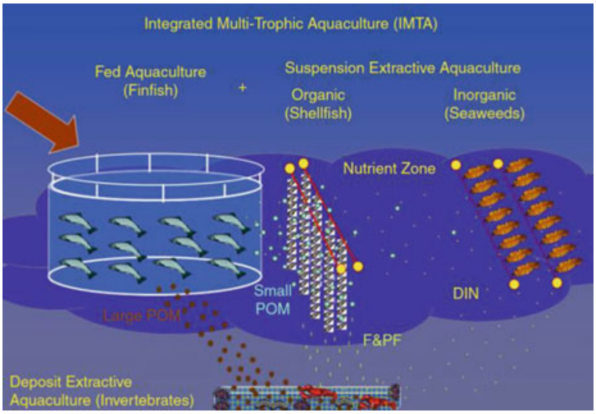


Fig. 9.5 Conceptual diagram of an integrated multi-trophic aquaculture (IMTA) operation including fish, bivalve, and seaweed (from Chopin 2013)

and can absorb up to 60% of the dissolved organic N and P in the water (Barrington et al. 2010; Klinger and Naylor 2012).

9.3.1.2 Spatial Integration

This type of integration is the co-culture of two or more aquatic species inhabiting at different water layers and/or possessing different feeding habits in order to utilize fully space and natural diet resource of farming waters. Usually, several fish species are stocked in inland large waters (reservoirs or lakes) simultaneously, such as silver carp (living at upper layer and filtering phytoplankton), bighead carp (living at mid-upper layer and filtering zooplankton), grass carp (littoral zone, grazing aquatic plants), common carp (bottom and feeding zoobenthos), and so on in China (Shi 1991). In mariculture spatial integration of kelp, undaria, scallop, mussel, sea cucumber, and abalone were done in China (Luo and Wang 1984).

9.3.1.3 Rotary Stocking and Harvesting

Traditionally, rotary stocking and harvesting includes rotation of different sizes of armed organisms, in which harvesting of commercial products is immediately followed by stocking smaller sizes of farmed organisms of the same species several times a year. This culture model originated in freshwater pond farming 400 years ago (Liu and He 1992). The example of rotation of species nowadays is the co-culture of shrimp and crab (Fig. 9.3). The purpose of rotary stocking and harvesting is most efficiently utilizing natural diet resources.

9.3.1.4 Temporal Integration

Temporal integration aims to make good use of time by culturing different species in different seasons in the same farming waters. Most of the aquaculture species in China are temperate eurythermal species, however, some belong to tropical species and some are boreal species. Temporal integration of tropical and boreal species in temperate regions in the same farming waters can make good use of time resource. One of the examples is integrated aquacultures of whiteleg shrimp (from May to

October) and mandarin fish (from October to next May) in Jiangsu Province, China (Shen and Zhang 2004).

9.3.1.5 Disease Prevention Integration

Integrated mariculture of shrimp with mollusk and/or crab and/or macro-algae is very popular, which can not only make full use of resources but also prevent the white spot disease of shrimp. The co-culture of puffer fish and whiteleg shrimp is an excellent example of disease control integration, because the fish prey on sick shrimp without becoming infected (Liu et al. 2007). In addition, ‘clean fish’, such as *Ctenolabrus rupestris*, in Atlantic salmon net cages can reduce sea lice disease by feeding on the parasitic sea lice on the surface of salmon body (Treasurer 2002).

9.3.1.6 Multi-function Integration

By means of this integration, multiple resources of aquaculture system are fully utilized. Integrated mariculture of sea cucumber, jellyfish, scallop, and shrimp in the pond is an example of multi-function integration to full use of multiple resources (time, space, and natural food resources) (Fig. 9.6). Sea cucumber is a deposit feeder, and is stocked and harvested multiple times a year; Jellyfish feeds on zooplankton, and are cultured from May to October; Scallop filters phytoplankton, and are cultured from October to next May; Shrimp is benthos feeder, and are cultured in summer when sea cucumber goes to aestivation (Zhang et al. 2008b; Ren et al. 2012; Li et al. 2013a). The jellyfish and scallop utilize plankton that the sea cucumber and shrimp cannot use, and the biodeposits of the former two species are food sources for the sea cucumber.

9.3.1.7 Other Integration

Besides the above-mentioned types of species integration there are also other types which are based on other considerations, such as co-culture of broodstock of carps with carnivorous fish. Mandarin fish prey on wild fishes that compete for feed with

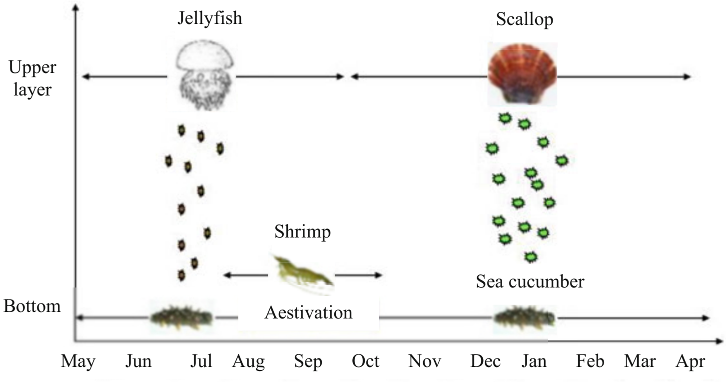


Fig. 9.6 Multi-function integration of sea cucumber, jellyfish, scallop, and shrimp (from Dong 2015b)

the broodstock fish (Yang et al. 2006). Another example is that carnivorous fish are co-cultured with live diet fishes in the same pond, such as mandarin fish with the small size of silver carp as live diet.

9.3.2 System Integration

System integration refers to the aquaculture integrated with other production activities. This IA may take place in the same waters or through sequentially linked sub-systems in order to create a mutually beneficial effect between the sub-systems or to make better use of the sub-system resources.

9.3.2.1 Integration of Aquatic Systems

This type of IA is an integrated approach that two or more different production activities are carried out in the same or related waters.

9.3.2.1.1 Partitioned Aquaculture Systems or Sequential Integration

For example, integration of tilapia, shrimp, oysters, and seaweed is based on the flow of waste streams to utilize the trophic relationship (Shen et al. 2007; Troell 2009). The shrimp feeds on pellets, the tilapia prey on zooplankton, the oyster filter phytoplankton, and seaweed absorb inorganic nutrients. The water flow direction and process of the system is: shrimp pond → tilapia pond → oyster pond → Gracilaria pond → shrimp pond (Fig. 9.7).

9.3.2.1.2 Aquaculture and Aquatic Agriculture Integration

This integration is aquaculture and aquatic agriculture is simultaneously implemented in the same waters. The relationship between the aquatic animals and the aquatic plants is mutually or partially beneficial (mutualism or commensalism), thus multiplying the ecological and economic benefits of the entire waters. Fish-rice

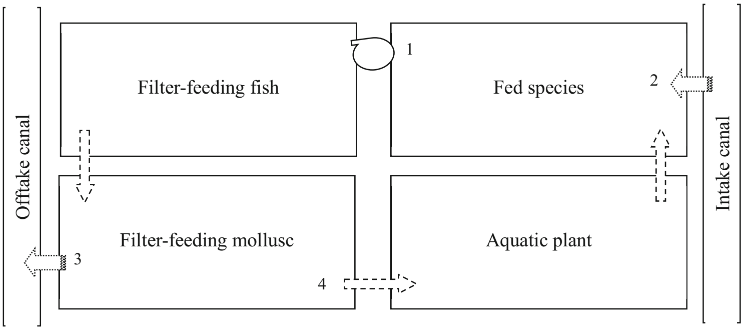


Fig. 9.7 Partitioned aquaculture system of fed species + filter-feeding fish + filter-feeding mollusk + aquatic plant (from Dong 2015b). (1) Pump; (2) Inlet; (3) Outlet; (4) Connecting pipe between two ponds

integration is the most popular type of this integration. In some areas, mitten crab, crayfish, and frogs are also farmed in paddy fields.

9.3.2.1.3 Aquaponics

When aquaculture is integrated with aquatic vegetables it is called 'Aquaponics'. A 1000 m^2 aquaponics system in Guangzhou, Guangdong Province, produced 2-3 t of fish and 10 t of vegetables per year (Ding et al. 2010). Aquatic vegetables can reduce the nutrient load of the waters and absorb inorganic nutrients from the water. However, the aquatic vegetable does not absorb CO_2 from the water and does not release oxygen into the water. Fish-lotus (root) combination is more common in China.

9.3.2.1.4 Aquaculture and Waterfowl Integration

This integration involves fish farming integration with duck and goose breeding in the same waters, which is now widely carried out in China. The waterfowl can stir up the water body, which is conducive to improving the ecological conditions of the pond, and waterfowl manure can be filtered by filter-feeding fish and is also a good organic fertilizer. Luo et al. (2002) showed that the co-culture of Chinese carps with duck improved the economic benefit of the pond, which was 5–6 folds of simple fish culture in the pond.

9.3.2.1.5 Fish and Amphibian Integration

It is popular to integrate fish with soft-shell turtle or frog farming in ponds (Zheng et al. 2004).

9.3.2.1.6 Aquasilviculture

In this IA mangrove is integrated with shrimp, oyster, or fish farming. The growth rates of the fishes (*Sciaenops ocellatus* and *Labidochromis flavigulus*) were improved in the IA of fish with mangrove forest (She et al. 2005).

9.3.2.1.7 Other Integrations

An example of other integrations is the tilapia cage in shrimp culture ponds. The fish kept in cages or pens can still regulate water quality but without feed competition with the shrimp (Sun and Dong 2010). In addition, the economic benefits of loach (*Misgurnus anguillicaudatus*) culture in net cages and carps outside the cages in ponds are also very promising (Zhu 2008).

9.3.2.2 Integration of Aquatic and Land Systems

This type of IA is the integration of aquaculture in waters with industrial activities carried out on its surrounding embankments or land. The aquaculture waters are linked to the surrounding land in some way that makes the waters and the land more productive and ecologically efficient. This type can be subdivided into three categories.

9.3.2.2.1 Integration of Pond with Livestock or Poultry Farming

Livestock and/or poultry are farmed on the dikes of aquaculture pond. The pond can provide water for the livestock and the manure from the livestock can fertilize the water in the pond. Recently food hygiene issue of this integration has aroused public concern, however, after fermentation the faces can be used safely (Cai et al. 2009).

9.3.2.2.2 Integration of Pond and Plantation

In this integration, the aquatic organisms are farmed in the pond, and grain, grass, vegetables, and fruit trees are planted on the dikes of the pond. Pond sediment rich in organic matter can be used as fertilizer for the land plants on the dikes, and the pond water can be used as irrigating water. The planted grasses can be used as feed for grass carp in addition to livestock.

The mulberry fish pond is an IA that was recorded 300 years ago in China. Although the model is formally an integrated fish-plant system, it is also an integration of all three, with the addition of silkworm breeding. Pond sediment can fertilize mulberry trees; silkworm feces can be fed to fish.

9.3.2.2.3 Other Integrated Land-Aquatic Systems

Integration of aquaculture with power plant is popular in China. In the past, there was also form of pond fish farming with urban domestic sewage (Huang 1992), but it has been abandoned due to food safety reason. In addition, in a broad sense, aquaculture combined with power generation, tourism, and game fishing also falls under the category of the IA.

9.3.2.3 Integration of Aquaculture with the Services Provided by the space above the Farm

The space above the aquaculture water body and ancillary land is a component of aquaculture ecosystem, and can provide physical space and energy for renewable energy production and other uses. There are many cases of fish ponds or coastal aquaculture combined with photovoltaic panels or wind turbines in the world (Chien et al. 2014; Chen et al. 2020; Zhou et al. 2020). Photovoltaic panels can be placed above the water surface (Chen et al. 2020) or floating on the water surface (Zhou et al. 2020). The research of Chen et al. (2020) showed that photovoltaic panels had little impact on shrimp farming, and the yields of the shrimp reached 4.7–4.42 kg/m^2, realizing the dual benefits of shrimp farming and photovoltaic power generation. However, the impact of wind turbines on farmed animals still needs further research.

9.3.2.4 Integration of Aquaculture with the Culture Services of the Farm

Willot et al. (2019) have identified 11 possible cultural ecosystem services, such as entertainment, scientific education, aesthetics, and heritage, which can be integrated with aquaculture activity. In general, mariculture not only consumes but also provides ecosystem services far beyond the provision of goods (Alleway et al. 2019). However, for the aquatic ecosystem where aquaculture is highly developed, the proportion of provision services will be higher. For example, the provision services, regulation services, and culture services accounted for 51.3%, 17.3%, and 31.4% of the total ecological service value, respectively, in Sanggou Bay, Shandong Province, China in 2003. Among which the value of food supply service was the highest, accounting for 50.45% (Zhang et al. 2007b).

The study of Yang et al. (2015) showed that the total values of pond aquaculture ecosystem service in Jiading and Qingpu districts of Shanghai, China, were 4.23 and 2.01 folds of net food supply, respectively, in 2011.

9.4 Structure Optimization of Integrated Aquaculture

Compared with monoculture systems, IA systems have many advantages and are generally considered to be sustainable models of aquaculture. Although farmers have historically optimized the 3:1 ratio of grass carp and silver carp polyculture, it was the result of their long-term exploration by trial-and-error trials. Although some scientific theories have been used to guide and structure optimization of IA models, numerous popular IA models in China are still determined by farmers by trial-and-error trials so far. In order to promote and guide the structure optimization of IA, this section will briefly introduce the principles and methodology of the structure optimization of IA.

9.4.1 Principles of Structure Optimization

The ecological rationales on which the current IA models are based include mainly the seven mentioned above, and the IA models established according to these rationales can achieve high ecological and economic benefits.

9.4.1.1 Ecological and Economic Benefits

Ecological benefits in aquaculture mean that the components of the aquaculture ecosystem are often in a state of mutual adaptation and coordination in terms of the output and input, and the structure and function, so that the natural resources of the waters can be reasonably utilized and protected. The basis of ecological benefits is ecological balance and the virtuous and efficient work of the ecosystem.

The ecological benefits of aquaculture waters reflect the degree of impact of farming activities on the environment, i.e., the impact of different farming systems on themselves and the surrounding environment. In natural waters that are less affected by human activities, the input energy of the system comes mainly from solar radiation, and the input and output of energy and material of the system can be kept in relative balance in a certain period of time.

In an autotrophic or extractive aquaculture system, one can produce an economic product from solar energy and nutrients in the waters by simply stocking seedlings. Although one can take measures such as fertilization to increase the output of the system, its productivity is ultimately limited by the utilization efficiency of solar energy. The system will export a large amount of nutrients, such as N and P, from the system each year with the harvest of the product, thus reducing the nutrient load of the system.

In a heterotrophic or fed aquaculture system, large amounts of feeds are constantly put into the system to maintain the growth of the farmed species and to obtain the required higher yields. Although a large amount of feed nutrients is exported out of the system with the capture every year, the system has limited utilization efficiency of the feed nutrients. So, parts of the nutrients are ultimately deposited in the system or discharged to the surrounding waters, causing self-pollution or eutrophication of adjacent waters. In recent years, eutrophication in the nearshore area has been increasing, and the discharge from coastal fed aquaculture can no longer be ignored in China (Cui et al. 2005; Cheng 2009). Therefore, whether a certain aquaculture model or system discharges pollutants to the surrounding environment during its operation, and the extent of the discharge, can be used as an important indicator of its ecological or environmental benefits.

Economic benefits are the results of economic activities, and the production aspect is the basis of the whole economic activity. Economic benefits reflect the economic performances of a particular production system, i.e., the relationship between the economic cost and the final benefits of that system. The economic benefits are often the first concern of a production operator. There are many indicators that reflect economic efficiency, commonly used are income (net and gross), output-input ratio, etc. The income is an absolute indicator that is highly influenced by prices and varies greatly with regions and time. The output-input ratio, on the other hand, is a relative indicator that is less affected by geographical and temporal factors. Using the output-input ratio as an indicator of economic benefits is more comparable across regions and years for the same farming system or across different farming systems.

For aquaculture systems the net income and output-input ratio can be used to reflect the economic benefits of different systems, while the N and P utilization rates and waste discharge rates of a farm are used as indicators to reflect the ecological performance of different systems. It should be noted that different scholars have different ways of expressing N and P utilization rates. General ecological studies examine the N and P utilization rate in the context of the N and P input and output of the whole system, which expresses the ratio of the N and P utilized by the farmed organisms as part of the system's output. In contrast, for aquaculture systems, we are more interested in the ratio of the N and P contained in the harvested products to the N and P artificially put into the farming system (feeds, fertilizers).

9.4.1.2 Harmonization of Ecological and Economic Benefits

The relationship between ecological and economic benefits is mutually constraining and causal. From a macro and long-term perspective, maintaining good ecological benefits is a prerequisite for achieving good economic benefits. The ecological and economic benefits generated in a given production system can be positive or negative. The most common situation is that the ecological benefits are often adversely affected in order to obtain more short-term economic benefits. In this case, the economic benefits are positive, while the ecological benefits are negative.

The ecological benefits are related to the overall and long-term economic benefits. If ecological benefits are damaged, the overall and long-term economic benefits will be difficult to secure. Therefore, people should maintain the ecological balance in production activities and strive to achieve both greater economic benefits and good ecological benefits, or at least should not harm the ecological environment.

For a long time, in aquaculture activities, farmers have mostly pursued economic benefits without paying more attention to ecological benefits, resulting in the imbalance in some aquatic ecosystems, in turn hindered sustainable economic development. IA is a pattern designed and established to maximize ecological and economic benefits and to achieve a ‘win-win’ situation in terms of economic development and ecological protection. The benefits of such aquaculture systems should also be evaluated by a comprehensive index system that combines economic and ecological indicators. In aquaculture, people are required to obtain high economic benefits while maintaining ecological balance, that is, to obtain the greatest ecological economic benefits.

In practical application, integrated benefit indexes that include several economic and ecological benefit indicators can be designed. For example, Li et al. (1999) compared the ecological and economic benefits of different farming models using the integrated benefit index (IBI)

$$\text{IBI} = (\text{Total yield} \times \text{Total utilization of N} \times \text{Output-input ratio})^{1/3}$$

Since each farming or stocking structure to be optimized has different concerns, the practical application of such indexes can also be designed differently depending on the specific needs, such as:

$\text{IBI} = (\text{Net yield} \times \text{Average individual weight} \times \text{Feed efficiency})^{1/3}$ (Xiong et al. 1993)

$\text{IBI} = (\text{Yield} \times \text{Average individual weight} \times \text{N or P relative utilization rate})^{1/3}$ (Wang et al. 1999a)

$\text{IBI} = \text{Total yield} \times \text{Shrimp size} \times \text{Average utilization of N or P} \times \text{Net income} \times \text{Output-input ratio}$ (Tian et al. 1999)

9.4.2 Methodology of Structure Optimization

Ecological studies or experimental methods can be classified as observational studies, mensurative experiments, and manipulative experiments or controlled experiments (Hurlbert 1984). In an observational study, the investigator can only observe the effect of the exposure on the study subjects; he or she plays no role in assigning exposure to the study subjects. Mensurative experiments involve only the making of measurements at one or more points in space or time; space or time is the only ‘experimental’ variable or ‘treatment’. Tests of significance may or may not be called for. Mensurative experiments usually do not involve the imposition by the experimenter of some external factors on experimental units. The defining feature of a manipulative experiment is that the different experimental units receive different treatments and that the assignment of treatments to experimental units is or can be randomized. Manipulative experiment has four important properties or elements, including control, replication, randomization, and interspersion (Hurlbert 1984). Manipulative experiments not only mean that certain ecological factors are controlled with high precision, but more importantly, the design and implementation of such experiments also follow strict rules that make the results obtained from such experiments repeatable and testable by others.

Experimental ecosystems can be broadly classified into three categories: small experimental ecosystems (microcosms), medium experimental ecosystems (mesocosms), and large experimental ecosystems (macrocosms). Microcosms can be defined as systems smaller than 1 m^3 or 0.1 m^2, mesocosms are the systems between 1–10^3 m^3 or 0.1–10^3 m^2, and macrocosms are the systems larger than 10^3 m^3 or 10^3 m^2. The size of the experimental ecosystems required varies due to the different purposes of the experiments and the different objects (organisms) studied. In general, some small containers can be used for studying the ecology of smaller organisms, such as microorganisms, plankton, and so on, while slightly larger containers are needed for studying the ecology of larger organisms such as fish. Larger water bodies are needed for studying IA systems.

Small experimental systems are easy to control and allow for precise control of experimental conditions. Multiple treatments and replicates can usually be designed simultaneously in such experiments. However, the experimental system often differs significantly from field aquaculture ecosystem. Larger experimental systems are closer to field aquaculture ecosystems, and some experiments, such as whole-lake ecological manipulation experiments, are conducted using natural lake ecosystems. However, such experiment is often limited to one treatment, no replicates, or a limited number of replicates due to various restrictions.

The Aquaculture Ecology Laboratory of Ocean University of China has been using experimental enclosures, medium- and large-sized artificial simulated ecosystems, since 1989 to study the structure and function of aquaculture ecosystems, carrying capacities, and structure optimization of IA systems (Li 1992; Li et al. 1993b, 1994). The experimental enclosure systems make it possible to carry out manipulative experiments, and is a more ideal method that balances experimental manipulability and realism. The experimental enclosure systems overcome the shortcomings of previous field aquaculture studies that were not easily replicable and indoor simulations that were severely distorted.

In the late 1980s, a team led by Professor Li developed suspended enclosures (Fig. 9.8), which have open top and closed bottom (Li et al. 1993b) to study the issues such as optimal structure and carrying capacities for IA in a reservoir. In the 1990s, Prof. Li's team (Li et al. 1998) began to optimize the structure of shrimp IA in seawater ponds and developed land-based pond enclosures (Fig. 9.9), which have open top and the bottom substrate of the pond.

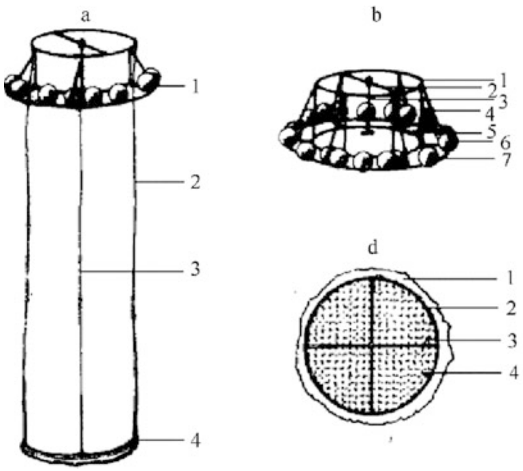


Fig. 9.8 The structure of the suspended experimental enclosure (from Li et al. 1993b). (**a**) The whole-body view: (1) Steel floated buoyant body; (2) Plastic-coated polyethylene woven cloth bag; (3) Rope; (4) Bottom tray. (**b**) Floating body and stirrer: (1) Neck ring; (2) Crossbeam for stirrer; (3) Stirrer; (4) Stand; (5) Inner ring; (6) Buoy; (7) Outer ring. (**c**) Inner net: (1) Iron ring; (2) Net. (**d**) Bottom tray: (1) Plastic-coated polyethylene woven cloth; (2) Brim ring; (3) Angle iron; (4) Iron net

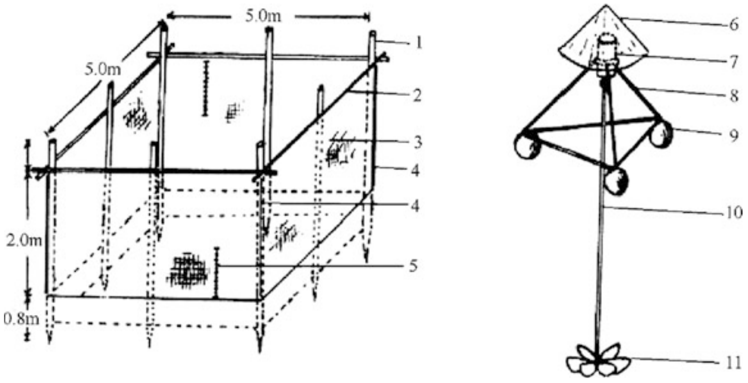


Fig. 9.9 The structure of the land-based experimental enclosure (left) and its water stirrer (right) (Li et al. 1998). (1) Wood pole; (2) Thick bamboo pole; (3) Plastic-coated polyethylene woven cloth; (4) Thin bamboo pole; (5) Zipper; (6) Rain-screening cap; (7) Motor; (8) Stand; (9) Float; (10) Transmission shaft; (11) Propeller

9.5 Structure Optimization of Integrated Aquaculture

Structure optimization of IA system refers to the process to optimize the species composition and stocking quantities of each species within a specific IA system. Optimized IA structure can obtain the best ecological and economic benefits. The optimization of the IA structure of reservoirs, seawater ponds, and open sea areas will be introduced in the following examples.

9.5.1 Structure Optimization of Integrated Aquaculture in a Reservoir

In the 1980s, common carp farming in net cages in reservoirs was very popular in China. However, there were also deterioration of water quality and mass mortality of the fish in some reservoirs. For this reason, people began to pay attention to and explore the model of integrating filter-feeding fish to improve water quality and increase the carrying capacity of the reservoirs.

Xiong et al. (1993) studied the optimal structure of fed common carp integrated with filter-feeding silver carp in Dongzhou Reservoir, Shandong Province, using suspended enclosures in situ (Fig. 9.7). The experiments were conducted with 30 enclosures, a depth of 5 m and a volume of 14.3 m^3 each. A total of 15 treatments were set with two replicates for each treatment (Table 9.2). The enclosures of treatment A were not stocked with common carp, while the enclosures of other four treatments, i.e., B, C, D, and E, were stocked with the carp at 75.5, 50.7, 37.8, and 30.1 kg/m^3, respectively. For silver carp, 1:3 (Group 2) or 1:2 (Group 3) of common carp loading were stocked.

Table 9.2 Ecological indicators and integrated benefit index in each treatment (from Xiong et al. 1993)

Treatments		Common carp					Silver carp			
		NP	GR	FE	CC	BSI	NP	GR	TNP	TCC
A	1	—	—	—	—	—	—	—	—	—
	2	—	—	—	—	—	55.0	68.8	55.0	471.2
	3	—	—	—	—	—	51.2	39.5	51.2	633.3
B	1	373.9	34.8	18.4	5065.5	11.5	—	—	373.9	5064.5
	2	418.8	38.6	20.8	5260.5	12.9	230.0	63.9	648.8	7320.7
	3	465.3	43.3	22.0	5379.0	14.1	295.0	52.5	760.3	8365.2
C	1	394.9	54.5	24.6	3912.0	15.7	—	—	394.9	3913.0
	2	495.0	64.2	29.7	4155.0	19.0	220.0	87.8	715.0	5796.9
	3	424.7	58.6	26.8	4015.5	16.9	273.0	73.9	698.1	6262.1
D	1	285.0	52.8	24.1	2880.0	13.5	—	—	285.0	2881.4
	2	340.0	63.0	28.7	3073.5	16.1	195.0	108.4	535.0	5382.2
	3	262.0	52.4	25.0	2863.5	13.6	220.0	81.5	502.0	4574.3
E	1	410.0	95.4	40.8	2934.0	21.4	—	—	410.0	2934.0
	2	410.0	95.4	44.3	2934.0	22.0	145.0	96.7	555.0	3964.0
	3	325.0	75.6	41.7	2637.0	18.5	216.0	100.0	540.0	4138.1

Note: Each treatment has two replicates. *CC* fish load (kg/hm^2), *FE* food efficiency (%), *GR* growth rate (%), *NP* net production (g), *TCC* total fish carrying (kg/hm^2), *TNP* total net production (g), *BSI* biological synthesis index, $= (NP_n \times W_n \times FE_n)^{1/3}$

The results of the 34 day's experiment showed that the stocking of silver carp reduced the quantities of phytoplankton, zooplankton, bacterioplankton, and the concentration of total phosphorus, which significantly improved the water quality. After 16 days of the experiment, the transparency of the waters with silver carp was significantly greater than that without silver carp, and the higher the stocking quantity of silver carp the greater the transparency was.

Dissolved oxygen content (DO) was negatively correlated with the common carp loading. DO in the 1:2 silver carp groups tended to be higher than that in the 1:3 groups. The hypoxia phenomenon of the farmed fish occurred in B, C, and D treatments since the 10th day of the experiment, indicating that the stocking quantities of common carp in these three treatments have exceeded the carrying capacity of the waters.

Chemical oxygen demand (COD) was positively correlated with common carp loading in the study, and was significantly lower in the treatments with silver carp than that without silver carp. The higher the ratio of silver carp stocked the lower the COD was. Biological oxygen demand (BOD) increased in all treatments during the experiment, and the degree of increase was positively correlated with common carp loading, but none of them exceeded 5.0 mg/L, the Water Quality Standard for Fisheries of China.

The ecological indicators and integrated benefit index of each treatment are shown in Table 9.2. The carrying capacity or fish loading (CC) of common carp in the treatments with silver carp, i.e., B2, C2, D2, and E2, was greater than or equal to that without silver carp. This indicates that integration with silver carp can increase the carrying capacity of common carp in the waters. In terms of the total carrying capacity of both common carp and silver carp, the carrying capacity of fish in E1 without silver carp was only 2934 kg/hm^2, while that in E2 with silver carp reached 3964 kg/hm^2, a 35% increase in carrying capacity.

The statistical results of the experiment also showed that the integration with silver carp improved not only the net production, growth rate, and feed efficiency of common carp, but also the total fish production and the integrated benefit index of the waters. From the E1 and E2 treatments, it can be seen that the integration with silver carp increased the feed efficiency of common carp by 10% and the total fish production by 35%.

Water quality measurements showed that the 1:2 integrated treatment outperformed the 1:3 integrated treatment. While the ecological indicators and integrated benefit index in Table 9.2 showed that the 1:3 integrated treatment was better than the 1:2 integrated treatment. Comparison between the E2 and E3, which represent the carrying capacity of the waters, both treatments could meet the Water Quality Standard for Fisheries of China, but the BSI of E2 (1:3) was better than that of E3 (1:2). Considering various factors, the best ratio of silver carp to common carp is 1:3 in the reservoir.

It should be noted that due to environmental protection China has gradually banned the net cage farming of fed fish in multi-functional reservoirs. Therefore, the main purpose of introducing the above case is to illustrate the methodology of IA structure optimization using suspended enclosures in deeper waters. This method has important reference to the small reservoir whose function is only aquaculture.

9.5.2 Structure Optimization of Integrated Aquaculture in Ponds

In 2004, our team optimized the IA structure of whiteleg shrimp, green clam (*Cyclina sinensis*), and seaweed (*Gracilaria lichevoides*) using land-based enclosures (Fig. 9.8) in Tanggu, Tianjin (Bao et al. 2006; Chang et al. 2006; Wang et al. 2006a; Dong et al. 2007). The experiment lasted 51 days by using 25 m^2 enclosures with four replicates for each treatment. The body weights of stocking shrimp and green clams were 0.11 ± 0.02 g/ind. and 6.03 ± 1.12 g/ind., respectively. The experimental design and main results are presented in Table 9.3.

At the end of the experiment, the body weight, survival rate, and net yield of shrimp were 5.30–6.12 g, 63.0%–78.2%, and 1065–1368 kg/hm^2, respectively. The body weight and net yield of green clams were 6.85–7.15 g and 51–328 kg/hm^2, respectively. The net yield of seaweed was 3900–9380 kg/hm^2. The ecological and economic benefits of the IA systems were better than those of shrimp monoculture. Under the experimental conditions, the optimal stocking ratio or structure of the IA was 30 ind./m^2 of the shrimp, 30 ind./m^2 of the clam, and 200 g/m^2 of the seaweed.

Nine kinds of IA structures of Chinese shrimp or whiteleg shrimp were optimized in seawater ponds from 1996 to 2005 by our team (Table 9.4). These optimized structures are not only economically efficient, but also ecologically beneficial. For example, compared with shrimp monoculture, the 1:0.3:2 structure of Chinese

Table 9.3 Effects of integrated mariculture of shrimp (*Litopenaeus vannamei*), seaweed (*Gracilaria lichevoides*), and clam (*Cyclina sinensis*) (from Dong 2015b)

	Treatments				
Items	P	PSC1	PSC2	PSC3	PSC4
Shrimp stocking rate (ind./m^2)	30	30	30	30	30
Clam stocking rates (ind./m^2)	0	7	15	30	45
Seaweed stocking rates (g/m^2)	0	360	280	200	120
Shrimp net productions (g/m^2)	115.4	119.1	116.6	136.8	106.5
Shrimp yield sizes (g/ind.)	5.47	6.12	5.30	5.53	5.32
Shrimp survival rates (%)	67.5	69.7	68.0	78.2	63.0
Clam net productions (g/m^2)	—	5.1	16.4	32.8	25.3
Seaweed net productions (g/m^2)	—	938.0	743.0	779.5	390.0
Photosynthetic conversion efficiencies (%)	0.12	0.71	0.64	0.81	0.54
Total energy conversion efficiencies (%)	42.62	90.97	82.77	92.07	60.48
N utilization rates (%)	24.5	38.2	34.7	35.6	26.3
P utilization rates (%)	7.2	13.9	14.3	17.2	9.5
Ratios of output and input	1.22	1.89	1.71	1.69	1.29

Note: *P* shrimp, Photosynthetic conversion efficiency (%) = (Total net output/Photosynthetic input) × 100%, *PSC* shrimp, seaweed and clam, Total energy conversion efficiency = (Total net output/Total input) × 100%

Table 9.4 Optimal structure of integrated shrimp mariculture in seawater ponds

Integration models	Optimized biomass ratios	Date sources
Fenneropenaeus chinensis with tilapia	1:1	Wang et al. (1998b)
F. chinensis with razor clam	1:3	Li et al. (1999)
F. chinensis with oyster	1:6	Su et al. (2003)
F. chinensis with bay scallop	1:1	Wang et al. (1999b)
F. chinensis with tilapia and razor clam	1:0.3:2	Tian et al. (2000)
Litopenaeus vannamei with *Cyclina*	1:0.8	Wang et al. (2006a)
L. vannamei with *Gracilaria*	1:5	Niu et al. (2006)
L. vannamei with *Cyclina* and *Gracilaria*	1:1.3:8.3	Wang et al. (2006a)
L. vannamei with *Scapharca* and *Gracilaria*	1:1:5.9	Niu et al. (2006)

Table 9.5 Benefits of shrimp, tilapia, and razor clam integration (from Dong 2015b)

Benefits	Shrimp	Shrimp + tilapia	Shrimp + razor clam	Shrimp + tilapia + razor clam
Total productions	100%	+40%	+104%	+82%
N discharge	100%	–23%	–63%	–86%
Output/Input ratio	100%	–3%	+7%	+10%

Table 9.6 Water and sediment quality in the pond of shrimp integration (%) (from Dong 2015b)

	Water		Sediment	Discharge rates	
Integration models	TN	TP	TOC	N	P
F. chinensis with *Ruditapes*	–5.2	–18.2	—	—	—
L. vannamei with *Cyclina*	–21.3	–10.5	–32.5	–24.5	–17.8
L. vannamei with *Gracilaria*	–21.0	–30.1	—	—	—
L. vannamei with *Cyclina* and *Gracilaria*	–42.6	–31.7	–239.8	–109.9	–252.7
L. vannamei with *Scapharca* and *Gracilaria*	–37.0	–37.5	—	—	—

Note: Taking shrimp monoculture as 100%

shrimp + tilapia + razor clam has 82% higher total production, 86% lower N discharge, and 10% higher output/input ratio (Table 9.5).

In addition, compared with shrimp monoculture, the 1:1.3:8.3 biomass structure of shrimp + *Cyclina* + *Gracilaria* has significant ecological benefits with substantial reductions in TN and TP levels of the water, TOC of the sediment, and N and P discharge rates of the pond system (Table 9.6).

9.5.3 Structure Optimization of Integrated Aquaculture in a Seawater Bay

Since the late 1980s, IMTA has been successfully practiced in Sanggou Bay, Shandong Province, which produces a total of more than 240 000 t/year of aquatic products from more than 30 farmed species in about 100 km^2 of sea area (Fang et al. 1996, 2016). There are several IMTA models in different areas of the bay (Fig. 9.10). These examples of IMTA maximize the utilization of mariculture space. Implementation of IMTA in the bay has improved economic benefits, maintained environmental quality, and created new jobs. Moreover, it increases the beneficial functions of an ecosystem. For example, fish farming integrated with bivalves can turn the system into a CO_2 sink through carbon sequestration of bivalve shells (Tang et al. 2011).

One example of IMTA in Sanggou Bay is the integration of abalone (*Haliotis discus hannai*) and kelp (*Laminaria japonica*) (Fig. 9.9A). The total ammonia excreted from the abalone in cages at a mariculture unit (1600 m^2) in the farming season is about 2.2 kg N. The kelp that is needed to absorb the excreted ammonia is 10,080 individuals. In the demonstration area (1600 m^2), 12,000 individual kelps were cultivated actually. The yield of abalone every 2 years was approximately 900 kg, resulting in a value of about 10,000 US$/1600 m^2 (Tang et al. 2013).

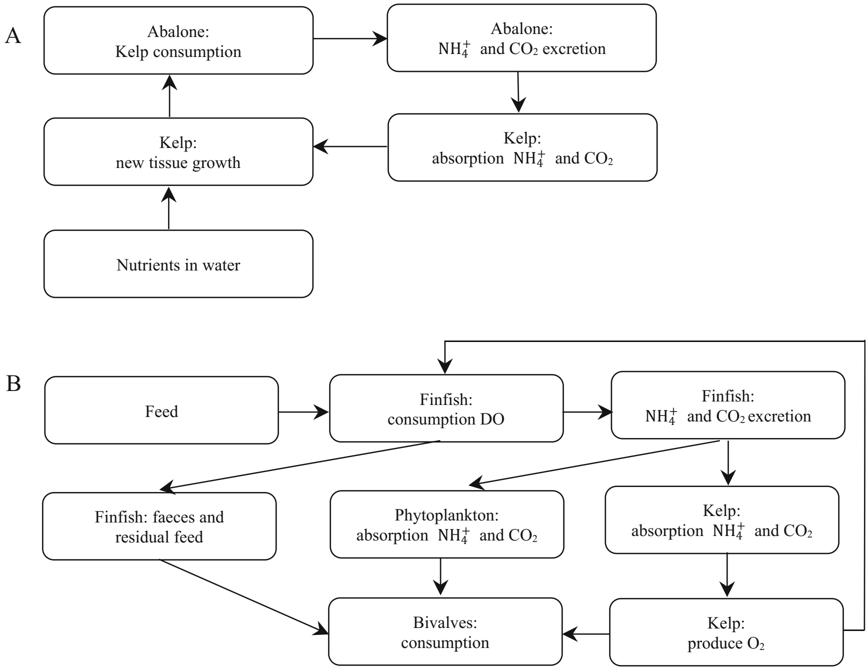


Fig. 9.10 Integrated multi-trophic aquaculture models in Sanggou Bay, China (from Fang et al. 2016). (**a**) Longline culture of abalone and kelp, (**b**) co-culture of finfish, bivalve, and kelp. *DO* dissolved oxygen

The anther example of IMTA in Sanggou Bay is the integration of finfish, bivalves, and seaweed (Fig. 9.9B). The seaweed absorbs inorganic nutrients excreted by the finfish and bivalves, and the bivalves filter suspended organic particles produced by the finfish. Since kelp is cultured from December to May and *Gracilaria lemaneiformis* is cultured from June to November, respectively, the algae can absorb inorganic nutrients from farming water throughout a year (Tang et al. 2013).

To optimize the integrated structure of finfish in net cages and seaweeds, sea bass (*Lateolabrax japonicus*) and black rock fish (*Sebastodes fuscescens*) were cultured in net cages and were fed with iced trash fish (Ge et al. 2007). Ammonia excreted from the fishes was 510 kg N and 5874 kg N in Winter/Spring and Summer/Autumn, respectively. N contents of *Laminaria* and *Gracilaria* in dry weight are 1.34% and 2.70%, respectively. To absorb the ammonia excreted by the fish in Winter/Spring the optimal ratio of wet weight fish to dry weight *Laminaria* is 1: 0.44 kg, and in Summer/Autumn the ratio of fish to *Gracilaria* is 1: 1.12 kg.

In Sanggou Bay, the assimilation efficiency of oysters (*Crassostrea giga*s) for the organic matter derived from the sea bass (10% feed residuals and 44% fish feces) is estimated at 54%. If, for example, 42% of the particle organic matters are within the suitable size range for the oysters, about 23% of the particle organic matters can be used by the oysters (Jiang et al. 2012a).

The third example of IMTA in Sanggou Bay is the integration of abalone, kelp, and sea cucumber (*Apostichopus japonica*). The inorganic products (NH_3, CO_2) excreted from the abalone are absorbed by the kelp. The kelp can in turn be consumed by the abalone. The sea cucumber feeds on decaying kelp and other organic matters, therefore, they are cultured in abalone cages, which are suspended from kelp longlines. The two year's production value of the integration was almost 90,000 CNY/1600 m^2, 19,000 CNY of which was from the sea cucumber in 2009 (Fang et al. 2009).

9.6 Development of Integrated Aquaculture

IA has been practiced in China for almost 2000 years, and the Western world has seen the advantages of IMTA and has been developing and promoting it for decades. The concept of IA has never been as deeply rooted in the world aquaculture community as it is now. However, there is still a lot of potential for the development of IA.

9.6.1 The Intensification Level of IA Models Still Needs To Be Improved

IA models are extremely popular in pond culture in China, and reasonable multi-species stocking is also advocated in lakes and reservoirs (aquaculture-based fisheries). The 'reasonable' here means to optimize the species composition and stocking quantities of each species according to the composition and productivity of the natural diet organisms in the waters. China's current IA models in ponds are mostly semi-intensive or even extensive models, parts of intensive pond farming are still monoculture. Therefore, some pond IA models with a high level of intensification and standardized discharge are urgently needed to be developed, which is very important for the sustainable development of the aquaculture industry! (see Chap. 15).

More intensive IA models may make management and operation more complicated, but some of novel pond IA models, such as in-pond raceway systems, partitioned aquaculture systems and so on, can make the operations easier (See Chap. 10).

9.6.2 Research, Extension, and Application Are Indispensable

Most IA models are invented by farmers in China, and a significant proportion of them have not been optimized. Therefore, many current IA models have a great room of optimization for higher economic and ecological benefits. The optimized results of IA are often expressed in terms of the best 'biomass ratios' (Table 9.4), equivalent to gross production ratios, whereas in application the farmers directly need the stocking quantity ratios. Although the 'biomass ratios' is the most scientific expression, there is still a distance from the direct application. It is not easy to calculate the 'biomass ratios' into the stocking quantity ratio, because it is related to the seedling sizes, length of production season, water quality, and so on. As can be seen, there is still a need for an 'extension' link between research and application by local aquaculture extension experts.

9.6.3 Commoditization and Certification

The IA models are normally used in family-owned ponds, and are usually limited in scale. Their products are rarely certified in China, making it difficult for such products to enter high-value chain markets, and in turn difficult to scale up. The solution is to implement third-party certification of the products and scale up. This requires local governments or fisheries associations or aquaculture extension stations to assist farmers in developing holistic farming plans and product certification.

9.6.4 Food Safety and Seaweed Market

IA is readily accepted in Asia, especially in China and Southeast Asia, but it is not easy to get the West to accept it. Westerners have a complex perception of 'nutrients' and 'manure' (Chopin 2012). For example, they consider mushrooms specifically grown on farmyard manure to be organic products (European Community Regulations No 2008R0889–Article 6) and can command premium market prices for such products. However, it is difficult to accept aquatic products from IMTA. An earlier version of the Canadian Shellfish Sanitation Program prevented the development of IMTA because of a clause that specified that shellfish could not be grown closer than 125 m of finfish net pens. After Chopin's work, the paragraph was amended so that IMTA practices could develop to a commercial scale legally (Chopin 2012). Nowadays, concerns about the safety of IMTA products still persist in the West (Little et al. 2016). It is true that direct feeding of fish with pig manure is undesirable, but fish, shellfish, and algae live together in nature, so there is no need to be so concerned about the trophic relationships between them.

Seaweed products from Asian IMTA are favorable food or chemical materials, whereas in the West, IMTA development first has to find a market for the seaweeds produced. So, we still have a lot of work to do regarding the safety of IMTA products and other issues.

9.6.5 Implementation of Effective Management

China has long been practicing nearshore IMTA on a large scale, but very few have actually been implemented according to an informed planning due to the lack of effective management and enough studies on social carrying capacity. Social carrying capacity is the maximum harvest or stocking density that is acceptable to other stakeholders. In the past decades, a lot of research work has been done on the physical, productive, and ecological carrying capacity of waters in China, while there are still few studies on social carrying capacity, let alone its implementation (see Sect. 3.3 for details). In the case of Sanggou Bay, in which there are several hundreds of farms (including family-owned ones), there is a need to develop and implement an overall farming plan (layout of farming areas, farming types, and densities) that is acceptable to all stakeholders. We have not yet completed this 'last a mile'.

Brief Summary

1. The generalized IA refers to the simultaneous culture of several aquatic species or culture of aquatic species together with other productive activities. The generalized IA includes the following three forms: (1) the co-culture of aquatic organisms in a pond, such as fish polyculture in a pond; (2) the culture of aquatic organisms with other agro-industrial activities in the same waters, such as fish farming together with duck farming in a pond; (3) the culture of aquatic organisms together with other industrial activities, such as the integration of aquaculture with ecotourism.
2. Currently, there are several dozen practices of IA in China. Although waste utilization is the most important consideration in those IA practices, other IA practices based on other considerations are also popular and important. The most important ecological rationales of IA are: (1) waste reclamation through trophic relationship, (2) water quality maintenance through complementary functions between species or systems, (3) water quality regulation through non-classic top-down effect, (4) full utilization of the resources (various diet organisms, space, and time) of aquaculture waters through different ecological niche species,

(5) diseases prevention ecologically, (6) benefit multiplication through integration of aquaculture and other activities. Therefore, IA is the aquaculture model that rationally integrates anthropogenic inputs with aquaculture ecosystem services or integration of multiple production activities.

3. China has the greatest variety of farmed aquatic species and production systems in the world. IA models in China can be summarized into two groups, namely the species integration and the system integration, and the latter group can be further divided into the integration of aquatic systems, integration of aquatic and land systems, integration of aquaculture with the services provided by the space above the farm, and integration of aquaculture with the culture services of the farm.
4. Trophic integration refers to polyculture of aquatic species from different trophic levels in an aquatic system. For example, finfish is integrated with inorganic extractive species such as seaweeds, and organic extractive species such as filter-feeding bivalves. Within the system an output from one species, which otherwise may have been wasted, becomes a food or nutrient to another species. The IA of trophic integration is more favored by Western scholars, and is called IMTA.
5. Structure optimization of IA refers to the optimization of species composition and stocking quantities of each species within a specific IA system. Optimized structure of IA system can obtain the best ecological and economic benefits.
6. Ecological studies or experimental methods can be classified as observational studies, mensurative experiments, and manipulative experiments or controlled experiments. The defining feature of a manipulative experiment is that the different experimental units receive different treatments and that the assignment of treatments to experimental units is or can be randomized. Manipulative experiment has four important properties or elements, i.e., control, replication, randomization, and interspersion.
7. Experimental enclosure is medium- and large-sized artificial simulated ecosystem, which makes it possible to carry out manipulative experiments, and is a more ideal method that balances experimental manipulability and realism. The experimental enclosure systems overcome the shortcomings of previous field aquaculture studies that were not easily replicable and indoor simulations that were severely distorted. Suspend enclosure can be used to optimize the IA structure in deeper waters, while land-based enclosure can be used to optimize the IA structure in shallower waters, such as ponds.
8. IA is a kind of aquaculture systems designed and established to maximize ecological and economic benefits and to achieve a ‘win-win’ situation in terms of economic development and ecological protection. The benefits of IA systems should also be evaluated by a comprehensive index system that combines economic and ecological indicators.
9. IA has been practiced in China for almost 2,000 years, and the Western world has seen the advantages of IMTA and has been developing and promoting it for decades. Some pond IA models with a high level of intensification and standardized discharge are urgently needed to be developed, which is very important for the sustainable development of the aquaculture industry.

Land-Based Intensive Aquaculture Systems 10

Xiang-Li Tian and Shuang-Lin Dong

Aquaculture production in China mainly derives from ponds, nearshore areas, lakes, reservoirs, and other waters in various forms. Generally, the intensification degree for these types of aquacultures is relatively low, and most of them are extensive or semi-intensive systems. To improve culture yield and economic benefits, aquaculture industry around the world has shown a tendency of intensification in recent years, i.e., increasing the proportion of fed species production, the adoption of intensive aquaculture systems (cage, pen, raceway, indoor facilities), and application of oxygenators. With the intensification of pond farming, increased freshwater consumption and pollutant discharge have affected the sustainable development of pond farming. Therefore, some land-based intensive aquaculture models have been adopted to solve these problems. This chapter will introduce the principles of land-based intensive aquaculture systems, such as recirculating aquaculture systems, solar recirculating aquaculture systems, raceway aquaculture systems, and biofloc-based aquaculture systems.

10.1 Recirculating Aquaculture Systems

Recirculating aquaculture systems (RAS), also called industrial aquaculture systems in China, are tank-based closed-loop aquaculture systems in which aquatic organisms can be cultured at high density under controlled environmental conditions. Conventional RASs are based on the function of microbial nitrification to retain and treat the water within the system, modern RASs are beginning to pay

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attention to microbial denitrification, and the role of plant photosynthesis is in removing dissolved nutrients from water.

10.1.1 Principles of Conventional Recirculating Aquaculture Systems

The ‘wastewater’ or ‘tailwater’ discharged from the RAS is slightly polluted, which can be treated and then recycled. The wastewater is treated with various physical, chemical, and biological methods. Generally, the essential treating process includes mechanical filtration, biofiltration, disinfection, temperature regulation, oxygen supply, etc. Normal components of RAS used for fish culture are as follows: a culture tank, sedimentation tank, physical clarification units, biofiltration units, and disinfection units (Fig. 10.1).

After aeration, sedimentation, filtration, and disinfection, the water discharged from the RAS culture tank is temperature-regulated, oxygenated, and supplemented with the appropriate amount of fresh water (1–10%, replenishing the lost or evaporated water in the system) according to the physiological requirements of different culture species and their growth stages, and then flows back into the culture tanks for recycling use. Generally, less freshwater is used by RAS, 3000–45,000 L/kg of fish in a typical culture system. Some RAS with artificial seawater even uses as little as 16 L/kg of freshwater (Klinger and Naylor 2012). This system is also equipped with water quality monitoring, flow rate control, automatic feeding, waste disposal, and other devices, and is automatically monitored by the central control room.

Compared with the traditional outdoor pond aquaculture systems, RASs possess the following obvious advantages: (1) Conserve heat and water through water treatment by biofilters. (2) Less pollutants are discharged and environmentally friendly. (3) Have predictable harvesting schedules according to market demands all year round. (4) Allow effective economies of scale, resulting in the highest

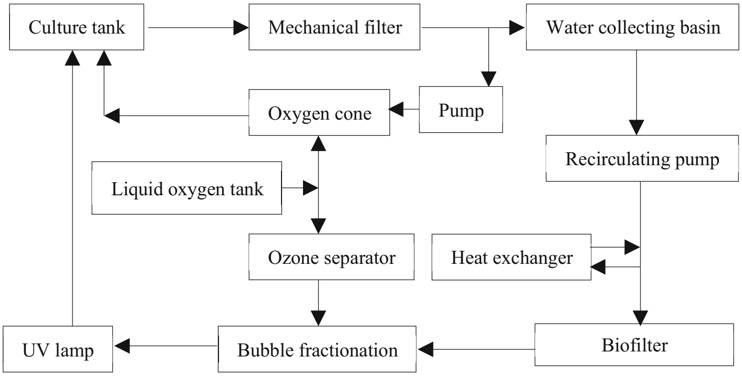


Fig. 10.1 A general diagram of water treatment process in a typical recirculating aquaculture system.

productivity. (5) Location can be more freely decided, e.g., the location can be close to the marketplace to reduce logistics costs. (6) Operation can be conducted according to specifications; therefore, their products are traceable, diseases are preventable, and food safety is guaranteed. (7) Employ a greater range of workers, such as the elderly and women due to high mechanization. (8) Biosafety is highly secured due to good containment. Some species with high biosafety requirements, such as transgenic fish, can be cultured safely.

The product quality between RAS and outdoor mariculture is also different apparently. For example, the tiger puffer fish *Takifugu rubripes* grown in RAS have less damage in caudal fin; their products have minimal risk of poisoning, have higher score in taste tests compared to those grown in net cage (Takeuchi 2017). In addition, marine RAS are not affected by red tides and epidemic pathogens directly, making RAS farming safer.

In recent years, great progress has been made in the research and development of genetic engineering technology for aquatic animals, and transgenic marine Atlantic salmon and transgenic freshwater Nile tilapia have been successful, and their growth rates and food utilization have improved about one time compared with the original species. RAS is the most ideal facility to guarantee the safety of transgenic animal farming, and in this regard, RAS also has a broad prospect.

In early or conventional RAS, all parts of the system are basically under aerobic conditions, especially for the biofilter, which is generally always under aerated conditions. Therefore, anaerobic denitrification is inhibited and can be ignored in the system. The aeration allows the microorganisms on the biofilter to full contact with the water, and the efficient nitrification oxidizes NH_4^+ to NO_3^-. At the same time, the pH of the aqueous environment decreases.

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^-$$

However, the total amount of dissolved inorganic nitrogen in the RAS does not reduce actually, and the microorganisms in the biofilter only convert NH_4^+, which is toxic to farmed animals, to NO_3^-. Although NO_3^- is not highly toxic to fish, its excessive accumulation in the RAS can also affect the growth and immunity of farmed fish and, in severe cases, endanger their survival (Freitag et al. 2015). Also, once a zero discharge RAS operated in long-term discharges, the total inorganic nitrogen concentration in the effluent will still exceed the corresponding limits of discharge standards.

Ammonia in the water exists in two forms, un-ionic ammonia (UIA, NH_3) and ionized NH_4^+, with the relative concentration primarily a function of pH and temperature. An increase in pH or temperature increases the proportion of UIA. UIA is highly toxic to fish at low concentrations. NH_4^+ and NH_3 in RAS water constitute the following equilibrium:

$$NH_4^+ + H_2O \leftrightarrow NH_3 + H_3O^+$$

Once the pH of the water increases, the proportion of UIA will increase as well. Some zero discharge RAS often reduce the pH of the water to 6.5 or less to ensure the safety of farmed animals. The acidic water environment is unfavorable to the growth and molting of aquatic animals. The high concentration of total inorganic nitrogen and the acidic water environment are the main defects of conventional RAS.

10.1.2 Denitrification in Modern Recirculating Aquaculture Systems

During the aerobic biofiltration process, ammonia is nitrified to the form of less toxic nitrate, which accumulates in the water. The water exchange rates of conventional RAS are generally 0.1–1.0 m^3/kg feed (Martins et al. 2010). To overcome the shortcomings of high total inorganic nitrogen accumulation in conventional RAS, modern RASs have introduced microbial denitrification unit into the systems to reduce the concentration of NO_3^- in the systems (Fig. 10.2). The denitrification unit in modern RAS converts NO_3^- and NO_2^- to N_2, which can eventually escape from the RAS system, under anaerobic conditions by the following reactions:

$$C_6H_{12}O_6 + 12NO_3^- \rightarrow 12NO_2^- + 6CO_2 + 6H_2O$$

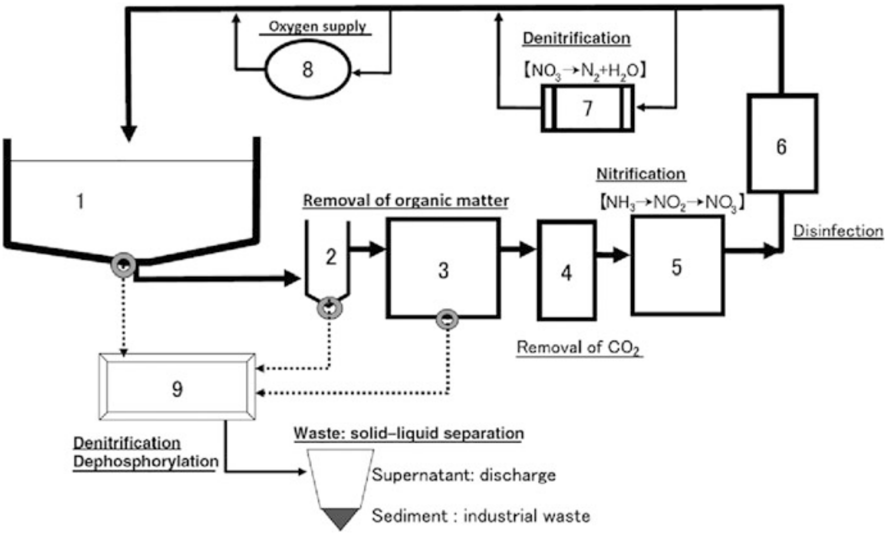


Fig. 10.2 Schematic diagram of equipments and its function in RAS (from Yamamoto 2017). (1) Rearing tank; (2) sedimentation tank; (3) physical filter unit; (4) degasifier; (5) biofilter unit; (6) disinfection unit; (7) denitrification unit; (8) oxygen supply unit; (9) waste treatment unit.

$$C_6H_{12}O_6 + 8NO_2^- \rightarrow 4N_2 + 2CO_2 + 4CO_3^{2-} + 6H_2O$$

Traditional denitrification theory suggests that denitrifying enzymes are active only under anoxic or partly anaerobic conditions. Robertson and Kuene (1984) reported the existence of aerobic denitrifying bacteria and aerobic denitrifying enzyme systems, which provides a new way for the removal of nitrate in aquaculture systems under aerobic conditions. Recent studies have shown that the reactor of heterotrophic nitrifying-aerobic denitrifying bacteria can directly use the nitrate nitrogen and nitrite nitrogen produced by the nitrification process as substrates for aerobic denitrification, which greatly reduces the operating costs and operational difficulties (Huang et al. 2018).

The main factors affecting aerobic denitrification are carbon source, dissolved oxygen, and the ratio of carbon to nitrogen (C:N). As carbon sources for denitrification of Siberian sturgeon (*Acipenser baeri*) aquaculture system, methanol, acetic acid, glucose, and hydrolyzed starch are effective in reducing nitrate-nitrogen concentrations from 11–57 mg/L to undetectable levels (Hamlin et al. 2008). In a CRAS for rainbow trout with a rotating disk filter serving as biofilter, water quality is maintained by the addition of hydrolyzed corn starch with organic C:N of 1.6:1 to promote the growth of aerobic denitrifying bacteria. During the culture period of 118 d, nitrate nitrogen decreased from 120 to 10 mg/L and stabilized thereafter (Kaiser and Schmitz 1988).

Aerobic denitrifying bacteria have a dissolved oxygen threshold, above or below which the rate of aerobic denitrification decreases. For example, the dissolved oxygen threshold of *Citrobacter diversus* is 5 mg/L. Aerobic denitrifying bacteria require a certain C:N ratio in water, and the optimal C:N ratio required by various aerobic denitrifying bacteria varies as well.

Compared with the aerobic nitrification process in RAS, the aerobic denitrification process has the advantages of small footprint and the ability to achieve simultaneous nitrification and denitrification. As an example, in a 600 MT/year Nile tilapia RAS farm integrating with a denitrification reactor using internal carbon source in the Netherlands, the water exchange rate is as low as 30 L/kg feed, corresponding to 99% recirculation (Martins et al. 2009). The requirements for water, heat, and bicarbonate are lower in the denitrification RAS than in the conventional RAS for tilapia farming (Eding 2009). The denitrification RAS has somewhat higher cost of oxygen, electricity, and labor, but the actual production costs for unit product are 10% lower than for the conventional RAS. Waste discharge is significantly reduced by the denitrification RAS compared with the conventional RAS (Eding 2009).

10.1.3 Commercial Application of Recirculating Aquaculture Systems

The concept of closed recirculating aquaculture system (CRAS) was first proposed by a Japanese scientist Saeki (1958), and by the 1970s, experimental research on

RAS began in Europe and the United States. The countries that started the commercial application of RAS earlier include the Netherlands and Denmark, etc. In 2018, China's industrial aquaculture (including RAS and flow-through systems) production was 469,000 t, of which 54.5% was from mariculture systems.

Most existing commercial RASs produce high-price species, including rainbow trout, salmon, tilapia, turbot, eel, African catfish, striped bass, sturgeon, arctic char, halibut, sea bass, whiteleg shrimp, etc. The most of RASs have been developed for small-scale operations ($<$50 t of output per year), and there are few large-scale ones ($>$50 t of output per year). High start-up costs combined with uncertain profitability have discouraged investments (Klinger and Naylor 2012).

Water quality of RAS relies entirely on water treatment facilities and dissolved oxygen supplementation. It is also necessary for RAS to regulate and control the temperature and lighting. Thus, RAS consumes much more operational energy than most other types of aquaculture systems. The total energy consumption per unit product for pond, industrial aquaculture (including RAS and flow-through systems), and net cage culture in China are 0.37, 8.66, and 3.16 kWh/kg (Xu et al. 2011). Klinger and Naylor (2012) also summarized that the total energy consumptions (including feed) of carnivorous-finfish RAS facilities, net pen, and flow-through systems are 16–98, 7.4, and 27.2 kWh/kg product. More energy consumption means more indirect CO_2 emission (1 kWh/kg = 0.997 CO_2) and high carbon footprint.

Since energy prices are relatively lower in developed countries and labor costs are extremely high, it is logical that RAS, which uses less labor and consumes more electricity, was invented in developed countries. However, compared with developed countries, China's relatively higher energy prices and still low labor costs make RAS products uncompetitive in many cases. However, due to the incentive policies of China government, the industrial farming production in China increases by 8.0% per year in the past decade. In fact, the sustainability of RAS development is not high in China (see Chap. 14). RAS products can be competitive only if the effluent from pond farming and groundwater extraction for aquaculture are strictly supervised in near future.

The energy consumption of RAS farming tiger puffer (*Takifugu rubripes*) in Japan accounts for 39.3% of the total costs (Takeuchi 2017). The energy consumption for flatfish farming in Europe accounts for 11%, while the corresponding cost in China accounts for 28% (Ying Liu, private communication). Therefore, reducing energy consumption is still an important task for the development of RAS in China. RAS can save energy with the help of other energy sources, such as farming warm water species with warm water drainage from power plants, farming cold-water fish with cold water drainage of liquefied natural gas (LNG) facilities, or farming aquatic organisms by artesian water of high-water level of water sources, etc.

Recently, the concept of Closed Ecological Recirculating Aquaculture Systems (CERAS) has been proposed and experimental studies of CERAS with phytoplankton, zooplankton, tilapia, and biofilters as the main components have been conducted (Takeuchi 2017). These researches are of great importance for future deep space exploration and construction of artificial floating islands at sea.

Food production systems without photosynthesis are usually not high in ecological efficiency because of the large amount of artificial energy, and material inputs are required to run such systems. The following will introduce the energy saving and emission reduction effects of integrating photosynthesis into a CRAS to build a solar recirculating aquaculture system.

10.2 Solar Recirculating Aquaculture Systems

The main problems of conventional RASs based on nitrification are high energy consumption and inorganic nitrogen accumulation, and RASs with denitrification function still have the problem of high energy consumption. The designers of RASs always try to achieve full artificial control of the aquaculture environment, ignoring or excluding the roles of ecosystem services, especially the photosynthesis, in regulating water quality. In this section, we introduce the solar recirculating aquaculture system (SRAS) that implants aquatic plants (submerged macrophytes, floating or emergent plant, phytoplankton) into RAS, including aquaponic system (APS) based on floating or emergent plant, submerged plant-based SRAS, and phytoplankton-based SRAS.

10.2.1 Aquaponic Systems

10.2.1.1 Principles and Advantages of Aquaponic Systems

Conventional RAS is one of the most productive aquaculture systems, but its drawback is that it eventually discharges wastewater. Hydroponics is one of the most productive agricultural production systems, but it requires additional nutrients input. Conventional RAS and hydroponics are somewhat complementary in terms of the nutrient balance of the system. Aquaponic system (APS) is a combination of conventional RAS and hydroponics, implanting emergent plants or floating plants into a recirculating aquaculture system. However, only the systems in which more than 50% of the nutrients absorbed by the ‘vegetables’ in the system can be called APS (Lennard and Goddek 2019).

APS takes advantage of the mutually beneficial effects of fish and plants fully. The implanted plants absorb and remove excess nutrients from the aquaculture environment, achieving the goals of water purification, effluent reduction, and economic benefit increment. The production of fish and aquatic plant in an ideal APS can be comparable to the number of fish produced by a RAS plus the number of vegetables produced by another hydroponics (Lennard 2005).

The basic units of APS consist of fish culture ponds or tanks, settling pond or sedimenter, biofilter, hydroponic component, and sump (Fig. 10.3). The hydroponic unit consists of a pond, a substrate of gravel and sand (or porous plastic films), and plants. The residual feeds and fecal particles produced by fish culture unit can be removed by settling tanks or mechanical filters; ammonia produced by the cultured

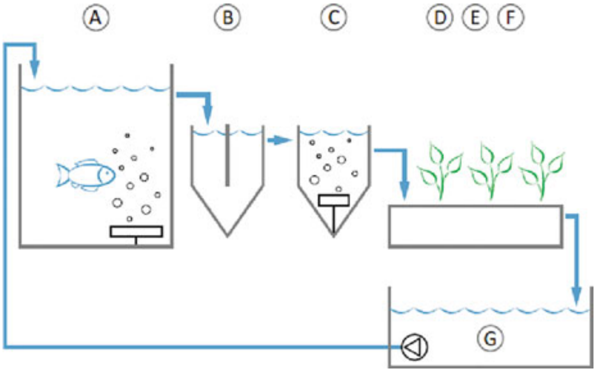


Fig. 10.3 Schematic diagram of an aquaponic system (from Palm et al. 2019). (**a**) Fish tank and aeration, (**b**) Sedimenter, (**c**) Biofilter with substrates and aeration, (**d**)–(**f**) Hydroponic unit, (**g**) Sump with pump.

fish is converted to nitrate by the biofilter and later reabsorbed and used by the cultivated plants together with phosphate.

The APS should be designed as the following: (1) The system should turn the waste derived from cultured fish into edible or commercial plants. (2) The system should improve the utilization of inorganic nutrients in the water derived from cultured fish by hydroponic plants as much as possible to reduce the direct impact of the system on the surrounding environment. (3) The system uses techniques that do not impede the use of water and nutrients by the cultured fish and cultivated plants. For example, the use of earthen ponds is not recommended, but rather plastic, fiber reinforced plastic, or cement ponds, because the seepage of water and the adsorption or release of nutrients from earthen ponds can interfere with the utilization of water and nutrients by fish and plants. (4) The wastewater and nutrients should not discharge outside the system, otherwise. If the wastewater and nutrients have to flow out of the system, these effluents and nutrients should also be reused by external plants to produce edible or commercial bio-products to avoid a wider impact on the environment. (5) APS should be built in environmentally controlled structures (e.g., greenhouses) to obtain optimal fish and plants production (Lennard and Goddek 2019).

Only 25–35% of the nutrients in the feed are used by RAS-farmed fish, the rest needs to be treated or will be discharged to the surrounding environment. Nitrate nitrogen and phosphate removal rates of RASs range from 9 to 93% and 0 to 53%, respectively (Endut et al. 2010; Graber and Junge 2009; Lennard and Leonard 2006). The water recycling rates of APS are 90% greater than standard RAS (Lennard 2005). Water recycling rates as high as 98% have been reported in some systems, translating to water use of about 320 L water/kg fish produced (Al-Hafedh et al. 2008). APS with better design and operation requires only 1.5% of water replenishment per day (to supplement for evaporative losses), and water consumption is only 1% of that of earthen pond culture. In addition, the construction of APS does not require consideration of the types of soil, which makes the site selection for construction more flexible and allows the use of wasteland or marginal land.

10.2.1.2 Management and Structural Optimization of Aquaponic Systems

For fully cycled APS, the control and regulation of the physicochemical parameters of the water quality should generally be based on the requirements of the cultured fish, since fish are usually more demanding on the environment than hydroponically grown plants and microorganisms in biofilters. However, the pH requirements of cultured fish, cultivated plants, and microorganisms in biofilters vary widely, and much work remains to be conducted in this regard, both in terms of feed composition and engineering techniques (Tyson et al. 2011; Endut et al. 2010). Considering hydroponic plants alone, a pH of 4.5–6.0 is optimal, but fish require a pH of 7.0–8.0. For this reason, additive buffer technology and a decoupled aquaponic system (DAPS) have been developed. Since calcium and potassium ions in fish feeds are insufficient for aquaponic plants, and microorganisms in the biofilter lower the pH of the water, buffers containing carbonic or bicarbonic acid or hydroxylated calcium or potassium compounds can be added in different units to meet the specific pH requirements of fish and plants. Water flowing through the hydroponic units in a DAPS no longer returns to the fish culture units, so some substances beneficial to plant or microorganisms can be added to the water after it flows out of the fish culture units and before it flows into the hydroponic unit and the biofilter (Goddek et al. 2019). However, the narrow definition of aquaponics given by some does not include such DAPS (Lennard and Goddek 2019).

APS yield, fish metabolic waste removal rates, and water recycling rate are related to plant species, water exchange rate, and biomass ratio of fish to plant. The optimal biomass ratio of fish to plants in APS is theoretically the cultivated plants that can just fully absorb the metabolic waste inflow from the previous unit (e.g., biofilter). When feeding tilapia with feeds containing 32% protein, 1 m^2 of cultivated plants can treat the wastewater from 60–100 g of feed input per day, so Rakocy et al. (2006) set the feeding rate at 60–100 $g/(m^2 \cdot d)$. The feeding rate is 15–24 $g/(m^2 \cdot d)$ for the APS of African catfish and *Ipomoea aquatica*. It can be seen that the feeding rates are species-specific.

Although integration of agriculture and aquaculture has a long history in China, Southeast Asia, and South America, modern APS originated in the United States in the 1970s, and James Rakocy and his team did much of the groundwork for the development of APS in the early 1980s (Goddek et al. 2019). There are more than 1500 aquaponic operations in the United States and an even greater number in Australia (Rakocy et al. 2010). This technology is used currently by commercial, research, educational, and not-for-profit organizations, as well as by private hobbyists. Most operations are small in scale (<50 t per year) (Klinger and Naylor 2012). Large-scale commercially operated APSs are mostly found in arid regions such as the Arabian Peninsula, Australia, and sub-Saharan Africa (Goddek et al. 2019). The most popular species combination in APS is tilapia and lettuce.

Despite the many advantages of APS, there are not many cases of large-scale commercial operation in regions other than arid areas due to economic constraints and technical obstacles. APS requires relatively large amounts of land and complex equipment, making land, construction, and operation costs high. To reduce construction and operation costs, many APSs now eliminate the water disinfection process. For soilless cultivation traditions in agriculture, water disinfection usually is a routine technique. Disinfection techniques are also commonly used in some high-density RAS systems to prevent disease in farmed animals. However, both decomposition of culture waste and nutrient uptake by plant roots require the involvement of microorganisms, thus, water disinfection is a double-edged sword. Considering that the gravel and facilities in the hydroponic unit already have a large surface area for microbial attachment, some APSs simply eliminate the biofilter unit as well. In the past, small-scale APS focused more on the utilization of input materials and the impact on the environment; however, a tradeoff between operating costs, metabolic waste utilization efficiency, and water recycling rate is an important consideration for every investor and operator of a large-scale APS (Goddek et al. 2019; Klinger and Naylor 2012).

Although APS has developed rapidly in recent decades, there are still many problems that need to be resolved furtherly. Compared with pond farming, APS is an aquaculture system with a relatively high carbon footprint, and there is still a lot of work needed on how to effectively use green energy to drive APS production. In addition, there are additional concerns about food safety and consumer acceptance of APS products for some Westerners (Goddek et al. 2019; Klinger and Naylor 2012). It is evident that there is still much work to be done on popularization of science, legislation, and product safety certification of APS. More about APS in detail can be read in *Aquaponics Food Production Systems* (Goddek et al. 2019).

10.2.2 Solar Recirculating Aquaculture Systems Based on Submerged Plants

10.2.2.1 Structure of SRAS Based on Submerged Plant

A submerged plant-based SRAS is formed by introducing submerged plants into RAS and allowing sunlight to be accessible to the photosynthetic unit (Fig. 10.4).

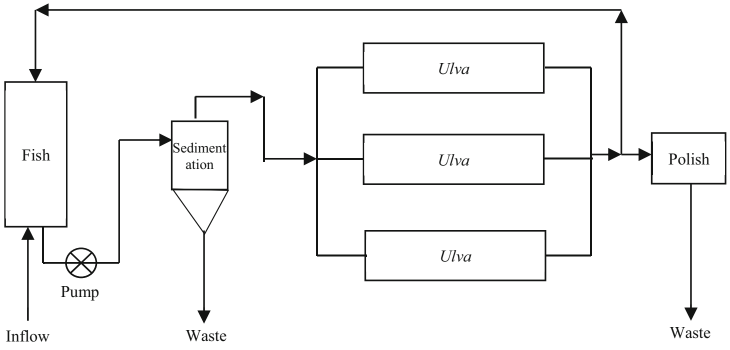


Fig. 10.4 Schematic diagram of fishpond-seaweed biofilter system (from Krom et al. 1995). Arrows indicate the direction of water flow.

The aquatic plants carry out the following photosynthetic reactions under the sunlight:

$$106CO_2 + 90H_2O + 16NO_3^- + 1PO_4^{3-} + \text{mineral elements} = 3258\ \text{g protoplasm} + 154O_2.$$

The aquatic plants absorb CO_2, NO_3^-, and PO_4^{3-} from the water, and release dissolved O_2 into the water, which purifies the water. If the aquatic plant is an economic plant, it will gain additional income from this new product. Thus, the implantation of the plants has the effect of eliminating pollutants, increasing dissolved oxygen and the income from new products.

Submerged plant implantation is divided into two categories: in situ and ex situ implantation. In situ implantation is the combination of photosynthetic unit and fish farming unit, i.e., polyculture of aquatic animal and plant in the same unit. The system shown in Fig. 10.3 is a SRAS with ex situ implantation, except for emergent aquatic plant. Some freshwater RASs discharge the effluent into an artificial wetland and use the plants in the wetland to absorb inorganic nutrients from the water. The principle of this type of system is similar to SRAS, except that the oxygen released by photosynthesis of the plants is not utilized by the RAS system.

10.2.2.2 Light and Temperature Control of SRAS

The sunlight is not necessary for RAS using microbial filters. In order to maintain the temperature in workshop, this type of culture system is usually equipped with thermal insulation facilities, and the roof of the workshop is mostly opaque or with low transparency. If the SRAS is treated in situ or if the photosynthesis unit is placed in the same workshop with the main culture unit, it is necessary to consider the light-transmission treatment of the roof of the culture workshop and to regulate the temperature in the culture workshop. Generally, the light compensation point of macroalgae is mostly above 2000 Lx; therefore, the plants in SRAS need a transparent roof to obtain sufficient light for photosynthesis. However, too much light may inhibit the normal growth of some cultured fish. Therefore, the control of light intensity should tradeoff between the photosynthetic needs of aquatic plants and the growth of cultured animals.

To control the light intensity in the workshop, various methods can be selected, such as shading the roof with materials suitable for light transmission or coverages of sunlight shading net with different light transmission, etc.

Temperature control of SRAS includes lowering temperature in summer and heating in winter. Indoor cooling system can use ventilation cooling, shading cooling, pad-fan cooling, spray cooling, etc. In addition, groundwater can be used for cooling as well, such as technique of Water Supply Heat Pump. Indoor winter heating technology, in addition to insulation devices, includes boilers, the warm water discharged from power plant, etc.

10.2.2.3 Ratio of Fish to Algae in SRAS Systems

The appropriate ratio of cultured animals to macroalgae or aquatic plants is one of the key issues that must be considered for in situ SRAS. Wang et al. (2016) investigated industrial in situ polyculture of *Gracilaria lichevoides* with hybrid grouper (*Epinephe lusfuscoguttatus* ♀ × *E. luslanceolatus* ♂) in a flow-through aquaculture system. The daily water exchange rate is 400%, and stocking rate of the fish is 18.3 ind./m^2 or 0.38 kg/m^2. All polyculture treatments are better than the grouper monoculture in terms of water quality and grouper growth indexes during the period of 2 months. The stocking density of seaweed has a significant influence on the growth performance of both fish and seaweed. In the experimental density range, the water quality tends to be better with the increase of seaweed stocking density. The seaweed yield is the highest at a stocking density of 500 g/m^2. The growth rates of fish in the polyculture treatments are significantly higher and the food conversion rate is significantly lower than those of grouper monoculture. The best growth performance is exhibited in fish polyculture with seaweed of 500 g/m^2.

10.2.2.4 Comparison of Polyculture Models of Grouper and Aquatic Plants

Both seaweeds and higher aquatic plants, as primary producers, can absorb inorganic nutrients from water and improve water quality, and have been widely used in water environment restoration and integrated aquaculture. *G. lichevoides* grows well in light of 120–300 μE/(m^2·s), temperature of 24–36 °C, and salinity of 20–35 ppt (Huang et al. 2013). Inorganic nitrogen and phosphorus concentrations are reduced by 36.8% and 15.2%, respectively in the polyculture ponds of *G. lichevoides* and *Epinephelus awoara* compared with the grouper monoculture (Xu et al. 2007b). *G. lichevoides* can also reduce significantly the inorganic nitrogen and phosphorus concentrations of fish culture area with net cage (Tang et al. 2005).

Caulerpa lentillifera (Chlorophyta) is an edible and high economic value seaweed, native to Southeast Asia, Japan, tropical and subtropical waters of Oceania (Jiang et al. 2014a). In recent years, it has been successfully cultured on a large scale in China (Jiang et al. 2014b; Tan et al. 2014). *Sesuvium portulacastrum* is a herbaceous plant and can grow in non-saline or saline environments. At its stable growth phase, it can remove ammonia and nitrite up to 74%–91% and 93%–98% respectively from mariculture ecosystems, and effectively improves water quality of the culture environment (Dou et al. 2011). However, compared with the in situ polyculture with seaweeds, the use of biofloating rafts has some limitations. For example, it cannot effectively absorb CO_2 in the water and cannot release oxygen into the water.

As compared to the monoculture system of hybrid grouper, water quality indexes in polyculture systems with *G. lichevoides* (submerged, FA, 500 g/m^2), *C. lentillifera* (submerged, FB, 500 g/m^2), and *S. portulacastrum* (emerged plant, FC, 2000 g/m^2) are improved totally (Wang 2016). Water quality of polyculture system of grouper with *S. portulacastrum* is the best, and concentrations of NH_4^+-N, NO_2^--N, PO_4^{3-}-P,

Table 10.1 Water quality and growth of aquatic plants for different treatments (from Wang 2016)

	Treatments			
Parameters	F	FA	FB	FC
NH_4^+-N (μg/L)	271.15 ± 13.14^{a}	230.42 ± 11.62^{b}	214.95 ± 10.20^{b}	220.15 ± 13.04^{b}
NO_2^--N (μg/L)	50.33 ± 2.19^{a}	43.65 ± 1.96^{b}	45.19 ± 2.02^{b}	42.73 ± 2.17^{b}
PO_4^{3-}-P (μg/L)	73.08 ± 1.99^{a}	68.17 ± 1.49^{b}	69.12 ± 1.28^{b}	63.70 ± 2.05^{c}
TN (mg/L)	2.10 ± 0.11^{a}	1.90 ± 0.06^{b}	1.94 ± 0.09^{ab}	1.83 ± 0.12^{b}
TP (μg/L)	182.04 ± 8.60^{a}	174.04 ± 8.59^{ab}	173.54 ± 13.68^{ab}	157.50 ± 12.21^{b}
COD (mg/L)	2.92 ± 0.12^{a}	2.36 ± 0.14^{b}	2.64 ± 0.40^{ab}	2.05 ± 0.13^{c}
Suspended solids (mg/L)	7.75 ± 0.32^{a}	5.17 ± 0.13^{b}	5.20 ± 0.26^{b}	4.58 ± 0.12^{c}
SGR of plants (%/d)	–	1.08 ± 0.04^{a}	1.63 ± 0.08^{b}	2.49 ± 0.09^{c}

Note: *A Gracilaria lichevoides*, *B Caulerpa lentillifera*, *C Sesuvium portulacastrum*, *F* grouper. Stocking densities of plants in FA, FB, and FC are 500, 500, and 2000 g/m^2, respectively

Table 10.2 Growth performance of the grouper in different treatments (from Wang 2016)

Treatments	Initial weight (g)	Final weight (g)	Weight gain rate (%)	*SGR* (%/d)	Food conversion rate
F	374.5 ± 6.71	566.1 ± 10.71^{a}	51.15 ± 2.64^{a}	0.69 ± 0.03^{a}	1.11 ± 0.02^{a}
FA	374.5 ± 6.71	594.6 ± 9.71^{b}	58.76 ± 1.79^{b}	0.77 ± 0.02^{b}	1.07 ± 0.01^{b}
FB	374.5 ± 6.71	602.2 ± 11.37^{bc}	60.80 ± 2.12^{bc}	0.79 ± 0.03^{bc}	1.05 ± 0.006^{bc}
FC	374.5 ± 6.71	613.8 ± 8.53^{c}	63.90 ± 2.12^{c}	0.82 ± 0.02^{c}	1.02 ± 0.004^{c}

COD and suspended solids are significantly lower than those of other treatments (Table 10.1).

Among three polyculture systems, the *SGR* of *S. portulacastrum* is the highest with 2.49 ± 0.09%/d, which is significantly higher than other two plants (Table 10.1). The *SGRs* of the grouper range from 0.69 to 0.82%/d, with the highest in the polyculture system with *S. portulacastrum*, significantly higher than those in polyculture system with *G. lichevoides* and grouper monoculture. The food conversion rates of the grouper range from 1.02 to 1.11, with the highest in the polyculture system with *S. portulacastrum*, significantly higher than those in polyculture system with *G. lichevoides* and grouper monoculture (Table 10.2).

Overall, the specific growth rates of the grouper in polyculture are higher than that in monoculture, and food conversion rates are lower. Among polyculture systems, the specific growth rate of grouper in polyculture system with *S. portulacastrum* (0.82%/d) is higher than those with *G. lichevoides* (0.77%/d) and *C. lentillifera* (0.79%/d). The food conversion rate of grouper in this system is the lowest (1.02) among them.

In terms of the added economic value of plants, *C. lentillifera* is much higher than other two aquatic plants; However, the effect of water quality improvement by *S. portulacastrum* is somewhat better than that by *C. lentillifera* (Jiang et al. 2014a). In addition, the culture process of *C. lentillifera* is more tedious than other two.

10.2.2.5 Research and Development of SRAS in Other Countries

There have been many researches and practices of using macroalgae and other plants as biofilters for water purification in aquaculture in other countries. Most of SRASs use ex situ culture macrophytes to treat the discharge water from culture units. The integrated culture system of *Sparus aurata* and *Ulva lactuca* biofilter designed by Krom et al. (1995) can remove 9–20% of N from the system (Fig. 10.3). Another integrated culture system consisting of abalone (*Haliotis discus hannai*) culture pond, sea bream (*Sparus aurata*) culture pond, and *Ulva lactuca* biofilter designed by Schuenhoff et al. (2003) can purify and recycle 50% of the culture water. Deviller et al. (2004) added a seaweed pond in a recirculating water culture system for European sea bass (*Dicentrarchus labrax*) consisting of *Ulva lactuca*, *Enteromorpha*, and *Cladophora*. It can reduce N by 25% and P by 9% more than a common recirculating aquaculture system. A commercial integrated aquaculture system for sea bream, abalone, and macroalgae filter ponds has been operated in Israel (Neori et al. 2004).

10.2.3 Solar Recirculating Aquaculture Systems Based on Microalgae

The high photosynthetic efficiency of phytoplankton in the pond allows for efficient uptake of nutrients in the water. High-rate algal pond (HRAP) can also be used to treat wastewater discharged from RAS. Figure 10.5 shows an HRAP-based RAS for European perch (*Dicentrarchus labrax*) designed by Metaxa et al. (2004). Components 1–9 of this system constitute a complete RAS. Water disinfected by UV light (6) can partially flow into HRAP (10), and clean water purified by the phytoplankton in the pond is returned back to the RAS. Compared with the single RAS system, the addition of HARP results in significantly higher survival and growth rate of cultured fish, a 25% reduction in TN, and a 9% reduction in TP in the water (Deviller et al. 2004). HRAP is a specially designed water purification system (Racault and Boutin 2005), and HRAPs in good operation have a removal efficiency of up to 175 gBOD/(m^3·d), compared with 5–10 gBOD/(m^3·d) in common ponds.

Phytoplankton in HRAP absorbs dissolved nutrients discharged from the RAS. However, large amounts of phytoplankton produced by HARP must also be utilized, otherwise they will cause secondary pollution to the environment. The phytoplankton biomass can be harvested by flocculation and can also be utilized through the culture of filter-feeding fish and shellfish (Martins et al. 2010).

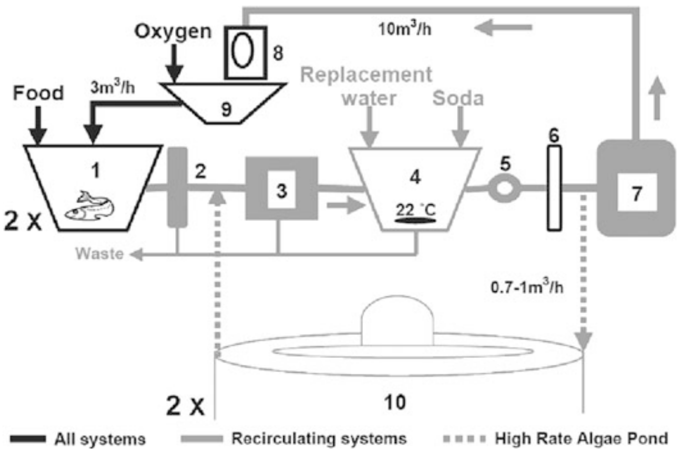


Fig. 10.5 Schematic diagram of high-rate algal pond (HRAP)-based RAS (from Metaxa et al. 2004). (1) Fish tank; (2) Particle trap; (3) Mechanical filter; (4) Pumping tank; (5) Pump; (6) UV lamp; (7) Biological filter; (8) Packed column; (9) Storage tank; (10) HRAP.

Other forms of microalgae-based recirculating aquaculture systems are possible depending on the type of animals cultured, water resources, quality requirements for discharge water, surrounding environment, market demand, etc. HRAP units can also be common aquaculture ponds.

10.3 Raceway Aquaculture Systems

Raceway aquaculture systems are the aquaculture systems that form high water flow in proportion to their volume in relatively shallow waters in order to sustain aquatic organisms. Raceway aquaculture systems include flow-through raceways, loop raceways, and in-pond raceways. Water flow in the systems can make fish metabolites diluted and dissolved oxygen replenished in time, thus achieving high productivity.

10.3.1 Conventional Raceway Aquaculture Systems

Flow-through raceways and loop raceways are conventional raceway aquaculture systems. Flow-through raceway aquaculture systems are found in mountainous or hilly areas with sufficient gradient, where creeks or springs flow by gravity through earthen ponds or concrete tanks connected in series. Compared with earthen systems, concrete raceways can increase production 25%–40% using the same quantity of water (Fornshell 2002). Because of the high altitude and proximity to the source of the stream, these aquaculture systems are often used to culture cold water fish and those with high water quality requirements such as trout and sturgeon.

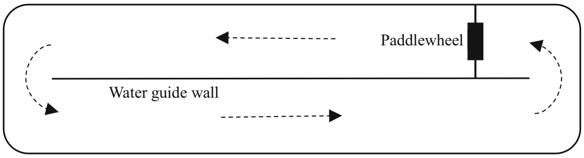


Fig. 10.6 Schematic diagram of loop raceway aquaculture system.

Compared with earthen ponds the productivity of flow-through raceways is much higher. In addition, flow-through raceways also offer a much greater ability to observe and monitor the growth and mortality of cultured fish. Its management such as size grading and harvesting are also easier. The greatest disadvantage of flow-through raceways is the constant discharge of wastes into the receiving river, which has drawn concern of the public and led to the enactment of strict environmental regulations in some countries.

Another type of conventional raceway aquaculture system is the loop raceway system (LRS), the basic structure of which is shown in Fig. 10.6. LRS is equipped with water pushing devices such as paddlewheel, which can drive the water flow in the loop raceway. The outdoor loop raceway aquaculture system is often used to culture phytoplanktons, such as *Spirulina*, *Chlorella pyrenoidosa*, and *Dunaliella salina*. These phytoplanktons can be made into health products, feed or biofuel, etc. (Pawar 2016). Loop raceway systems built indoors are commonly used to culture phytoplankton, fish, shrimp, etc. The water flow created in the raceway facilitates the growth of cultured organisms.

10.3.2 In-pond Raceway Aquaculture Systems

In-pond raceway system (IPRS), also known as in-pond recirculating aquaculture system, etc., is the combination of traditional raceway system and pond aquaculture system. IPRS was first developed by Auburn University in the early 1990s (Masser 2012) and then extended to China by the aquaculture experts from U.S. Soybean Export Council.

10.3.2.1 Structure and Principle of IPRS

The IPRS is a paradigm of partial intensification of traditional aquaculture system. A complex IPRS in a pond consists of a flow-through raceway area, a faces and residual collection area, a mollusk rearing area (in seawater), and an aquatic plant (seaweed) planting area (Fig. 10.7), thus achieving a step-by-step utilization of input feeds. More detailed structural design can be found in the literatures by Masser (2012), Yu and Wang (2016), and Wang et al. (2019a, b).

The fish rearing area consists of airlift pumps or paddle wheels and a number of fish rearing raceways. Airlift pumps or paddle wheels can effectively add oxygen into the water in addition to creating a directional water flow in the raceways. The velocity of flow in the raceway can be controlled by the power of the pumps or paddle wheels. Auburn University experts recommend that the flow velocity in the

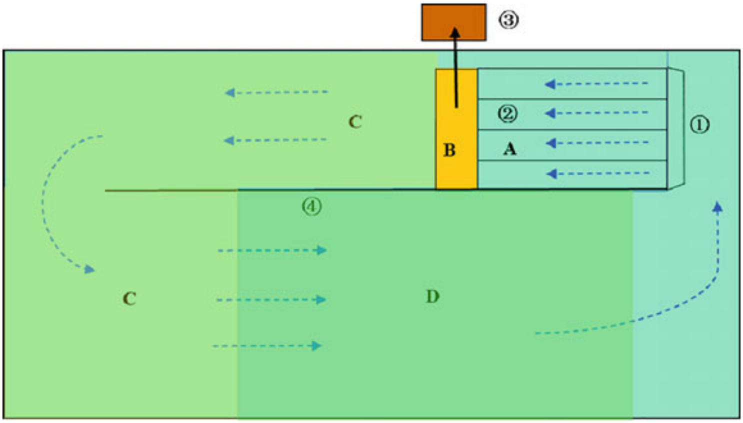


Fig. 10.7 Schematic diagram of In-pond raceway system in seawater. (1) Air lift pumps, (2) Fish rearing raceway, (3) Settling chamber for faces and residue, (4) Water guide wall; (**a**) Fish rearing area, (**b**) Faces and residue collecting area, (**c**) Mollusk rearing areas, (**d**) Aquatic plant or seaweed planting area.

raceway should generally be controlled at about 0.06–0.09 m/s, but the specific flow rate needs to be determined based on the cultured species, fish size, stocking density, feed types, etc.

The feed residue and feces collecting area consists of a collection area and a solids-settling chamber. The larger-sized feed residue and feces in the raceway will be settled in the collection area. A short wall at the end of this area can form an eddy or relatively static flow area, which will accelerate the sedimentation of feed residue and feces. The sedimentation rate of them can also be controlled by the velocity of flow generated by the pumps or paddle wheels. The feed residue and feces are then transferred by a suction device to the settling chamber, and treated there. Due to the artificial treatment of large particles of residual feed and feces produced by cultured fish, the carrying capacity of IPRS has been enhanced significantly compared with that of traditional polyculture ponds.

The function of the mollusk rearing area is the utilization of fine-grained organic matter. The water flowing from the residual feed and feces collection area also contains living planktons, fine particles of residual feed and feces, and dissolved substances. The filter-feeding mollusk in the raft or bottom-sowing area can use the fine-grained organic matter and convert these ‘wastes’ into aquatic food products. The mollusk rearing area can also be bottom-sowing with deposit-feeding animals, such as sea cucumber *Apostichopus japonicus* in seawater ponds of northern China.

The function of the aquatic plant or seaweed planting area is to absorb and utilize the inorganic nutrient dissolved in the water. The water flowing from the mollusk rearing area still has a large amount of dissolved inorganic nutrients that mollusk cannot utilize. Aquatic plants such as macrophyte (macroalgae) in this area absorb these inorganic nutrients and convert them into aquatic food products.

Table 10.3 Comparison of IPRS with cage, pond, flow-through raceway, and RAS (from Masser 2012)

Systems	IPRS	Cage	Pond	Flow-through raceway	RAS
Stocking density	1	–	–	=	–
Food conversion ratio	1	–	–	=	=
Production/area	1	–	–	=	–
Overwintering	1	=	+	+	+
Labor	1	–	–	=	–
Economic efficiency	1	–	–	+	–
Water quality	1	–	–	+	+
Solid waste removal	1	–	–	–	+

Note: + be superior to, = similar to, - inferior to

The zoned culture of mollusk and macrophytes (macroalgae) is helpful for management. Of course, they may be co-cultured in the same area in practice. Filter-feeding mollusk can also be replaced by filter-feeding fish. The co-cultured filter-feeding fish can be distributed in the remaining areas of the pond except for the fish rearing raceway and the residual feed and feces collection area.

Compared with a fish pond aquaculture system, an IPRS in good operation has the following advantages:(1) Easy to manage. Since farmed fish (except filter-feeding fish in free range) are cultured in the raceway and mollusk and aquatic plants are also stocked in different areas of the pond, it is easier to implement harvesting and intelligent management. (2) High feed utilization rate. Since fed fish are cultured in the raceway and can be fed centrally, it is easier to observe the feeding activity of the fish and achieve appropriate feeding satiation. Especially, when floating feed is given, it can keep the feed trapped within the raceway, resulting in reducing feed loss. (3) Higher fish yield. Since IPR is environmentally superior in terms of solid waste removal including residual feed and faces, the carrying capacity and fish yield of the system are higher. (4) More energy saving. Since the aeration is only supplied in the flow-through raceway, power expenditure is reduced. (5) Less waste discharge, even zero discharge. Since the residual feed and faces collection area, mollusk culture area, and macrophyte (macroalgae) planting area can collect, absorb, and utilize the large particles of residual feed and faces, fine particles of organic matter, and dissolved inorganic nutrient, it is easier to meet the requirements of effluent discharge standards. If the proportions between each functional area are designed and set properly, IPRS can also realize zero discharge of organic matters. (6) More feasible to multi-species and multi-specification culture practice according to market demand. Since each raceway unit can operate independently, it is possible to realize multi-species and multi-specification culture in separate units to meet the market demand for continuous and characteristic products (Masser 2012). In addition, a certain water flow in the raceway will have a favorable impact on the quality of cultured fish as well (Liu et al. 2019).

IPRS has some significant advantages over net cage, conventional raceway, and recirculating aquaculture systems (Table 10.3), and is one of the best-extended aquaculture systems among land-based intensive aquaculture systems.

10.3.2.2 Carrying Capacity of IPRS

As a conservative design benchmark, a culture raceway (5 m^3 × 22 m^3 × 1.5 m^3) in temperate regions requires 6666 m^2 (=10 acres) of pond water with an average depth of 1.5–2.0 m, according to the recommendations of Auburn University experts. In tropical areas, the ratio of raceway to pond water can be considered appropriately increased.

The base carrying capacity of IPRS can be estimated by the productivity of the whole pond culture system. It is generally believed that the fish productivity of conventional ponds ranges from 0.5 to 0.6 kg/m^3, from which the productivity of the entire pond can be calculated. With the data on the productivity of the whole pond, the fish loading of the raceway area can be obtained by dividing it by the raceway volume, and the stocking number and biomass of fish fingerlings can also be estimated accordingly.

Considering the role of removing feces and residual feed in the collection area and the purification capacity of the pond to the excreted wastes derived from farmed fish, the experts from Auburn University suggest that the fish productivity in a pond installed IPRS can reach 1–1.5 kg/m^3. Therefore, the fish productivity of a pond installed IPRS with an average water depth of 1.7–2.0 m can reach 20,000–25,000 kg/(hm^2·yr).

The carrying capacity of IPRS is related to many factors, such as the volume of pond, culture species, feed quality, aeration efficiency of the air lift pumps or paddle wheels, and the purification capacity of the mollusk rearing area and macrophyte planting area. Therefore, the carrying capacity of an IPRS should be analyzed on a problem-specific basis and there is no uniform parameter.

The ratio of raceway volume to whole pond volume is a key parameter for IPRS design. According to the estimation of Yang and Guan (2019), the volume ratio of raceway with 100 kg/m^3 fish and whole pond could be 1.03%–1.55% and 1.18%–1.77%, respectively, when the collection efficiency of residual feed and faces is 30 and 60%.

The aeration and water flow generated by air lift pumps or paddle wheels make partial intensification of pond farming possible, but a suitable density of cultured fish is still very important. For example, the optimal stocking density of GIFT tilapia (*Oreochromis niloticus*) in IPRS is 90 ind./m^3 (Wang et al. 2019a, b). Obviously, low stocking density is not conducive to realizing the production potential of IPRS, while over-stocking will influence the physiological status of cultured fish (Wang et al. 2019a, b) and the community structure of fish intestinal microbiota (Li et al. 2020).

The carrying capacity of IPRS needs further study if the effluent is considered to meet the requirements of discharge standards or achieve zero discharge of waste.

10.3.2.3 Ecological and Economic Benefits of IPRS

According to trial data of Auburn University, the yield of spotted catfish using freshwater IPRS installed in a pond (Fig. 10.8, left) is significantly higher than that of net cages and ponds, while the costs are significantly lower than that of net cage and pond culture, in a total culture water area of 0.4 hm^2 (Table 10.4). The N and P utilization efficiency of spotted catfish for input feeds in IPRS are 34.0% and 34.1%, respectively (Brown et al. 2012). Therefore, IPRS is more economically and ecologically efficient than ponds and net cages for spotted catfish farming.

A comparative study was conducted on an IPRS (Fig. 10.8, right) set up in a seawater pond (4 hm^2 in area) and a conventional polyculture pond (4 hm^2 in area, 1.8–2.0 m in depth) for puffer fish (Li 2020). The structure of the IPRS is similar to Fig. 10.7, and the cultured species include puffer fish (*Takifugu rubripes* and *T. flavidus*), sea bass (*Lateolabrax maculatus*), filter-feeding clam (*Mercenaria mercenaria*), and aquatic plant (*Sesuvium portulacastrum*). Among them, puffer fish and sea bass are stocked in raceway, clams are bottom sowing in the pond, and aquatic plant grows in floating rafts. The culture species of polyculture pond are puffer fish, swimming crab (*Portunnus trituberculatus*), and Chinese shrimp (*Fenneropenaeus chinensis*). For IPRS, the survival rates of *T. rubripes*, *T. flavidus*, sea bass, clams, and aquatic plant in the IPRS are 78.8%, 95.4%, 72.2%, 45.2%, and 98.8%, respectively, while those of *T. rubripes*, swimming crab, and Chinese shrimp in the polyculture pond are 76.4%, 5.66%, and 2.23%, respectively. The total production of the IPRS is significantly higher than that of the polyculture pond.

Fig. 10.8 In-pond raceway systems. Left photo, IPRS for freshwater channel catfish in Alabama, USA; Right photo, IPRS for seawater puffer fish in Hebei, China

Table 10.4 Economic comparisons between IPRS, cages, and pond catfish culture (0.4 hm^2 pond; from Masser 2012)

Systems	IPRS	Cage	Pond
Yield (kg)	2433	1286	1730
Death loss (%)	10	10	6
Feed conversion efficiency	1.45	1.6	1.8
Protein content of feed (%)	36	36	32
Total costs ($)	5272	3241	3923
Breakeven price ($/kg)	2.17	2.52	2.27

Table 10.5 Energy conversion coefficients in in-pond raceway systems and earthen seawater pond systems (from Li 2020)

Parameters	IPRS	Pond
Total yield (MJ)	201843.20 ± 1274.23[a]	39515.25 ± 534.27[b]
Photosynthetic conversion efficiency (%)	0.11 ± 0.03[a]	0.04 ± 0.01[b]
Feeding energy conversion efficiency (%)	57.48 ± 6.29[a]	14.05 ± 1.53[b]
Total energy conversion efficiency (%)	40.37 ± 1.52[a]	16.43 ± 0.93[b]
Feeding energy consumption per unit of net yield (MJ/Kg)	10.14 ± 2.08[a]	54.85 ± 6.05[b]
Total energy consumption per unit of net yield (MJ/Kg)	10.63 ± 2.19[a]	55.01 ± 7.67[b]

Note: Photosynthetic conversion efficiency = Total yield (MJ)/Solar energy (MJ) × 100%, Feeding energy conversion efficiency = Total yield (MJ)/Feeding energy (MJ), Total energy conversion efficiency = Total yield (MJ)/Total input energy (MJ), Feeding energy consumption per unit of net yield = Feeding energy (MJ)/Total yield (Kg), Total energy consumption per unit of net yield = Total input energy (MJ)/Total yield (Kg)

N and P from residual feed and faces account for 10.6 and 16.1% of total N and P expenditures, respectively, in IPRS, while the corresponding values were 31.7% and 21.1%, respectively, in the polyculture system. The utilization efficiencies of N and P in IPRS are 29.2% and 15.3%, respectively, while those in polyculture system are 4.91% and 3.17%, respectively. Therefore, IPRS can not only improve the utilization efficiency of N and P compared with the polyculture system, but also can use the water resources more effectively and reduce the pollution to the receiving waters.

IPRS is significantly higher than the polyculture system in terms of net biological yield energy, photosynthetic conversion efficiency, feeding energy conversion efficiency, and total energy conversion efficiency. However, its feeding energy consumption per unit of net yield and total energy consumption per unit of net yield are significantly lower than the polyculture system (Table 10.5).

IPRS is being extended very fast, especially in China. According to incomplete statistics, there are now more than 6000 aquaculture raceways in China, and more than 20 species have been cultured. However, IPRS in China is mainly applied in freshwater aquaculture, and IPRS in mariculture is still less reported.

The average water consumption of grass carp in IPRS is 460 m^3/t, which is 78.5% less than that of common pond culture; IPRS discharges 57% less waste (Wei et al. 2018). According to data from four IPRSs in Hangzhou, Zhejiang province, water quality in IPRS is significantly improved, with an average decrease of 41.5% in total nitrogen, 23.65% in total phosphorus, and no water exchange during the culture duration (Ma et al. 2019).

IPRS is a model for the implementation of partial intensification of aquaculture ponds, and has some significant advantages over other land-based intensive aquaculture systems. Generally, the IPRS simplifies feeding, grading, harvest, and disease treatments, which reduces labor requirements compared with other systems. IPRS appears to be more environmentally sustainable than cages, raceways, and intensive open-pond production. However, according to current practices in China, the economic benefits of IPRS for different regions still vary greatly. For example, in Anhui Province, the yield of IPRS in good operation can be 50–150 kg/m^3, the average yield is 35–75 kg/m^3, and the lower one is 15–50 kg/m^3. As for culture benefits, the profitable, loss-generating, and break-even IPRSs are one-third of each among those in operation. Therefore, there are still many problems for IPRS needed to be resolved and many technologies need to be improved. Particularly, cost-effective solid and liquid waste reduction methods need to be evaluated and further developed. Moreover, more attention is generally paid to the construction of flow-through raceways rather than water purification function in IPRS, which needs more technological innovation and proper guidance for this aquaculture system.

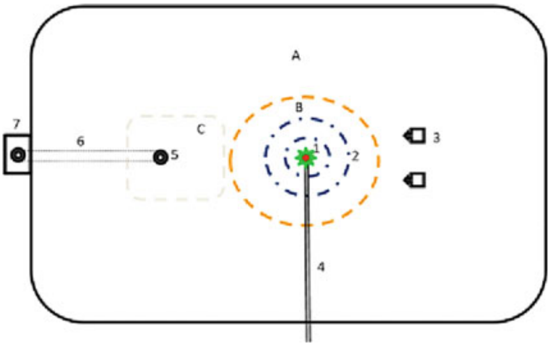
10.3.3 Local Intensification of Aquaculture Ponds

The essence of IPRS is the local intensification of an aquaculture pond, i.e., intensive modification of the fish rearing area in a pond (Fig. 10.7). Because the runways use whole water of the pond, coupled with the aeration effect of air lift pumps, the output of the runways is not lower than that of an ordinary pond with the same area. There are other forms of local intensification of aquaculture ponds, such as local aeration and feeding of pond and split-pond system.

10.3.3.1 Local Aeration and Feeding of Pond

Fig. 10.9 is an aquaculture system of local aeration and feeding of pond for co-culture of grass carp and crucian carp in Panyu, Guangdong Province in China. The pond is divided into three areas, namely pond area (A), aeration and feeding area (B), and collection area of particle waste (C). The aeration and feeding area is provided with a feed jet nozzle (1) and aeration plates (2). The bottom of the collection area of particle waste is a hardened funnel, and a waste collecting hole (5) is arranged in the center. The pelleted feeds are sprayed into the air through feeding pipe (4) and nozzle, and then fall into the aeration and feeding area. When the farmed fish swim to this area for feeding, the aeration begins to work. At a period of time before and after fish feeding paddle wheels (3) operate to drive feed residue

Fig. 10.9 Top view of local aeration and feeding pond. (**a**) pond area, (**b**) aeration and feeding area, (**c**) collection area of particle waste; (1) feed jet nozzle, (2) aeration plates, (3) paddle wheels, (4) pipes of feeding and aeration, (5) waste collecting hole, (6) waste collection channel, (7) waste collection well.



and feces to the collection area of particle waste. The particle waste is pumped out regularly from waste collection well (7) through waste collection channel (6).

Like IPRS, the aquaculture systems of local aeration and feeding of pond also function as centralized feeding, residual feed, and feces collection. The oxygen consumption intensity of fish during feeding is high and all of them are concentrated in the aeration and feeding area. Aeration in this area can meet the demand of fish respiration, and can save energy. In addition, at night, when phytoplankton photosynthesis stops and the pond is hypoxic, aeration is needed only in the aeration and feeding area. Therefore, the aquaculture systems of local aeration and feeding of pond have the advantages of energy saving and high yield compared with common aeration ponds.

10.3.3.2 Split-pond System

Split-pond system is another example of local intensification of aquaculture ponds, and was developed in the 1990s to exploit existing catfish ponds for building zero-discharge of aquaculture systems (Boyd et al. 2020). Split-ponds are built by constructing an earthen levee and dividing the pond into two sections (Fig. 10.10), in which water is circulated between the two sections with pumps, but only fish-holding basin is aerated or intensified. Split-ponds have a relatively larger algal basin or water treatment section (about 80%–85% of the total area) and a smaller fish basin. Compared with IPRS, the fish basin stocks fish at much lower densities in order to afford a safety margin against unexpected accidents such as loss of electrical power. Catfish production in commercial-scale split-ponds in the southeastern United States is 14–18 t/ha.

10.3.3.3 Net Cages in a Pond

Another example of local intensification of an aquaculture pond is a fish cage in a pond (Fig. 10.11 left). The cage in the pond has functions similar to the system of local feeding and aeration. In the pond of waterlogged salt-alkali land, which lacks freshwater resources normally, it is convenient to catch common carp in the cages

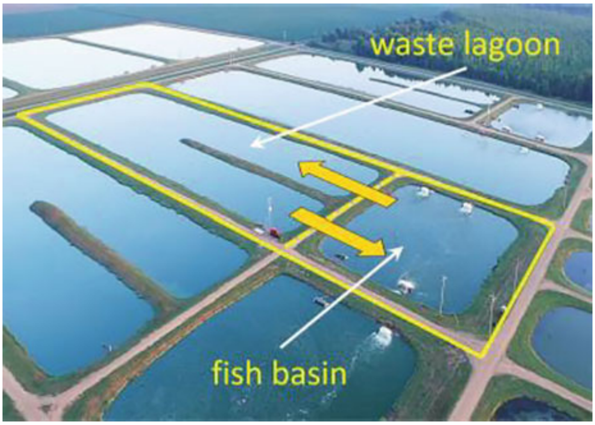


Fig. 10.10 Split-ponds for ictalurid catfish in Mississippi, USA (Boyd et al. 2020). The middle pond is highlighted to show partitioning of the original 3.2-ha pond into a 0.6-ha fish-holding basin and a 2.6-ha algal waste-treatment lagoon. Arrows show direction of daytime pumped-water circulation through culverts.

Fig. 10.11 Fish cages in a pond (left) and fish farming with containers (right)

and can save water. Since common carp are a benthic fish, thorough harvesting of the carp outside the cages usually requires draining the pond. In addition, tilapia kept in the cages can still regulate water quality but do not compete pelleted feed with the shrimp outside the cages (Sun and Dong 2010; see Sect. 11.5.3 for detail). Furthermore, the use of pond cages for tilapia farming in the pond can prevent tilapia from spawning.

Fish farming with containers (Fig. 10.11 right) is also a land-based intensive aquaculture system in China. It is easy to disassemble and assemble, and not strict to the operation site requirements. It is suitable for fish farming at the corner and spare land, such as using the cooling water of a power plant to culture tilapia, and also suitable for implementing aquaculture on sandy land. To supply water to the containers, it needs to lift several meters of water head compared to other local intensification systems, and requires additional energy consumption. Therefore, it is not recommended to carry out container farming activities except for special needs.

10.4 Biofloc-based Aquaculture Systems

Feeding strategies in pond culture are divided into two categories: those that feed high-protein feeds whose nutrients largely meet the needs of cultured animals, and those that feed low-protein feeds based on crop products and rely on natural foods to supplement the nutrient-deficient portion of the feed. The natural foods utilized by cultured animals are usually photosynthesis-based primary and secondary producers in aquaculture systems. This section focuses on natural foods based on heterotrophic bioflocs. Biofloc-based aquaculture systems emerged in the 1990s, and widely farmed species now are tilapia and shrimp, which can directly utilize natural productivity (Browdy et al. 2012).

10.4.1 Introduction to Biofloc-based Aquaculture Systems

With increasingly stringent restrictions on the waste discharge of aquaculture systems, coupled with the worldwide spread of epidemic viral diseases in shrimp, attention has been focused on the development of closed, non-feeding aquaculture systems based on microbial communities. The concept of establishing heterotrophic food web-based aquaculture systems was proposed by Israeli scientists in the 1970s and 1980s, and later developed with the support of Solar Aquafarms in Israel, a biofloc culture system that is commercially operated today (Browdy et al. 2012). In the early 1990s, two groups at the Technion University of Israel and at the Waddell Mariculture Center of the United States systematically studied biofloc-based culture technologies for tilapia and shrimp with reduced and then zero exchange, respectively (Avnimelech 1993; Hopkins et al. 1994).

In terms of culture types, biofloc-based culture is available in outdoor earthen, lined and raceway ponds, indoor ordinary concrete ponds, and recirculating aquaculture systems. The single-crop yield of this system for farmed shrimp is 1–2 kg/m^2, with a high of 10 kg/m^2; the biomass of farmed tilapia can reach 10–30 kg/m^2 (Browdy et al. 2012).

The average utilization of organic carbon, nitrogen, and phosphorus in feeds by typical aquaculture animals is 13%, 29%, and 16% respectively, and unused nutrients also need to be mechanically filtered out, sedimented, microbially transformed, or drained directly from the culture system. In contrast, for a biofloc-based aquaculture system, feeding is not necessary in low-density culture system, and farmed fish and shrimp can utilize the biofloc formed by the microbial community. In higher-density culture system, supplemental low-quality feed is required; however, residual feed and faces can be decomposed and utilized by microorganisms, then formed into biofloc (nutrients) that can be utilized by farmed animals. In RAS, the surface of the biofilter also hosts or cultivates a large number of microorganisms, whose function is mainly to decompose the metabolites of the farm animals, while the microorganisms in the biofloc-based aquaculture system are both waste decomposers, transformers, and food for farmed animals.

Bioflocs are widely found in aquatic ecosystems and contain mainly inanimate humid acids, proteins, fats, polysaccharide compounds, etc., but also animate bacteria, fungi, viruses, various phytoplankton, protozoa, ciliates, nematodes, etc. The general biofloc dry matter contains 25%–50% crude protein and 0.5%–15% crude fat.

Biofloc particles in biofloc-based aquaculture systems can be as large as a few millimeters and can be directly ingested by farmed fish and shrimp. Generally, the presence of floc particles larger than 5 μm can contribute to increased shrimp production (Moss and Pruder 1995). The size of floc particles in biofloc-based aquaculture systems is related to the aeration method and intensity, etc. The sizes of biofloc particles vary among culture systems. The systems with more water pumping activity tend to have smaller particles, while the systems with airlift mechanisms tend to have larger particles.

A biofloc is a micro-ecosystem in itself, with multiple ecological functions. Addition of carbon or/and carbohydrates is required for the cultivation of the floc microbial community, and aeration and pH adjustment are required for the maintenance of good water quality for the cultured animals and microorganisms.

Biofloc-based aquaculture technology provides disease prevention for shrimp in three ways: Firstly, the closed system and less water exchange rate reduce the possibility of harmful exogenous pathogens invading the culture system and enhance the biosecurity of the culture system. Secondly, microorganisms in bioflocs compete with pathogenic bacteria for living space and nutrients, disrupting the quorum-sensing system of pathogenic bacteria and thus inhibiting the growth and reproduction of pathogenic bacteria in the water. Thirdly, bioflocs contain a variety of bacteria and their secretion products, such as poly-β-hydroxybutyric acid, polysaccharides, and other active substances, which are likely to have growth-promoting and immune-enhancing effects on farmed animals.

The main advantages of a well-run biofloc-based aquaculture system include: (1) Less energy consumption. Since the cost of aeration is usually lower than the cost of water exchange, the energy costs of a biofloc-based aquaculture system will be lower than that of a culture system that requires flow-through water or large water exchange. (2) Less or no high-protein feed required. Tilapia and shrimp cultured in biofloc systems can feed on the natural food incubated in the system and do not require high-protein feeds, only carbon or/and carbohydrates for cultivating microbial communities are added to the system. (3) Water saving. The system requires essentially no water exchanges and usually only the water lost to evaporation needs to be supplemented. (4) Good prevention of shrimp epidemics. First of all, the system is a closed system, less susceptible to foreign pathogens; secondly, the microbial community in the system can effectively inhibit pathogenic microorganisms of farmed shrimp. (5) Possible zero discharge. The system does not need water exchange. (6) Land saving. Compared with some open ponds, the system occupies less land and has lower costs of leased land.

10.4.2 Water Quality in Biofloc-based Aquaculture Systems

Like other aquaculture systems, biofloc systems undergo a process of community succession or maturation, from the receiving impoundment to the formation of a stable biological community in the system, with corresponding changes in water quality. The main ecological processes affecting water quality in the systems include photosynthesis, heterotrophic assimilation, nitrification, and denitrification.

10.4.2.1 Photosynthesis of Phytoplankton

When the outdoor culture system is activated under adequate light, the first thing that is seen is that the water color gradually turns to green. Then, the phytoplankton community grows in an exponential phase, and finally self-shading occurs due to high density. After that, the system starts to change from a type dominated by phytoplankton autotrophy to the one dominated by microbial heterotrophy. This transition is accelerated by insufficient light and high feeding rates. During this period, the dissolved oxygen, CO_2, pH, etc., in the water also change regularly with the relative changes in the intensity of photosynthesis and microbial 'water respiration'.

The accumulation of bioflocs also reduces the light intensity in the water, which affects the uptake of ammonia nitrogen by phytoplankton. In addition, even under strongly aerated conditions, dissolved oxygen contents show regular diurnal fluctuations. Generally, when the daily feeding rate is below 30 g/m^2, phytoplankton photosynthesis will be the main factor controlling water quality. As the feeding rate increases, the biological community in the system will change from phytoplankton dominated to bacterial community dominated (Xu 2014).

10.4.2.2 Assimilation of Bacteria

Early biofloc microbial communities are predominantly heterotrophic, with heterotrophic bacteria using residual feed and feces as a carbon and energy source. Heterotrophic bacteria and other microorganisms use carbohydrates (sugars, starch, and cellulose) as a food to generate energy and to grow (Browdy et al. 2012):

$$\text{Organic C} \rightarrow \text{CO}_2 + \text{Energy} + \text{C assimilated in microbial cells.}$$

The percentage of the assimilated carbon with respect to the metabolized feed carbon is defined as the microbial conversion efficiency (E) and is in the range of 40–60%. Of course, the microbial cells assimilate organic C from feeds and also assimilate organic N from residual feeds and faces at the same time.

Due to the continuous input of protein-containing feeds, the content of soluble nitrogen (including inorganic and organic nitrogen) in the water of culture systems will continue to increase, and the deficiency of soluble organic carbon becomes a limiting factor for the growth and reproduction of heterotrophic bacteria. In aquaculture practice, the *C*/*N* of the water environment is often increased by adding organic carbon sources (sugars, starch, and cellulose) or by reducing the protein content of the feed to maintain a healthy microbial community. The amount of carbon assimilated by microorganisms (ΔC_{mic}) and the amount of carbohydrate supplement (ΔCH) required to reduce the ammonium can be calculated as follows (Avnimelech 1999):

$$\Delta C_{\text{mic}} = \Delta\text{CH} \times \%C \times E$$

where $\%C$ is the carbon contents of added carbohydrate (roughly 50% for most substrates).

The amount of nitrogen needed for the production of new cell material (ΔN) depends on the *C*/*N* ratio in the microbial biomass, which is about 4.

$$\Delta N = \Delta C_{\text{mic}}/(C/N)_{\text{mic}} = \Delta\text{CH} \times \%C \times E/(C/N)_{\text{mic}}$$

And using approximate values of $\%C$, E, and $(C/N)_{\text{mic}}$ as 0.5, 0.4, and 4, respectively:

$$\Delta\text{CH} = \Delta N/(0.5 \times 0.4/4) = \Delta N/0.05$$

Thus, the CH addition needed to reduce total ammonia nitrogen (TAN) 1 mgN/L (i.e., 1 gN/m^3) is 20 mg (20 g/m^3). This relationship enables a manager of culture ponds to calculate how much carbohydrate substrate must be added to reduce ammonia nitrogen in an emergency (Browdy et al. 2012).

With the excretion of cultured animals and decomposition of residual feed and faces, inorganic nitrogen in the water begins to accumulate gradually. At a certain pH, temperature, and salinity, a corresponding balance between NH_3 and NH_4^+ is also established. NH_3 in the system can be utilized or transformed by phototrophic autotrophic bacteria (cyanobacteria) and autotrophic nitrifying bacteria.

10.4.2.3 Nitrification of Bacteria

As the concentration of ammonia and nitrogen in the water environment gradually increases, under aerobic conditions, nitrifying autotrophic bacteria begin to convert NH_3, which is toxic to farm animals, into NO_2^- and NO_3^- in steps through nitrification. If the feeding rate is too high at the early stage of system establishment, the peak concentration of NH_3 and NO_2^- will appear rapidly in the system (Fig. 10.9), and the high concentration will also affect the growth of cultured animals and even cause fatal injury to them.

Nitrification is a slow, long-term process, but eventually 25%–50% of input feed nitrogen will be converted to nitrate nitrogen in the process. This mechanism is particularly important in farming systems with a high degree of intensification, i.e., a high feeding rate.

The addition of organic carbon sources can be stopped after the nitrifying bacteria has developed and reached stability in the biofloc aquaculture system. The gradual accumulation of nitrate nitrogen is a characteristic of strong nitrification over heterotrophic assimilation and denitrification (Fig. 10.12).

10.4.2.4 Denitrification of Bacteria

Nitrate (NO_3^-) can be reduced to nitrogen gas (N_2) through denitrification under anaerobic conditions, resulting in the removal of N_2 from the aquaculture system. Due to high aeration intensity, the biofloc aquaculture system as a whole is in an aerobic state; however, local anoxia can occur inside the biofloc particles, and denitrification also occurs in the system. Therefore, the nitrogen balance in the biofloc aquaculture system is more complex. Denitrification is conducted by

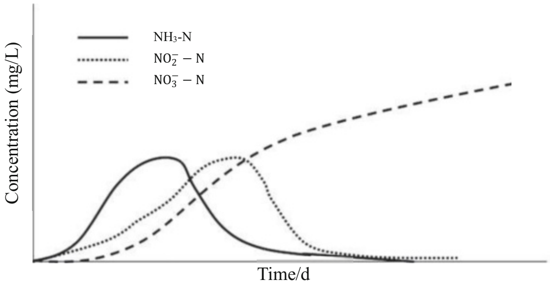


Fig. 10.12 Typical nitrification startup curves (from Browdy et al. 2012)

heterotrophic bacteria capable of utilizing NO_3^- in the absence of O_2 to produce nitrite (NO_2^-) and then N_2 as a product.

10.4.3 Regulation of Water Quality in Biofloc-based Aquaculture System

During the development, maturation, and stabilization of biofloc aquaculture system, in order to maintain good water quality, the manager needs to adjust C/N and pH of the water, supply oxygen to the system, control the density of biofloc, etc.

10.4.3.1 C/N Regulation

The stoichiometric balance of ammonia nitrogen nitrification and heterotrophic assimilation occurring in biofloc aquaculture system is shown in Table 10.6. Heterotrophic assimilation requires applying about 15.17 g of carbohydrate for removing 1 g of ammonia-nitrogen. Therefore, carbohydrates should be added to the system during the active phase of heterotrophic assimilation.

Feeds for aquatic animals usually contain high crude protein with a C/N ratio of 6–10, while the C/N suitable for heterotrophic bacteria to assimilate ammonia nitrogen is about 12–15. The C/N of the aquatic environment can be improved by adding organic carbon sources to the water or using low protein content compound feeds during the culture process. Organic carbon sources commonly used in aquaculture practice are simple carbohydrates, such as glucose, sucrose, etc., and complex carbohydrates, such as starch, tapioca, cereal flours, etc. The former has the advantage of being fast-acting and the disadvantage of requiring continuous application. The latter is characterized by the opposite of the former. Simple carbohydrates can be applied at the beginning of a biofloc aquaculture system operation or for emergency C/N regulation. Complex carbohydrates should also be applied initially for the purpose of continuous and stable C/N regulation thereafter.

When using feeds containing 30%–38% crude protein, theoretically 0.5 or 1.0 kg of carbohydrates is required for every 1 kg of feed delivered. The amount of carbohydrates applied can be reduced if there is photosynthesis in the water that can absorb ammonia nitrogen. Obviously, applying such a great amount of

Table 10.6 Comparison of stoichiometric balances for removing 1 g of ammonia-nitrogen by nitrification and heterotrophic assimilation (from Ebeling et al. 2006)

	Nitrification (g)	Heterotrophic assimilation (g)
Carbohydrate consumed	0	15.17
Alkalinity consumed	7.05	3.57
Oxygen consumed	4.18	4.71
Bacterial biomass produced	0.20	8.07
CO_2 produced	5.85	9.65
$NO_3^- - N$ produced	0.976	0

carbohydrates is a significant cost, so the search for cheaper complex carbohydrates to replace simple carbohydrates is a hot issue of concern.

10.4.3.2 pH Regulation

Nitrification consumes great amounts of alkalinity (bicarbonate) and produces CO_2, which lowers the pH of the aquatic environment (Ebeling and Timmons 2007):

$$\mathrm{NH_4^+ + 1.83O_2 + 1.97HCO_3^- \rightarrow 0.0244C_5H_7O_2N + 0.976NO_3^- + 2.90H_2O + 1.86CO_2}$$

Therefore, failure to observe and adjust pH in a timely manner can affect the growth of cultured animals and shrimp molting. Both alkalinity and oxygen are consumed by nitrification or heterotrophic assimilation of ammonia in biofloc aquaculture systems, and nitrification in particular consumes more alkalinity. About 7.05 g of HCO_3^- is required for removing 1 g N to maintain alkalinity. Therefore, lime or sodium bicarbonate should be applied into the system routinely to replenish the depleted alkalinity and prevent a significant drop in pH to ensure good growth of nitrifying bacteria and farm animals. In an intensive autotrophic bacteria-dominated biofloc aquaculture system, about 0.25 kg of sodium bicarbonate is applied for every 1 kg of feed delivered. Of course, during actual farming operations, alkalinity is monitored regularly at least weekly and the amount of sodium bicarbonate applied is determined as needed.

10.4.3.3 Concentration Regulation of Biofloc Particles

The concentration or total suspended solids (TSS) of biofloc particles in biofloc-based aquaculture system is usually very high. High concentration of biofloc particles means more food for fish and shrimp, but at the same time the oxygen requirements of the water will be high as well, and the costs of aeration will be correspondingly high. High concentration of biofloc particles may result in gill clogging and hindering gas and ion exchange of the gill. Therefore, the concentration regulation of biofloc particle is an important task in the management of biofloc aquaculture systems. When suspended particle concentration is in the range of 100–300 mgTSS/L in a biofloc aquaculture system of raceway, it is advantageous for the feeding of shrimp. When the particles are in the range of 200–500 mgTSS/L the system operates well with moderate microbial oxygen consumption (Ray et al. 2010). Higher concentration of biofloc particles may increase aeration costs and stress on the culture animals.

For the biofloc aquaculture system of lined pond where the stocking density of shrimp and aeration intensity are not very high, concentration of biofloc particles should be lower. Biofloc concentrations are more beneficial for shrimp culture in a pond when the settling volume is 10–15 mL/L (Xu 2014). Phytoplankton in outdoor biofloc aquaculture systems are important participants in regulating water quality, and low concentration of biofloc particles can provide better light conditions for phytoplankton and facilitate photosynthesis.

The bottom of the aquaculture system can be regularly dredged with central sewers and settling ponds, or bioflocs can be regularly removed with foam fractionators, etc. Since heterotrophic assimilation requires a great input of carbohydrates and produces about 40 times more solid waste than nitrification, it is even more important to remove sludge from the system in a routine manner.

Biofloc technology has shown great promise for shrimp aquaculture. However, bioflocs themselves are still full of unknowns. The structure and function of bioflocs, their regulation, nutritional value, and growth-promoting factors still need to be studied in depth. Biofloc aquaculture systems require great amounts of electrical energy inputs, which not only results in a high carbon footprint of the aquatic products, but also limits the application of this aquaculture model in the areas with intense electricity supply and expensive electricity.

10.5 Development of Land-based Intensive Aquaculture Systems

Aquaculture originated from pond farming of freshwater fish. In the 1950s and 1960s, the extensive use of pelleted feeds and aerators promoted pond production significantly. Flow-through earthen ponds or concrete tanks in mountainous or hilly areas promoted the production of cold-water fish and those with high water quality requirements. With the rapid expansion of intensive pond farming, arable land use, freshwater consumption, and pollutant discharge have aroused people’s concern. Therefore, in order to alleviate the conflict with the agriculture in land and freshwater uses and to reduce the pollutant discharge, some land-based intensive aquaculture systems have been innovated along three technical routes, i.e., RAS, raceway, and bioflocs (Fig. 10.13).

The key of RAS is the treatment and recycling of aquaculture water, depending mainly physical dilution, microbial conversion of compounds as well as removal of particle wastes (Fig. 10.1). However, the aerobic environment of conventional RAS makes the denitrification in the system negligible, and the aerobic biofilter only changes NH_4^+ into NO_3^-, and the total dissolved inorganic nitrogen will accumulate in the system.

In order to deal with the problem of inorganic nitrogen accumulation, denitrification units or large aquatic plants or water treatment ponds are integrated into conventional RASs, forming modern RAS with denitrification function (Fig. 10.2), aquaponics (Fig. 10.3), solar SRASs (Fig. 10.4), high-rate algal pond-based RAS (Fig. 10.5), etc. Another technical route is to build land-based raceway aquaculture systems (Fig. 10.6), which can form circulating water flow in the aquaculture waters to dilute wastes and meet the requirements of farmed organisms. The third technical route is the biofloc aquaculture systems based on heterotrophic food web for culturing tilapia and shrimp, which have the functions of saving high protein feed and disease prevention.

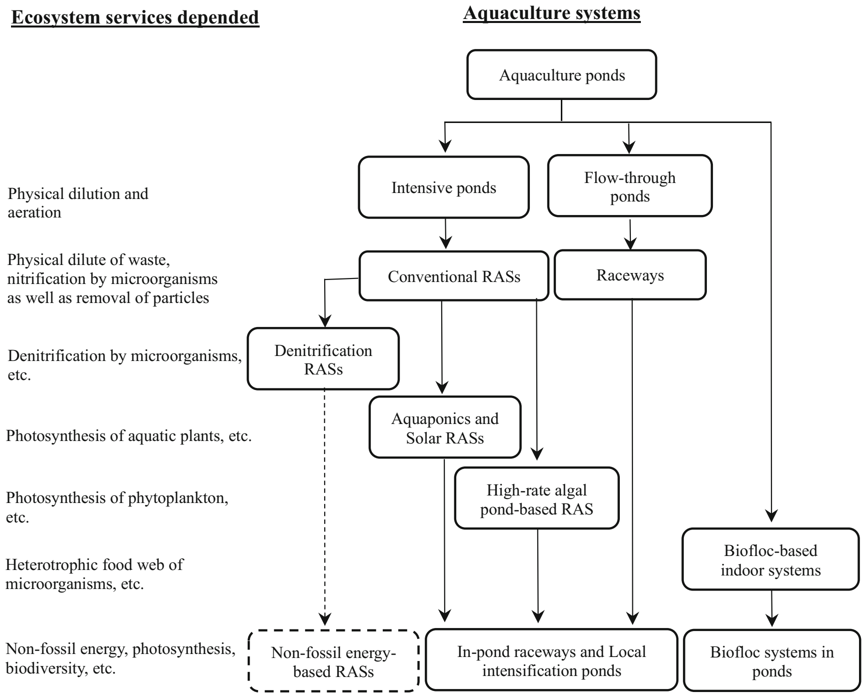


Fig. 10.13 Development of land-based intensive aquaculture systems and ecosystem services depended.

RASs, raceway systems, and biofloc systems are all energy-consuming aquaculture systems with high production cost. In order to make use of the natural purification capacity of outdoor pond, outdoor biofloc systems and local intensification of pond systems are developed, such as in-pond raceways (Fig. 10.7 and 10.8), local aeration and feeding system (Fig. 10.9), split-pond (Fig. 10.10), fish cage in a pond (Fig. 10.11 left), etc. These land-based intensive aquaculture systems are popular with conventional producers.

The greenhouse shrimp farming in cement pond and filter-feeding bivalve farming in earthen pond have been integrated to realize the two system complementation in some regions in China. The inflow of high-density microalgal tail water from shrimp ponds into shellfish ponds not only solves the issue of tail water treatment of shrimp ponds, but also solves the fertilization issue of shellfish ponds. It should be an important development direction for land-based intensive aquaculture systems to realize the complementation of different land-based farming systems.

The carbon footprint of land-based intensive aquaculture systems will gradually decrease in the future as the proportion of non-fossil energy in total energy consumption increases. As each country becomes carbon neutral, aquaculture production will also become carbon neutral. Therefore, whether the production costs can be reduced is the key to the eventual adoption of a land-based intensive aquaculture system.

Brief Summary

1. Land-based intensive aquaculture systems include recirculating aquaculture systems, solar recirculating aquaculture systems, raceway aquaculture systems, and biofloc-based aquaculture systems.
2. Recirculating aquaculture systems (RAS), also known as industrial aquaculture systems, are tank-based closed-loop aquaculture systems in which aquatic organisms can be cultured at high density under controlled environmental conditions. The 'wastewater' or 'tailwater' is treated and recycled with mechanical filtration, biofiltration, disinfection, temperature regulation, oxygen supply, etc. RASs have advantages including: less water consumption, less pollutants discharge, less space occupied, high yield and predictable harvesting schedules, traceable products, etc.
3. The aerobic environment of conventional RAS makes the denitrification in the system negligible, and the aerobic biofilter only changes NH_4^+ into NO_3^-, and the total dissolved inorganic nitrogen will accumulate in the system. Modern RAS introduce denitrification by microorganisms into the system. The denitrification unit reduces NO_3^- and NO_2^- to N_2 under anaerobic conditions, which eventually escapes from the RAS system, avoiding the accumulation of inorganic nitrogen. RASs with denitrification function still have the problem of high energy consumption.
4. Solar recirculating aquaculture systems (SRAS) are the systems that implant aquatic plants (submerged or floating or emergent plants, or phytoplankton) into RASs, which have lower cost of water treatment than that of conventional RAS.
    - Aquaponic system (APS) is a combination of conventional RAS and hydroponics, implanting emergent plants or floating plants or submerged macrophytes into a recirculating aquaculture system. APS takes advantage of the mutually beneficial effects of fish and plants fully. The implanted plants absorb and remove excess nutrients from the water environment, achieving the goals of water purification, effluent reduction, and economic benefit increment.
    - Compared with the APSs based on emergent plants or floating plants the systems based on submerged macrophytes can absorb CO_2 from the water and release dissolved O_2 into the water.
    - The SRAS based on phytoplankton is the aquaculture system that integrates a high-rate algal pond (HRAP) to treat RAS effluent.
5. Raceway aquaculture systems are the aquaculture systems that form high water flow in relatively shallow waters in order to sustain aquatic organisms. Raceway aquaculture systems include flow-through raceways, loop raceways, and in-pond raceways. Compared with ponds, raceway aquaculture systems have several advantages, such as electricity power energy saving, high production per unit of

space, easy to manage, high feed utilization, less even zero discharge of organic matters, and easier to implement multi-species and multi-specification culture according to market demand.

- Flow-through raceway aquaculture systems are often found in mountainous or hilly areas with sufficient gradient, where creeks or springs flow by gravity through earthen ponds or concrete tanks connected in series.
- Loop raceway systems are equipped with water pushing devices, which can drive the water flow in the loop raceway. The outdoor systems are commonly used to culture phytoplankton, while the indoor systems are often used to culture fish, shrimp, etc.
- In-pond raceway system (IPRS), also known as in-pond recirculating aquaculture system, is the combination of traditional raceway system and pond aquaculture system. The IPRS is a paradigm of partial intensification of traditional aquaculture system. A complex IPRS in a pond consists of a flow-through raceway area, a faces and residual collection area, a mollusk rearing area, and an aquatic plant (seaweed) plantation area, thus achieving a step-by-step utilization of input feeds.

6. Biofloc-based aquaculture systems are culture systems based on the concept of heterotrophic food webs, and are now widely used to culture tilapia and shrimp that can directly utilize natural productivity. The advantages of the systems include: less energy consumption, no or less high-protein feed required, water savings, good prevention of shrimp epidemics, zero pollutant discharge, and land savings.
7. The main ecological processes affecting the water quality of biofloc aquaculture system include photosynthesis, heterotrophic assimilation, nitrification, and denitrification. Since the C/N of heterotrophic bacteria is higher than that of high-quality feed, the C/N of the water should be increased by applying organic carbon sources or using low protein content compound feeds. Since both nitrification and heterotrophic assimilation consume great amount of bicarbonate, alkaline compounds need to be applied to the water frequently to stop the significant drop in pH of the water.

11

Pond Aquaculture in Waterlogged Salt-Alkali Land

Shuang-Lin Dong and Li Li

Salt-alkali land refers to the soil with high levels of salt content or/and alkalinity, which interferes with the normal growth of crops. There are 800 million hm^2 of salt-alkali land (mainly distributed in the Asia-Pacific region) in the world, accounting for about 6% of the global land area and 20% of the agricultural land. More than 100 countries in the world embrace salt-alkali land and the ones with large salt-alkali land areas are Russia, India, Pakistan, China, and so on. Every day for over 20 years, an average of 2000 ha of irrigated land in arid and semiarid areas in 75 countries have been degraded by salt. The sea level rise caused by global climate change may also accelerate land salinization (Dagar et al. 2019). Therefore, how to efficiently and sustainably exploit these salt-alkali land resources is one of the important issues that human beings face.

About 2000 BC, farmers in Lower Egypt started to use a land reclamation technology which is highly productive and still be used today (Fagan 2017). During the spring they dug large ponds in saline soil and flooded them with freshwater for 2 weeks. The lower salinity of the standing water forced the saline groundwater downward. They drained the ponds, repeated the process, and discarded the second flooding as well. Then they filled the pond with 30 cm of water and stocked it with mullet fingerlings caught from the ocean. Nowadays, the integrated utilization of salt-alkali land by aquaculture and agriculture is one of the effective technologies to exploit salt-alkali land resources. This chapter will briefly introduce the pond-based aquaculture-agriculture system on salt-alkali land, tolerance of farmed aquatic animals to saline and alkaline water, water quality control of the ponds, etc. In this chapter, salinity refers to the total concentrations of all ions in seawater only; as for

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the total concentrations of all ions in other water types such as freshwater, and inland-brackish water, the term salt content is used.

11.1 Pond-Based Aquaculture-Agriculture Systems

11.1.1 Introduction to Salt-Alkali Land

Salt-alkali soils are divided into saline soil and sodic soil. Saline-humid soil with high salt content but low pH is also introduced here. Influenced by seawater, the saline soil of coastal areas is mainly chlorinated. The inland saline soil and alkaline soil are mainly formed by the accumulation of salt and alkali in the surface soil after water evaporation. Saline-humid soil, rich in humic substances, is usually influenced by rhythmic ocean tides and has a low pH.

In China, there is about 34.67 million hm^2 of salt-alkali land, mainly distributed in the northeast, northwest, north China, and coastal areas. The salt-alkali land in northeast China is mainly saline soil and alkaline soil. The groundwater table is 1.5–3.0 m, and the salt content is 2–5 g/L. In some areas, salt content can even reach more than 10 g/L, and is dominanted by carbonate. Sulfates and chlorides dominate the salt-alkali soils in north China, and there are bicarbonate soils in partially closed, waterlogged areas. The groundwater table is 1.0–2.0 m and the salt content is 1–2 g/L. The salt content in the surface soil of salt-alkali land in northwest China is 1–10 g/kg, and the salt compositions are mainly sulfate and chloride. The groundwater table in the waterlogged areas is about 1.0 m, the salt content is 1–2 g/L, and the highest salt content can reach more than 10 g/L (Yang 2000). The saline soils in the coastal area are mainly chlorinated and mainly affected by seawater.

The formations of waterlogged salt-alkali land are mainly due to the low topography of the area, relatively high groundwater level, and long-time poor drainage of rainwater. Various soluble salts are redistributed horizontally and vertically in the topsoil, thus causing salts to gradually accumulate in the surface layer of the soil. The main means or techniques to exploit this part of the land is to directly or indirectly lower the water table and suppress the rate of water evaporation to reduce the salt content and alkalinity or acidity of the surface soil.

The salt-alkali land can be reclaimed by chemical, biological, and engineering measures. Phosphogypsum, furaldehyde residues, and peat have been used to reclaim alkaline soil and alkaline fluvo-aquic soils. In general, some chemical technical measures are not applied on a large scale due to the obvious side effects or immature of the technology (Song et al. 2000; Zhao et al. 2001).

China is a pioneer in the reclamation of salt-alkali land by using engineering technical measures (Li et al. 2003a). Methods including vertical drainage (or electromechanical drainage), open ditch drainage, concealed pipe drainage, and so on are commonly used to lower the groundwater table (Yang 2000). Electromechanical drainage can effectively reduce the groundwater table by pumping well water, but this method can only temporarily prevent the salt from rising to the surface. Once there is a major flood, or if the drainage stops then the previous work will be in vain. The open ditch drainage and concealed pipe drainage methods can permanently solve the problem, but the project is large and costly.

The method of biodrainage, also known as afforestation, is also used to lower the groundwater table. Biological drainage is a method of reducing groundwater table in waterlogged areas through evapotranspiration of deep-rooted and fast-growing plants. The method uses biological energy rather than conventional electricity. According to the study of Singh and Lal (2018), the evapotranspiration of plants can reach 6500–28,000 m^3/hm^2, and the water table can decrease by 1–2 m in 3–5 years. The plants used are *Eucalyptus*, *Populus*, *Acacia,* etc. The biological drainage method can only be used in the area with the groundwater of low salt content and low alkalinity. In addition, the afforestation method has a very limited area to lower the water table, and the groundwater table a few hundred meters away from the afforestation area is barely affected (Yang 2000).

Some agricultural measures, such as deep plowing, application of organic fertilizer, and so on, can reduce soil alkalinity to some extent (Yang 2000). Nowadays, another engineering technology has been invented to reclaim waterlogged salt-alkali land and saline-humid land, that is, pond-based aquaculture-agriculture system, which will be illustrated in the following part. The system is capable of drainage and irrigation, which is a very efficient model of integrated development of aquaculture and agriculture in salt-alkali land (Dong 2003; Yang 2000).

11.1.2 Pond-Based Aquaculture-Agriculture Systems

In China, adjacent to the river system, there are three million hm^2 of deserted waterlogged salt-alkali land that can be exploited for aquaculture. In the 1990s, China began to use the digging ponds and raising land technology (Fig. 11.1) to construct the pond-based aquaculture-agriculture system (Dong 2003), which is also called land shaping technology in India (Dagar et al. 2019). The height of raising land should be at least 1 m higher than the critical depth above the groundwater table. In the areas with clay soil, the ponds are usually dug at a depth of 1.5–2 m in the original soil, and it is appropriate to build 1.5–2 m high terraces above the original ground. As for the sandy soil areas, it is suggested to dig 2–2.5 m deep to build the ponds and to raise land 2–2.5 m high for terraces. The pond-based aquaculture-agriculture systems are popular nowadays in China. The area ratio of

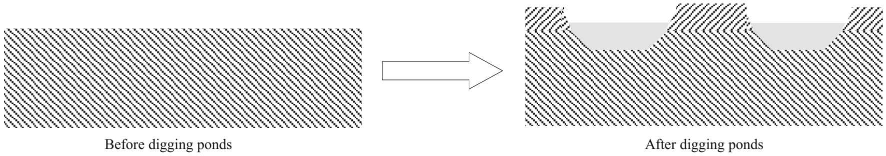

Fig. 11.1 Longitudinal profile of waterlogged salt-alkali land before and after digging ponds

Table 11.1 Salt contents in the soil of the terraces with different heights of bed (%) (from Duan et al. 2002)

	Year 1997			Year 1998			Year 1999		
Sites	May	Jul.	Oct.	May	Jul.	Oct.	May	Jul.	Oct.
Control	2.74	2.45	1.00	1.52	1.63	1.90	2.95	1.11	1.00
Low terraces (1.35 m)	1.35	0.69	0.32	0.56	0.30	0.75	0.99	0.86	0.59
High terraces (2.63 m)	0.39	0.56	0.17	0.23	0.087	0.27	0.26	0.63	0.077

ponds, terraces, and drainage ditches plus roads is 4:4:2 in Shandong Province, China.

After building the pond-based aquaculture-agriculture system, the salt-alkali water leaking into the pond from underground water is drained first, and then the freshwater from a river is introduced into the pond to culture fish.

As the soil of the excavated pond is used to build the terraces above the original ground, the groundwater table is relatively reduced, taking the terrace as a reference point, and the evaporation of groundwater is restrained. Over time, the salt content and alkalinity of the terrace soils will gradually decrease due to rainfall leaching and irrigation. For example, in Yucheng, Shandong Province, the terraces were raised by 2.63 m or 1.35 m, respectively, above the groundwater table. After 3 years of development, the salt contents of the terraces soil were significantly reduced (Table 11.1). However, the higher terraces are more effective in reducing the salt content in soil than the lower terraces. Meanwhile, the organic matter concentration in the soil of higher terraces increased from 0.58 to 0.99%, and the pH decreased from 8.35 to 7.91. The yield of wheat and maize planted on the terraces increased gradually over time (Duan et al. 2000, 2002).

It is even better when using the plastic film technology, i.e., putting a plastic film between the terrace and the original ground. The salt content of terraces (0.5 m high) with the film decreased from 23.54 g/kg to less than 12 g/kg after 2 years, while the salt content of the terraces (0.5 m high) without the film increased from 2.4 to 18 g/kg (Duan et al. 2000).

There was no apparent decrease of the salt content of the groundwater in this area after 3 years of aquaculture, but the salt content of the pond water had been maintained at a low level, which was suitable for culturing freshwater fish (Table 11.2).

In the waterlogged salt-alkali areas along the Yellow River in Shandong Province, many types of aquaculture-agriculture patterns such as fish-cereal crop, fish-cotton, fish-alfalfa, fish-duck, fish-fruit plants, fish-mulberry, etc., have been developed recently. The development of the patterns is determined by the geographical characteristics, resources, soil conditions, and the groundwater table of the area (Gu et al. 2000).

Table 11.2 Salt contents (g/L) in ponds and underground water after digging pond and raising land (from Duan et al. 2002)

Time		Year 1997			Year 1998			Year 1999		
		May	Jul.	Oct.	May	Jul.	Oct.	May	Jul.	Oct.
Yuxi	Pond water	2.27	1.54	3.41	1.41	1.85	1.59	1.79	1.72	1.78
	Underground water	6.12	7.21	4.69	4.96	7.05	6.42	5.07	5.42	6.03
Gaoqing	Pond water	1.62	1.69	1.59	1.23	1.69	1.53	1.25	1.34	1.50
	Underground water	10.00	13.43	10.01	15.55	14.42	12.79	13.28	10.85	11.41

In the Pearl River Delta region of China, the integration of aquaculture and agriculture has also been developed by using ditch-terrace systems. The fruits, vegetables, etc., are planted on raised terraces, while fish, snails, or aquatic plants are cultured in the ditches (Yang 2000). In sum, the technique can be used in various types of waterlogged land.

The waterlogged acidic saline-humid soils affected by marine tides can also be developed using the above-mentioned method. In India, Velmurugan et al. (2016) built the raised bed and furrow (RBF) system in the coastal lowlands of the humid tropics to reduce the soil salt content in the area. The annual rainfall in that area is 2900–3100 mm, the salt content of the surface-clayed soil is 7.19 ± 1.34 g/L, and the pH and the organic carbon content of the soil are 4.9 ± 1.1 and 8.7 ± 1.83 g/kg, respectively. The furrows of 1.5 m deep and 6 m wide were dug. The 1 m high beds were made by excavating the soil from either side of the bed and putting it in the bed area. The bed soil was washed by rainfall to reduce salt, and the natural rainwater was collected in the furrows. The water depth of furrows was 20–60 cm in dry seasons and 100–120 cm in rainy seasons. The salt content of the bed soil decreased from 6.98 g/L in March 2009 to 0.96 g/L in March 2013, and the salt content of the furrow water also decreased from 1.66 to 0.45 g/L, which could be used to culture freshwater fish.

11.2 Water Quality and Biological Environment of Salt-Alkali Ponds

11.2.1 Water Quality of Salt-Alkali Ponds

The ratio of the ions is usually not balanced in salt-alkali ponds. The ion compositions of water vary in different areas. The general trend is when evaporation is getting strong and there is less precipitation, the process named land salinization is accelerated. Accompanied by the increase in salt content, the Na^+ will gradually replace Ca^{2+} and Mg^{2+} in the water. For the anions, the SO_4^{2-} and Cl^- will gradually replace HCO_3^- . At the same time, other physical and chemical parameters and biological compositions of the pond water also change.

The middle reaches, lower reaches, and estuaries of the Yellow River have a large area of typical waterlogged salt-alkali land, where large-scale pond-based aquaculture-agriculture systems are concentrated. In the upper reaches of the Yellow River, the temperature and evaporation are low, the soil is dominated by mountain meadow soil. The salt contents in soil and water are generally low, and the water usually belongs to the bicarbonate type. The middle reaches of the Yellow River are in arid and semi-arid regions. The soil and groundwater in the area have high salt and alkali contents, and most of the water belongs to the carbonate type. The groundwater in some regions (such as Gan-ning Bitter Water Area) and some water bodies (such as Lake Qianjinhu in the Ningxia Hui Autonomous Region) belong to the sulfate water type (The Fishery Resources Survey Collaborating Group of the

Yellow River 1986). The salt content in the soil and groundwater of the lower reaches of the Yellow River is usually not high, but there is still some waterlogged salt-alkali land along the two sides of the Yellow River. The salt content and ion compositions of the soil and groundwater in the Yellow River estuary are mainly influenced by seawater, the main cation is Na^+ and the anion is Cl^-.

Along the Yellow River in Shandong Province, from coastal heavy salt-alkali land up to inland waterlogged salt-alkali land, the proportion of chloride ions in water gradually decreases, but the proportion of carbonate and bicarbonate increases gradually. In general, the salt contents of groundwater in these waterlogged salt-alkali lands are less than 5 g/L, but the alkalinity and pH of pond water are high. The pH of pond water is generally above 8.0, and in some cases can exceed 9.0. Although the alkalinity of soil and pond water decreases in July due to rainfall, it is also generally above 2.0 mmol/L and tends to increase with distance from the estuary.

There are obvious seasonal variations in water quality in salt-alkali ponds (Zhang et al. 2000). For example, conductivity varied in the range of 1.46×10^3– 9.75×10^3 μs/cm of the pond water in Gaoqing, Shandong province. The lowest values occurred in ponds that had just been filled with Yellow River water, and the highest values occurred in ponds that had gone out of use for several years. Alkalinity, which was mainly composed of the bicarbonate alkalinity, ranged from 1.73 to 11.6 6 mmol/L with the average value of 5.98 mmol/L. Alkalinity was lower in July and August, and higher in winter. The pH varied from 7.08 to 9.64 throughout the year, with an average value of 8.29. The lowest values were observed in October and November. Daily fluctuations of pH were also obvious in the ponds because of the poor buffering capacity of the water. The buffering process could be illustrated by the following two equations, which exist in the water of salt-alkali ponds:

$$2HCO_3^- \leftrightarrow CO_3^{2-} + CO_2 + H_2O$$

$$CO_3^{2-} + Ca^{2+} \leftrightarrow CaCO_3 \downarrow$$

The photosynthesis process consumes CO_2, and more CO_3^{2-} will be produced. When there is abundant Ca^{2+} in water, it could react with CO_3^{2-} to form $CaCO_3$ precipitate, slowing the rise of pH in the water. When photosynthesis weakens, the respiration process will produce more CO_2 to promote the dissolution of $CaCO_3$. The CO_2 homeostasis system and the presence of Ca^{2+} ions will act as an effective buffer against pH changes in the water. However, Ca^{2+} is often deficient in salt-alkali ponds, and thus the buffering capacity of the water is greatly reduced, which may endanger the safety of farmed animals in the ponds (Wen et al. 2000).

In general, P is the limiting nutrient element in freshwater ponds, while N is the limiting nutrient element in seawater ponds. N is usually the limiting nutrient element in chloride type of salt-alkali ponds (Wen et al. 1999), which is probably due to the high ionic strength and high solubility of the phosphate compounds in salty water.

11.2.2 Aquatic Organisms of Salt-Alkali Ponds

11.2.2.1 Phytoplankton and Primary Productivity in Salt-Alkali Ponds

In general, the higher the salt content, alkalinity, and pH, the lower the quantity of phytoplankton species and diversity index (Zhao 1992; He et al. 1989). In the late 1990s, a total of 120 genera and 197 species of phytoplankton were detected in a chloride type of waterlogged salt-alkali pond in Gaoqing, Shandong Province. There were 76 species and 45 genera in Chlorophyta, which accounted for 38.58% of the whole phytoplankton community. There were 46 species and 28 genera in Bacillariophyta, which was the second most abundant phylum, and accounted for 23.35% of the community. The phytoplankton was mostly salt tolerant or halophile species, and some of them were typical saltwater species (Zhao et al. 2002; Shentu et al. 2000a).

There are apparent seasonal variations of phytoplankton biomass in ponds. The phytoplankton biomass in the salt-alkali ponds in Gaoqing ranged from 0.60 to 368 mg/L with an average of 49.90 ± 31.92 mg/L. Phytoplankton less than 10 μm in diameter contributed more to the biomass and primary production in the ponds (Zhao and Dong 2003).

The average chlorophyll *a* content in waterlogged salt-alkali ponds in Gaoqing was 115.12 μg/L, and chlorophyll *a* accounted for 61.76% of the total chlorophyll content. The chlorophyll *a* content was positively correlated to phytoplankton biomass, water temperature, total nitrogen, total phosphorus, and silicate content, and negatively correlated to the transparency of pond water (Zhao et al. 2000c).

In the farming season (from April to September) of the salt-alkali ponds in Gaoqing, the primary productivity of phytoplankton was 9.42 ± 4.21 $gO_2/(m^2 \cdot d)$, the daily *P/B* coefficient was 0.24 ± 0.18, and the utilization rate of effective solar radiation by phytoplankton was 1.53%. The main ecological factors affecting the primary productivity of phytoplankton in salt-alkali ponds were phytoplankton biomass, transparency, water temperature, and salt content (Zhao et al. 2003).

11.2.2.2 Zooplankton in Salt-Alkali Ponds

A total of 89 genera and 159 species of zooplankton were detected in the salt-alkali ponds in Gaoqing. The most numerous zooplankton were protozoans, with 48 genera and 78 species. The second ones were rotifers, with 27 genera and 58 species. Zooplankton were mainly halophile or salt-tolerant species, some of which were typical saltwater species (Zhao et al. 2001a). The biomass of zooplankton varied from 0.002 to 308 mg/L with the average of 9.47 mg/L. Two peaks of zooplankton biomass were observed in spring and early autumn.

11.2.2.3 Macrophytes and Benthic Animals in Salt-Alkali Ponds

A total of 12 species of macrophytes were found in the salt-alkali ponds in Gaoqing, characterized by few species but prominent dominant species (Zhao et al. 2001b). Under the conditions of water surface illumination of 7200 Lx and water temperature of 28–30 °C, the gross primary productivity of the dominant species *Potamogeton crispus*, *Zannichellia palustris,* and *Charophyllum* sp. are 1.70, 1.56, and

1.50 $mgO_2/(h \cdot g)$, respectively. The primary productivity of these macrophytes is significantly affected by light intensity, temperature, pH, salt content, and alkalinity of the water. For example, *P. crispus* and *Z. palustris* have the highest primary productivity at a salt content of 3 g/L. The highest primary productivities occur at the water alkalinity of 6.69 and 3.82 mmol/L for the two species, respectively.

A total of 14 species (3 phyla and 6 classes) of zoobenthos were found in salt-alkali ponds in Gaoqing. There were 3 species and 3 families in Gastropod class of Mollusca; 4 species and 3 classes in Annelida phylum; 7 species, 4 orders, and 2 classes in Arthropoda phylum. The dominant species were *Chironomus plumosus* and *Limnodrilus udekemianus* (Zhao et al. 2001c). The density and biomass of zoobenthos in the ponds without farmed fish were much higher than those with farmed fish. For example, the density and biomass of zoobenthos in the ponds without fish were 40–2085 ind./m^2 and 0.15–12.9 g/m^2, respectively, while those with fish were 54–161 ind./m^2 and 0.14–0.54 g/m^2, respectively. There was a peak in the density and biomass of zoobenthos at the turn of spring and summer.

11.3 Salt and Alkalinity Tolerance of Aquaculture Animals

The pH, salt content, and alkalinity of water have a significant impact on the farmed animals in the waterlogged saline-alkali ponds. These three factors are also the more commonly used water quality indicators for water quality regulation in ponds, so it is of great theoretical and practical importance to understand the effects of these factors on farmed animals.

11.3.1 Effects of pH on Aquacultured Animals

The buffering capacity for acids and bases of water in salt-alkali ponds is usually poor due to a deficiency in Ca^{2+} concentration. Dramatically rising pH to a certain threshold due to intensive photosynthesis may stress aquatic animals, especially the young fry. There is an interaction effect between pH and Ca^{2+} on the growth and energy budget of shrimp (*Macrobrachium nipponense*) by affecting the energy ingestion of the animals (Dong et al. 1994).

The tolerance range of pH for black carp (*Mylopharyngodon piceus*), grass carp, silver carp, and bighead carp are 4.6–10.2, while the range for common carp is 4.4–10.4. The carp can sense small changes in pH of 0.2 (Zhang 1960). In terms of alkaline tolerance, black carp and grass carp can tolerance higher alkalinity than silver carp and bighead carp; while in terms of acid tolerance, black carp, grass carp, and bighead carp are stronger than silver carp. The concentration of hydrogen ions in water could affect the respiration physiology of fish. When the concentration of hydrogen ions is not in the appropriate range, fish requires more dissolved oxygen for respiration. The juvenile common carp could obtain less oxygen at pH 4.0 than at pH 7.0. In the temperature range of 18–26 °C, when the pH is 4.0, the low pH can damage the respiratory system of juvenile common carp. If the obtained dissolved oxygen by the fish is less than 7.0 mg/L, the mortality rate of the fish is very high.

11.3.2 Salt Tolerance of Aquiculture Animals

The tolerance of fish, shrimp, and crab to salt content has been studied by diluting seawater, adding NaCl to tap water, adding NaCl to salt-alkali water, or evaporating salt-alkali water. Eight species of aquatic animals are commonly cultured in waterlogged salt-alkali ponds in Shandong Province, China. NaCl contents of LC_{50} for these species in the pH range of 8.2–8.9 are listed in Table 11.3. The LC_{50} of these species is in the order of mitten carb ≈ giant freshwater prawn < red pacu ≈ gibel carp ≈ crucian carp ≈ silver carp < common carp < Nile tilapia (Zhang et al. 1999c; Zheng et al. 2001; Wang et al. 2001a).

Zang et al. (1989) also studied the salt tolerance of farmed fish under pH 7.00–9.90, and the salt tolerance order of fish studied is bighead carp > grass carp > blunt snout bream (*Megalobrama amblycephala*) > silver carp. The optimal salt content for giant freshwater prawns is 0–6.83, and the survival of the species is not affected when the salt content is less than 15.66 (Zheng 1993).

Likongwe et al. (1996) studied the effects of temperature (24, 28, and 32 °C) and salt content (0, 8, 12, and 16 ppt) on the growth and feed utilization efficiency of juvenile Nile tilapia. Results showed that temperature, salt content, and their interactions had significant effects on feed conversion and protein utilization efficiency of the fish. The growth rate and feed utilization rate were the highest at 32 °C and salt content of 8 ppt, and lowest at 28 °C and salt content of 16 ppt.

Allan and Maguire (1992) studied the effects of pH and salt content on the survival, growth, and osmotic pressure of shrimp (*Penaeus monodon*), and found that the 96 h LC_{50} of pH for the shrimp was 3.7 when salinity was 32 ppt. But the value was 5.9 when salinity was 30 ppt. The interactions between salinity and pH were significant.

Table 11.3 NaCl contents (g/L) of LC_{50} for different aquaculture species (data from Zhang et al. 1999c; Zheng et al. 2001; Wang et al. 2001a)

Species	24 h	48 h	72 h	96 h	pH and water temperature (°C)
Red pacu (*Colossoma brachypomum*)	11.99	11.41	10.99	10.43	8.21 ± 0.07, 23 ± 1.0
Nile tilapia (*Tilapia nilotica*)	18.37	14.66	14.39	14.25	8.91 ± 0.11, 18–23
Common carp (*Cyprinus carpio*)	13.69	13.46	12.01	11.91	8.60 ± 0.18, 25 ± 2.0
Silver carp (*Hypophthalmichthys molitrix*)	11.24	8.96	8.55	8.15	8.60 ± 0.18, 23 ± 2.0
Gibel carp (*Carassius auratus gibelio*)	11.53	10.77	9.35	8.58	8.8 ± 0.1, 24.5 ± 1.5
Crucian carp (*Carassius auratus*)	10.23	7.91	7.81	7.78	8.56 ± 0.25, 25 ± 1.0
Mitten carb (*Eriocheir sinensis*)	8.12	6.47	5.29	4.88	8.33 ± 0.13, 20.3 ± 1.4
Giant freshwater prawn (*Macrobrachium rosenbergii*)	8.58	5.32	3.47	2.19	8.40 ± 0.18, 23.6 ± 1.0

11.3.3 Alkalinity Tolerance of Aquaculture Animals

The LC_{50} of several fish species to alkalinity was tested by using the concentrated water from Dali Lake, Inner Mongolia Autonomous Region (Shi 1981). Dali lake is a salt-alkali lake with a pH of about 9.4, total alkalinity of 44.5 mmol/L, and salt content of 5.5 ppt. The results showed that the order of tolerance to the alkalinity of tested fish was: naked carp (*Gymnocypris przewalskii*) $>$ amur ide (*Leuciscus waleckii*) $\approx$ topmouth gudgeon (*Pseudorasbora parva*) $>$ crucian carp. The chronic toxic effects of high alkalinity and high pH saline water on fish have common characteristics, i.e., rotten fins, blindness, muscle ulcers, and gangrene, which is also known as ‘alkalosis’ or fibrous corrosion and necrosis.

The main composition of alkalinity that is toxic to farmed fish is CO_3^{2-}, and the 24 h LC_{50} value of CO_3^{2-} for silver carp is 12.4 meq/L (Lei et al. 1985). Water pH could change the proportion of CO_3^{2-} in total CO_2 homeostasis system and causes synergistic effects with alkalinity on fish. The safety threshold of alkalinity for fish farming is 10 meq/L. The order of alkalinity tolerance of commonly cultured species in waterlogged salt-alkali ponds is Nile tilapia $>$ spotted sea bass $\approx$ crucian carp $\approx$ gibel carp $>$ giant freshwater shrimp $\approx$ mitten crab $\approx$ red pacu $>$ silver carp (Table 11.4).

Table 11.4 LC_{50} (mmol/L) of alkaline for different species (data from Zhang et al. 1999c; Zheng et al. 2001; Wang et al. 2001a)

Species	24 h	48 h	72 h	96 h	pH and water temperature (°C)
Red pacu (*Colossoma brachypomum*)	83.25	56.99	53.43	45.70	8.85 ± 0.18, 23 ± 1.0
Nile tilapia (*Tilapia nilotica*)	142.1	128.28	124.25	103.62	8.32 ± 0.35, 18–21
Common carp (*Cyprinus carpio*)	55.91	25.94	23.41	21.33	8.59 ± 0.33, 25 ± 2.0
Silver carp (*Hypophthalmichthys molitrix*)	51.41	27.06	23.74	15.74	8.74 ± 0.34, 23 ± 2.0
Gibel carp (*Carassius auratus gibelio*)	98.74	79.49	74.08	64.19	8.84 ± 0.26, 24.5 ± 2.5
Crucian carp (*Carassius auratus*)	90.29	69.15	60.82	59.82	8.87 ± 0.29, 25 ± 1.0
Spotted sea bass (*Lateolabrax maculatus*)	101.05	63.27	56.84	46.18	8.4 ± 0.25, 18.5 ± 0.5
Mitten carb (*Eriocheir sinensis*)	52.97	42.44	26.27	24.96	8.33 ± 0.17, 20.3 ± 1.4
Giant freshwater prawn (*Macrobrachium rosenbergii*)	51.02	37.02	27.19	21.54	8.59 ± 0.31, 23.6 ± 1.0

Some experiments have proved that the toxic effects of NaCl content and alkalinity on farmed aquatic animals are synergistic. The relationship equations of NaCl content (S) and alkalinity (Alk) in 24 h LC_{50} value are:

Red pacu	$Alk = 256.2–24.69\ S$, $n = 8$, $r^2 = -0.9017$;
Nile tilapia	$Alk = 513.9–29.79\ S$, $n = 5$, $r^2 = -0.9878$;
Common carp	$Alk = 78.89–4.777\ S$, $n = 5$, $r^2 = 0.9195$;
Silver carp	$Alk = 34.17–1.78\ S$, $n = 6$, $r^2 = 0.7247$;
Giant freshwater shrimp	$Alk = 72.15–7.813\ S$, $n = 7$, $r^2 = -0.9920$;
Spotted sea bass	$Alk = 125.1–2.18\ S$, $n = 7$, $r^2 = 0.9518$;

The suitable alkalinity for the growth of Nile tilapia is <8 mmol/L; the suitable NaCl content for the growth of mitten crab is <1.0 g/L; and the suitable alkalinity and NaCl content for the growth of red pacu are <5 mmol/L and <7.0 g/L, respectively.

11.4 Effects of Cations in Water on Shrimp

Whiteleg shrimp (*L. vannamei*) is a disease-resistant, euryhalinity, and fast-growing economic crustacean, and has been widely farmed in inland and coastal salt-alkali ponds in many countries. However, due to the great difference in water quality in different regions, especially the difference in concentration and composition of cations, mass mortality of farmed whiteleg shrimp is common at the juvenile stage. The main cations in water include K^+, Na^+, Ca^{2+}, and Mg^{2+}. Both absolute quantities and the proportions of the cations could significantly affect the growth and development of shrimp. Therefore, this section will focus on the effects of cations in water on the growth of the whiteleg shrimp.

11.4.1 Adaptability of Shrimp to Na^+/K^+ Ratios in Water

K^+ content of groundwater in many salt-alkali areas is low and cannot be used directly for shrimp culture or the culture results are not satisfactory. The specific growth rates of whiteleg shrimp in the water with Na^+/K^+ ratios ranging from 47 to 76 are significantly higher than that with Na^+/K^+ ratios over 98 (Zhu et al. 2005). The Na^+/K^+ ratios of the water have significant effects on the energy budget of the shrimp (Table 11.5). The Na^+/K^+ ratios of water can affect the growth of the shrimp by influencing the food conversion efficiency and the proportion of energy allocation to growth. When the shrimp is cultured in K^+-deficient water with a salt content of around 15 ppt, it is necessary to reduce the Na^+/K^+ value of water to below 76 by adding potassium salt into the water to obtain better farming results.

When the salt content of the water increases to 30 ppt, the effect of Na^+/K^+ ratios on the growth of the shrimp becomes inconspicuous (Fig. 11.2). Salt content, Na^+/

Table 11.5 Effects of Na^+/K^+ ratios on the energy budget of *L. vannamei* at salinity 15 ppt (from Zhu et al. 2004)

Na^+/K^+	*C* (kJ)	*G*/*C* (%)	*R*/*C* (%)	*F*/*C* (%)	*U*/*C* (%)	*E*/*C* (%)
47	48.22 ± 2.35^a	18.30 ± 1.02^a	62.67 ± 1.06	12.78 ± 0.39^a	5.45 ± 0.16	0.80 ± 0.15^a
62	46.80 ± 5.62^{ab}	18.14 ± 0.33^a	62.31 ± 0.35	12.87 ± 0.69^a	5.52 ± 0.01	1.16 ± 0.08^{ab}
76	45.11 ± 2.09^{abc}	18.86 ± 1.11^a	61.59 ± 1.32	12.74 ± 0.42^a	5.83 ± 0.13	0.98 ± 0.15^a
88	38.46 ± 1.71^{bc}	18.30 ± 1.50^a	60.06 ± 1.96	14.74 ± 1.15^{ab}	5.51 ± 0.23	1.38 ± 0.12^{ab}
98	36.26 ± 2.53^c	13.48 ± 1.42^b	65.77 ± 2.00	13.07 ± 0.80^a	5.88 ± 0.30	1.80 ± 0.11^{bc}
116	36.85 ± 1.19^c	13.55 ± 1.50^b	62.61 ± 1.49	16.12 ± 0.37^b	5.73 ± 0.25	1.99 ± 0.27^c

Note: $Na^+ + K^+$ is 239 mmol. The values with different letters in the same column are significantly different from each other ($P < 0.05$)

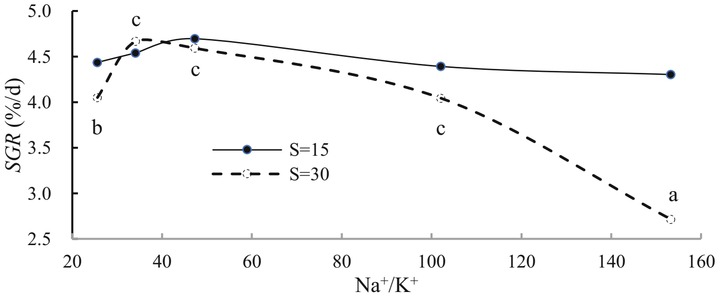

Fig. 11.2 Specific growth rate of whiteleg shrimp reared at different salinities and Na^+/K^+ ratios (from Zhu et al. 2006a). Means with different letters within the same salt content are significantly different ($P < 0.05$)

K^+ ratio and their interactions could significantly affect the growth of the shrimp (Zhu et al. 2004, 2006a).

The shrimp may not be able to absorb K element effectively from feed, and only the K^+ concentration in water has a significant effect on the growth of shrimp (Zhu et al. 2006b).

In the Yellow River Delta of China, southern Australia, and some coastal regions of India, the groundwater is chloride type and the salt composition of the water is mostly identical to seawater. However, the K^+ concentration is usually 90–95% lower than that of normal seawater, and the Na^+/K^+ ratio is 8–20 times higher than those of normal seawater. Therefore, special attention should be paid to potassium deficiency when culturing shrimp or fish in these or similar areas.

11.4.2 Adaptability of Shrimp to Ca^{2+} Concentration in Water

Calcium in water plays an important role in the survival, growth, and metabolism of crustaceans. A moderate increase in Ca^{2+} concentration under low salt content conditions can significantly improve the survival of shrimp. At the salt content of 0.5 ppt, Ca^{2+} concentration below 15 mg/L will significantly affect the growth of whiteleg shrimp. The adaptability of shrimp to Ca^{2+} is salt content dependent, and more Ca^{2+} is required with higher salt content. At a Ca^{2+} concentration of 5 mg/L, the survival rates of the shrimp are about 80%, 70%, and 0% at salt contents of 0.5, 5, and 10 ppt, respectively (Hou 2011). At the salt content of 15 ppt and Ca^{2+} concentrations of 180–750 mg/L, the shrimp grow fastest and the proportion of ingested energy allocated to growth is the largest (Dong et al. 2005).

The adaptability of Chinese shrimp (*F. chinensis*) to Ca^{2+} is also salt content dependent, and the shrimp requires more Ca^{2+} at higher salt content. At the salt content of 5 ppt, the 96-h survival rates of juvenile Chinese shrimp are 46.7 and 93.3% at Ca^{2+} concentrations of 0.0 mg/L and 43.75 mg/L, respectively. At the salt content of 15 ppt, the 96-h survival rates are 0 and 3.3% at Ca^{2+} concentrations of 0.0 mg/L and 43.75 mg/L, respectively.

Ca^{2+} concentration affects the growth energy accumulation of Chinese shrimp by affecting its feeding and metabolic rate. When the Ca^{2+} concentration is 1200 mg/L, the energy allocated to growth can reach 24.5%. In shrimp culture, increasing Ca^{2+} concentration in calcium-deficient water can significantly improve aquaculture efficiency (Dong 2005).

11.4.3 Adaptability of Shrimp to Mg^{2+}/Ca^{2+} Ratios in Water

At the salt content of 30 and the Mg^{2+}/Ca^{2+} ratio in the range of 0.11–7.87, the survival rate of juvenile whiteleg shrimp is 100%. However, there is high mortality at the Mg^{2+}/Ca^{2+} ratio of 11.81 and the Ca^{2+} concentration of 94 mg/L, which is mostly due to the difficulty of hardening the shell after molting (Zhu et al. 2010). Just as mentioned above, juvenile whiteleg shrimp grow well at the salt content of 15 ppt and the Ca^{2+} concentration of 60 mg/L. Thus, the mortality of the shrimp may be related to the improper Mg^{2+}/Ca^{2+} ratios instead of the Ca^{2+} concentrations in water.

When the Mg^{2+}/Ca^{2+} ratio is in the range of 0.53–7.87, the energy intake and the energy allocated to the growth of whiteleg shrimp are relatively great, and respiration and excretion are normal. In production, it is recommended to keep the Mg^{2+}/Ca^{2+} ratio in the range of 0.5–5.0 to obtain better growth of the shrimp.

Zhu (2005) has also studied the effect of water $(Mg^{2+} + Ca^{2+})/(Na^{+} + K^{+})$ ratios on the growth and budget of whiteleg shrimp. Among the seven ratios ranging from 0.05 to 0.71, the shrimp have a significantly less growth energy allocation at the ratio of 0.05 than the other six ratios, however, there are no differences in growth among the seven ratios. Whiteleg shrimp is weaker to tolerate lower $(Mg^{2+} + Ca^{2+})/(Na^{+} + K^{+})$ ratios in water and somewhat stronger to tolerate higher $(Mg^{2+} + Ca^{2+})/(Na^{+} + K^{+})$ ratios.

11.5 Water Quality Management in Salt-Alkali Ponds

For ponds with high levels of sulfur iron (FeS_2), common in coastal brackish water areas, the application of lime is enough to improve their water quality (see Chap. 8 for details). In contrast, water quality management in salt-alkali ponds is complex, and many physical, chemical and biological methods have been developed to improve their water quality. The pond-based aquaculture-agriculture-terrace system described above is one type of physical method; moreover, aeration and sediment stirring can be conducted in the pond to improve the water quality. Chemical and biological methods will be introduced in the following part.

11.5.1 Effects of Fertilization on Water Quality of Salt-Alkali Ponds

Both inorganic fertilizer and organic fertilizer are used. Inorganic fertilizer refers to the chemical compounds containing large amounts of elements such as nitrogen, phosphorus, and potassium, while organic fertilizer mainly refers to manure. The feed residuals and feces can also be regarded as organic fertilizer.

As the water alkalinity and pH of the ponds in salt-alkali land are high, the use of alkaline fertilizers is undoubtedly inappropriate. Acidic fertilizers should be used, which not only provide the necessary nutrients for the pond but also neutralize alkalinity, reducing the threat of high alkalinity and pH to farmed fish and shrimp.

Acidic fertilizers, such as urea (carbamide) and ammonium nitrogen fertilizer, are often applied in the pond (Boyd 1982):

$$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$$

$$2NH_3 + 2H_2O \rightarrow 2NH_4^+ + 2OH^-$$

$$2NH_4^+ + 4O_2 \rightarrow 4H^+ + 2NO_3^- + 2H_2O$$

According to the above equations, nitrification of 1 mmol urea or ammonium nitrogen can produce 2 mmol acid and reduce 2 mmol alkalinity. However, as ammonium nitrogen is the primary nitrogen source of phytoplankton, the ammonium nitrogen applied is usually absorbed by phytoplankton before nitrification when there is light in the pond. In this way, the alkalinity in the pond will not decrease but increase. An increase in alkalinity and pH were reported in previous studies after ammonium nitrogen application (Pote 1990; Knud-Hansen and Pautong 1993). Similarly, the application of nitrate fertilizer will also increase alkalinity and pH due to photosynthesis. The process is illustrated in the following equation:

$$106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+ \rightarrow C_{106}H_{263}O_{110}N_{16}P + 138O_2$$

Thus, the application of urea and inorganic fertilizer to the salt-alkali pond that is low in inorganic nitrogen generally increases alkalinity and pH. The experiment of Shentu (1999) also showed that different levels of pH increase were observed after applying NH_4Cl, NH_4NO_3, and $(NH_4)_2SO_4$ in ponds. Hence, attention should be paid when these inorganic fertilizers are used to prevent the alkalinity and pH from rising too high to harm the cultured animals.

In addition to nitrogen and phosphorus, organic fertilizer also contains trace elements such as iron, manganese, zinc, and copper. The organic matter in the organic fertilizer can be mineralized under the action of bacteria.

$$C_{106}H_{263}O_{110}N_{16}P + 138O_2 \rightarrow 106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O \\ + 18H^+$$

The mineralization process can not only provide nutrients for the ponds but also produce carbon dioxide and organic acids that can reduce the pH of the pond water. Previous studies reported the reduction of alkalinity after the application of organic fertilizers (Manjunatha and Shetty 1991). The decrease in total alkalinity is the result of organic acid production, while the CO_2 generated by decomposition can lower the pH of the water. Assuming the organic matter contains 35.8% carbon, in theory, 1.31 kg CO_2 can be produced when 1 kg of organic matter is completely decomposed. These CO_2 can produce 29.8 mol acidity, which can dissolve 2.98 kg of $CaCO_3$, i.e., producing 2.98 kg alkalinity (calculated by $CaCO_3$) (Boyd 1997). Therefore, the application of organic fertilizer could significantly reduce the pH in salt-alkali ponds, which is proven by many researchers (Yang 2000).

But organic fertilizer also has many disadvantages. Organic fertilizer has a slow effect and unstable nitrogen content. Moreover, compared with the amount of phosphorus, the nitrogen content of organic fertilizer is usually low. Therefore, organic and inorganic fertilizers are often used together in salt-alkali ponds to stimulate microbial activity and promote the decomposition of organic fertilizer.

Residual feeds have similar effects on water quality as organic fertilizer. Hence, the uneaten feed and feces can increase the carbon dioxide in a pond and decrease the water pH (Zhang et al. 2002a).

11.5.2 Water Quality Improvers for Salt-Alkali Ponds

The K^+ deficiency and high pH in salt-alkali pond water often harm the farmed animals. Application of KCl and $CaCl_2$ can effectively improve the water quality of the pond, and increase the survival rate and yield of cultured animals.

11.5.2.1 Effects of KCl Application on Shrimp Farming

Shrimp farming in salt-alkali ponds is popular in China, giving a strong impetus to the exploitation of salt-alkali lands. However, K^+ deficiency is found in the soil and groundwater of many salt-alkali areas due to the chemical geological processes over a long period of time. When using the water for aquaculture, the K^+ deficiency or unbalanced cations may harm cultured animals, causing unnecessary losses from time to time. The K^+ deficiency was also reported in Australian snapper (*Pagrus auratus*) culture in Australia and shrimp culture in India. We have tried to solve this problem by adding KCl to the shrimp feed, but it didn't work well. The effects of KCl application to the K^+ deficiency ponds in Dongying, Shandong Province, are shown in Table 11.6. The original Na^+/K^+ (mol/mol) ratio of the pond water was 154, in which whiteleg shrimp would die in days after stocking. By applying different amounts of KCl to the ponds the Na^+/K^+ (mol/mol) ratios were decreased. The highest survival rate, yield, and food conversion rate were achieved at the Na^+/K^+ of 40 (Table 11.6).

Table 11.6 Net production, body weight, and survival of *L. vannamei* in the brackish water ponds at different Na^+/K^+ ratios (from Jie 2006)

Na^+/K^+ (mol/mol)	Yields (g/45 m^3)	Weight (g/ind.)	Survival (%)
10	2840.5 ± 24.6^a	12.17 ± 1.48^a	23.55 ± 2.53^a
20	6969.3 ± 539.9^b	11.53 ± 3.13^a	63.23 ± 15.55^b
40	8323.1 ± 343.6^c	11.92 ± 2.53^a	71.86 ± 14.52^b
80	7966.3 ± 45.9^c	11.78 ± 1.95^a	68.87 ± 11.11^b
154 (control)	0	0	0

Note: Salt content of the pond water was 9 ppt

11.5.2.2 Effects of $CaCl_2$ Application on Water Quality in Pond

A certain concentration of Ca^{2+} is required by shrimp. In addition, the buffering capacity of water is poor when there is a lack of Ca^{2+} in water, which is common in chloride-type salt-alkali ponds. The poor buffering capacity will lead to drastic fluctuations in pH when there is strong photosynthesis by phytoplankton, which is harmful to cultured animals. Therefore, Shentu et al. (2000b) applied $CaCl_2$ to the pond to reduce the alkalinity and pH of pond water and demonstrated that $CaCl_2$ was an efficient improver on the water quality in salt-alkali ponds.

As can be seen from Fig. 11.3, after the application of 2 mmol/L $CaCl_2$ for 2 days, the pH of pond water decreased significantly. Although the pH increased slowly then, it remained at a relatively low level after 16 days. The total alkalinity decreased dramatically in the first 2 days and then decreased slowly in the following 14 days. Thus, $CaCl_2$ fertilization can effectively reduce the pH and total alkalinity, and improve the buffering capacity of water. In addition, $CaCl_2$ fertilization can significantly increase the phytoplankton diversity without a change in the phytoplankton biomass.

11.5.2.3 Effects of Other Acidic Chemicals Application on Water Quality in Pond

Boyd and Tucker (1998) suggested introducing carbon dioxide or strong acids to reduce the pH of pond water. Hydrochloric acid can quickly reduce the water pH for

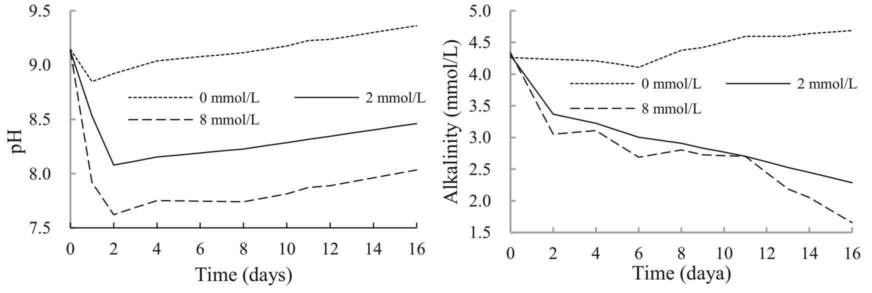

Fig. 11.3 Changes of pH and alkaline after $CaCl_2$ fertilization (from Shentu et al. 2000b)

a short time and it is not suitable to be used as a water quality improver in salt-alkali ponds.

Application of $NaHCO_3$ to the pond can also reduce the pH of water, but it must be applied in high concentration, and it will reduce the buffer capacity of water (Shentu et al. 2000b). Calcium sulfate has also been used as an improver in high alkalinity and low hardness ponds.

Pote (1990) used aluminum sulfate $[Al_2(SO_4)_3 \cdot 14H_2O]$ as an improver. Aluminum sulfate can release hydrogen ions by hydrolysis. However as aluminum can be easily precipitated in the form of $Al(OH)_3$ and $AlPO_4$, the total phosphorus and soluble reactive phosphorus in the water will be significantly reduced.

11.5.3 Water Quality Regulation by Filter-Feeder Fish in Salt-Alkali Ponds

Previous studies have shown that aquatic plant plantation in the salt-alkali ponds can reduce the alkalinity of water; however, the concentration of inorganic nitrogen and phytoplankton biomass in water is also reduced. The filter-feeders such as silver carp, bighead carp, and tilapia can feed on large plankton, and thus relieve the feeding pressure of the zooplankton on phytoplankton, increasing phytoplankton abundance, primary productivity in the pond (see Chap. 7 for details). The following will introduce a new inner net partitioned polyculture method of shrimp with tilapia.

11.5.3.1 Inner Net Partitioned Polyculture of Shrimp and Tilapia

Polyculture of whiteleg shrimp with Nile tilapia is common to prevent the white spot disease of the shrimp in salt-alkali ponds. However, the system has three disadvantages. Firstly, the tilapia in the polyculture system will swoop feeding the relatively expensive shrimp feed, which contains higher protein content compared with the tilapia feed. Secondly, the tilapia can rapidly suppress and reduce zooplankton populations throughout the pond due to their high filter feeding capacity (Zhang et al. 1999a; Sun et al. 2010), thus blocking the food chain from phytoplankton to tilapia, affecting tilapia's indirect use of phytoplankton primary productivity and in turn affecting the growth of tilapia (Tian et al. 1997). Thirdly, tilapia may also prey on molting shrimp. To solve the above problems, we have developed the inner net partitioned polyculture of shrimp and tilapia in salt-alkali ponds.

Whiteleg shrimp and Nile tilapia are polycultured in inner net partitioned polyculture ponds (Fig. 11.4). The ponds (36 m × 14 m × 2 m) are divided into three parts by two nets, tilapia is stocked in the middle area of 7 m × 14 m to prevent the fish from competing for the high-value shrimp pellet and from preying on the zooplankton in other areas.

In a trial (Jie 2006), three ponds were stocked with shrimp only; three ponds were stocked with shrimp and tilapia without feeding the fish; the other three ponds were stocked with both shrimp and tilapia, and both were fed by formulated feed. Shrimp (0.01 ± 0.01 g) were stocked in ponds at a density of 45 ind./m^2 and fish (51.74 g ± 19.63 g) were stocked at a density of 51.6 g/m^2. During the 95 days of culture trial, there were no significant differences in dissolved oxygen and pH among

Fig. 11.4 Inner net partitioned polyculture of shrimp and tilapia in ponds (from Dong 2015b). Left: Schematic sketch; Right: Actual photos

treatments, but the transparency of the shrimp monoculture pond was significantly lower than that of the other two treatments. The survival rate of shrimp in polyculture without feeding the fish was 48.6% and 23.7% higher than that of shrimp monoculture and polyculture with feeding the fish, respectively. In addition to the additional yield of tilapia, compared with the shrimp monoculture, the net yield of shrimp increased by 13.1% and 12.5%, respectively in the polyculture ponds.

11.5.3.2 Effects of Tilapia on Phytoplankton Community

Compared with the common polyculture model of shrimp and tilapia, the inner partitioned polyculture system can improve the plankton community structure and in turn improve the growth of tilapia (Sun and Dong 2010; Sun et al. 2010). In fact, in the inner partitioned polyculture system, the areas where shrimp are cultured are zooplankton refuges. The average rotifer biomass is significantly higher in the farming waters with zooplankton refuge than the farming waters without refuge (Fig. 11.5).

The average phytoplankton biomass in waters with refuge is 101 mg/L, which is significantly lower than the waters without refuge (140 mg/L). In addition, the setting of the refuge can significantly increase the phytoplankton diversity. At the end of the trial, the average fish weight is 5.4 times higher in the waters with refuge than the waters without refuge (Table 11.7).

To make good use of primary productivity, it is important to maintain a certain amount of zooplankton biomass. The rotifers are prolific and are good food sources for tilapia, and can make better use of the phytoplankton in the water. The above

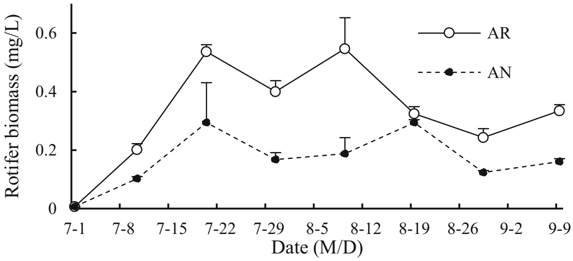

Fig. 11.5 Rotifer biomass in the pond water (from Sun and Dong 2010). *AN* without zooplankton refuge, *AR* with zooplankton refuge

Table 11.7 Growth of tilapia in the water with and without refuge (from Sun et al. 2010)

Treatments	Stocking biomass of fish (kg/28 m^2)	Fish number	Average growth increment of fish (g)
With refuge (AR)	5.05 ± 0.04	31.33 ± 0.33	23.5 ± 6.00
Without refuge (AN)	5.06 ± 0.03	31.33 ± 1.20	3.17 ± 4.19

study demonstrates that the zooplankton refuge, i.e., the inner partitioned polyculture system, is effective in increasing zooplankton biomass and thus increasing fish yield.

11.5.3.3 Structural Optimization of Shrimp and Tilapia

In a 36-day study, 12 land-based enclosures (each 5 m × 6 m) were set in a salt-alkali pond with an average water depth of 1.3 m to find the optimal stocking structure of shrimp and tilapia with the highest energy conversion efficiency. All fish were cultured in net cages (1.2 m × 1.2 m × 0.7 m) inside the enclosures. The results showed that the fish had a significant effect on the biomass of phytoplankton (Table 11.8), and the transparency of the water with fish was significantly higher than that without fish. The transparency of the polyculture system with a medium stocking density of fish (P2) was the largest. As the stocking density of fish increased, the ratio of primary production to community respiration (*P/R*) increased.

The shrimp yield in P2 is 40.9 g/m^2, which is significantly higher than those of CO (25.8 g/m^2), P1 (27.7 g/m^2), and P3 (27.0 g/m^2). Shrimp in the P2 also had the highest individual weight gain, survival rate, and lowest feed conversion efficiency.

Table 11.8 Ecological effects of inner net partitioned polyculture of tilapia with shrimp (from Jie 2006)

Indicators	CO	P1	P2	P3
Dissolved oxygen (mg/L)	9.36 ± 0.62^a	8.82 ± 0.30^b	8.33 ± 0.40^b	8.02 ± 0.70^b
Transparencies (cm)	38 ± 6^a	42 ± 6^b	45 ± 3^b	42 ± 8^b
Primary production/ community respiration	1.06 ± 0.24^a	1.25 ± 0.10^{ab}	1.34 ± 0.18^{ab}	1.44 ± 0.11^b
Photosynthetic energy input per unit net product	80.59 ± 12.89^a	55.81 ± 5.49^b	29.24 ± 3.67^c	28.22 ± 2.62^c
Biological energy input per unit net product	24.62 ± 1.42^a	19.78 ± 0.27^b	12.95 ± 1.10^c	15.08 ± 0.84^d
Total energy input per unit net product	105.41 ± 13^a	81.27 ± 5.54^b	50.50 ± 4.97^c	57.26 ± 4.90^c

Note: Shrimp were stocked at 59 ind./m^3. Individual weight of the shrimp was 0.01 ± 0.01 g, and individual weight of tilapia was 139.68 ± 39.40 g. CO is control, without tilapia; P1. Tilapia 7 ind./m^3; P2. Tilapia 22 ind./m^3; P3. Tilapia 48 ind./m^3; Photosynthetic energy input for unit net product (kJ/fish or shrimp) = Photosynthetic input/Total net product; Biological energy input for unit net product (kJ/fish or shrimp) = Biological input/Total net product; Total energy input for unit net product (kJ/fish or shrimp) = Total energy input/Total net energy product

Net photosynthetic energy consumption per 1 g shrimp produced by CO treatment without tilapia was 80.59 kJ, which was significantly higher than those of the treatments with tilapia. The least biological energy input for unit net product and total energy input for unit net product occurred in P2, which were 12.95 kJ/g and 50.50 kJ/g, respectively.

The results of the above study show that the inner net partitioned polyculture of whiteleg shrimp with tilapia is effective in reducing the waste of shrimp feed fed by the tilapia and improving the survival of shrimp. In the medium fish stocking density, the shrimp yield is highest, individual weight gain is highest, the feed conversion efficiency is lowest, and ecological indicators are all at best conditions.

Brief Summary

1. The saline soils in the coastal area are mainly affected by seawater and are chloride type. The formations of waterlogged salt-alkali land are mainly due to the low topography, relatively high groundwater level, and long-time poor drainage of rainwater.
2. Pond-based aquaculture-agriculture system is a very efficient model for the exploitation of waterlogged salt-alkali land and waterlogged acidic saline-humid soil areas influenced by rhythmic ocean tides.
3. Inland waterlogged salt-alkali ponds are usually characterized by high alkalinity and high pH. Ca^{2+} deficiency in salt-alkali ponds results in poor buffering capacity of the water. When there is strong photosynthesis, dramatically rising pH to a certain threshold value may stress the farmed aquatic animals.
4. The main composition of alkalinity that is toxic to farmed fish is CO_3^{2-} . The safety threshold of alkalinity for fish farming is about 10 meq/L.
5. The K^+ deficiency is often found in the groundwater of some salt-alkali land. KCl can be applied to the shrimp pond to increase the K^+ in water, and the Na^+/K^+(mol/mol) ratio should be regulated at about 40. The lower the salt content of the water, the more sensitive the farmed shrimp to the change in Na^+/K^+ ratio.
6. Increasing the concentration of Ca^{2+} in calcium-deficient water can significantly improve the aquaculture benefits. The amount of $CaCl_2$ application is related to the salt content of the water, and more $CaCl_2$ should be applied in higher salt content water. When the salt content is 5 ppt, the Ca^{2+} concentration should be kept above 44 mg/L; when the salt content is 15 ppt, the Ca^{2+} should be kept above 87 mg/L; and when the salt content is 30 ppt, the Ca^{2+} should be kept above 350 mg/L.
7. Delivering feeds, applying organic fertilizer and $CaCl_2$ can efficiently reduce the alkalinity and pH of aquaculture water.
8. Setting up zooplankton refuges in the filter-feeding fish pond, such as the inner net partitioned polyculture of whiteleg shrimp with tilapia, is an effective way to increase fish production by maintaining a certain amount of zooplankton in waters.

Cage Farming of Fish in Open Waters

12

Qin-Feng Gao and Shuang-Lin Dong

Aquaculture cage is usually a kind of box-shape facility for holding or farming aquatic animals in marine or fresh waters. The cage frame is generally made of wood, high-density polyethylene, steel or other firm materials, and the bottom and side are covered with mesh or netting which are made of polyethylene, nylon, copper alloy, or other such kinds of flexible materials. Some of the cages are top-open while others are top-closed with net coverage depending on the cultured species and the conditions of aquaculture waters. Such kind of structure retains the cultured animals within the cage and facilitates the water exchange between the inside and outside parts of the cages through the net meshes. The difference between the net cage and the net pen is that the net cage possesses a bottom structure and is usually floated on the water surface or suspended in the water column, while the pen has no bottom structure and is constructed based on the natural substrate of the aquaculture waters. The water area enclosed by the pen is usually much larger than that by the net cage. The aquaculture principles of the net cage and the pen are basically same. As such, the related principles of the pen are not repeated circumstantially in this chapter.

Since modern net cages were introduced to China in the 1970s, cage farming of fish has been rapidly promoted in reservoirs, lakes, rivers and bays, which greatly expanded the aquaculture scale in terms of volume and water areas in China. However, with the rapid expansion of the cage farming scale, its negative impacts on the environment have gradually emerged. In order to improve the utilization of cages in practical aquaculture and reduce or even avoid its negative impacts, history, principles, carrying capacity and biofouling of cage farming are introduced in this chapter.

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12.1 Overview of Cage Farming

12.1.1 History of Cage Farming

The development of cage farming in the world can be generally divided into three stages, including simple cage stage, modern cage stage and offshore cage stage.

12.1.1.1 Simple Cage Stage

As early as the Han Dynasty (220–202 BC), primitive cages were used to temporarily raise fish in China (Li 1994). ZHOU Mi (1232–1298 AD) of the Song Dynasty recorded in his book '*Gui Xin Za Shi*' that 'The fry actively move about in the cages with the waves as if they enjoy playing. One or half a month later, the fry grow big enough for marketing. The cloth cages are fine-meshed cages. The bamboo sticks serve to frame the cages in which the caught fry is nurtured' (Beveridge 2004). Such fish culture with the cloth bag is one of the earliest recorded rudiments of fish cage farming.

At the end of the nineteenth century, Cambodians began to temporarily breed and fatten the captured fish such as snakehead fish (*Channa*) and catfish (*Clarias*) by using wooden or bamboo floating cages. Such technology later spread to Vietnam and other countries along the Mekong River (Beveridge 2004). It is believed that with the progress of archaeology and literature excavation, more evidence regarding the early application of cages for the temporary breeding, transporting, and fattening of fish will be found in other countries worldwide.

The structures of simple fish cages include frame made of wood or bamboo and net made of cotton, flax or bamboo. The artificial synthesis of high polymer material phenolic resin by American Leo Baekeland in 1909, especially the successful synthesis of polyethylene in the 1940s, made the construction of modern fish cage possible.

12.1.1.2 Modern Cage Stage

The nets of modern fish cages are made of artificially synthetic fibers and/or metal alloys. In 1954, Fisheries Laboratory at Kinki University, Japan, firstly started experiment with cage on yellowtail (*Seriola quinqueradiata*) culture and then it was mass-produced (Beveridge 2004). At the same time, a small reconditioned coaster from Alaska was converted to a floating hatchery ship, the 'Brown Bear', in Puget Sound of Manchester, USA. Around its side a flimsy complex of floating cages was constructed to hold more smolts and broodstock of coho salmon (*Oncorhynchus kisutch*) (Nash 2011). Afterward in the 1960s, Auburn University in the United States began to culture tilapia (*Oreochromis* spp.) with net cages. Meanwhile, two brothers, Sivert and Ove Gröntvedt from Trondheim, Norway, designed and constructed a large octagonal cage with floating collars, which is a prototype of modern offshore farming cages. The floating collars were made of wood and foam polyester which facilitated the operation of salmon farming.

Thanks to the application of polyethylene (PE), polyvinyl chloride (PVC), and especially high-density polyethylene (HDPE) in aquaculture, floating cages are constructed with HDPE pipes in replacement of wood or foam polyester. Because HDPE pipe is more economical and flexible than steel materials, it is more resistant to wind and waves. In the 1970s, the promotion of circular HDPE gravity floating cage enhanced the large-scale development of salmon and trout cage farming in Norway (Nash 2011; Grøtum and Beveridge 2007). Such techniques afterward spread around the world. It has been found that fish cultured in large cages grow faster and are of higher quality. As a result, the sizes of HDPE floating cages tend to be increasingly large. The perimeter of the cages used for tuna farming, for example, has reached 300 m.

In 1973, the common modern cages were introduced to China from Japan. By using the cages, silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*) were cultured in reservoirs successfully (Hu 1988). However, because of the security limitation, such common net cages can only be applied in inland waters or semi-closed bays. HDPE gravity cage was introduced to China from Norway in 1998, and the cage construction was localized very soon. In 2019, the total production of marine cage farming in China reached 760,000 tons, 27.6% of which were from the deep-water (>20 m) cages, or 33.1% increase relative to the figure of 2018, showing the huge developmental potential of marine cage farming, especially the deep-water cages.

12.1.1.3 Offshore Cage Stage

With the rapid expansion of marine fish farming in nearshore areas, the ecological loss, disease risk, product safety of mariculture as well as its conflict with other sectors in the usage of sea areas have become increasingly prominent. Therefore, mariculture expansion toward offshore even deeper-offshore is one of the prior ways to promote the sustainable development of aquaculture (Naylor et al. 2021). The oceanographic and climate characteristics of open areas, such as severe storm and roaring waves, call for new technical requirements for aquaculture equipment. Moreover, in order to enhance the market competitiveness of mariculture products, the selection of suitable culture species has become a hot issue (Beveridge 2004; Lovatelli et al. 2013; Dong 2019b).

To withstand the tough environmental conditions in open seas, the cage structure shall be semi- or fully submersible and made of steel and/or HDPE. In 1986, Sweden built steel semi-submersible offshore cage Farmocean, which was soon popularized to Europe and the Mediterranean region (Lovatelli et al. 2013). The farming volume of the cage is 2500–6000 m^3 and can withstand waves of 5 m high. In the late 1990s, the United States built conical submersible cages Seastation™ with the volume of 2000 m^3 for fish farming under high sea condition with significant wave height greater than 9 m. Similar equipment includes geodesic sphere submersible cage Aquapod™, octagonal Sadco-Shelf cage (2000 m^3), etc. The main advantage of the conical and the spherical cages is the high resistance ability to wind and waves, while the main disadvantages of them are the difficulty of fish harvest and the equipment berthing.

Most offshore cages built in recent years in the world belong to the experimental facility with small size and few of them are profitable (Lovatelli et al. 2013). In

Fig. 12.1 Floating (**a**), semi-submersible (**b**), and submersible (**c**) aquaculture cages (Photo B from the internet)

recent years, in order to realize scale merit as soon as possible, Norway and China have built the 250,000 m^3 semi-submersible ‘Ocean Farm 1’ and 50,000 m^3 submersible ‘Deep Blue 1’ steel cage (Fig. 12.1), respectively, and their nets are both made of ultra-high molecular weight polyethylene.

12.1.2 Types of Farming Cages

There are various types of aquaculture cages and no unified classification standard has been widely accepted so far. In the annual report of China on fisheries and aquaculture statistics, aquaculture cages are classified into two types, i.e., ordinary cage and deep-water cage. Aquaculture cages can also be classified according to the shapes (such as rectangle, polygon, circle, ship-like, cone, sphere, etc.), sizes (such as small, medium and large), frame material (such as floating rope, wooden, polyethylene, high-density polyethylene, metal materials, etc.), degree of intensification, ways to keep the shape of cage meshes or nets, floating status in waters, distance away from the seashore, culture spices and so on.

12.1.2.1 Classification Based on the Floating Status

In terms of the floating status in water column, aquaculture cages are classified into fixed cages which are generally appropriate for shallow waters, floating cages (Fig. 12.1a), semi-submersible cages (Fig. 12.1b), and submersible cages (Fig. 12.1c). Submersible cages may enable a better production environment to be accessed during poor surface conditions such as harmful algal blooms and inappropriate surface temperature, and, moreover, provide the functions to reduce specific environmental impacts related to fish farming in sea cages such as fish escapes during storms and sea-lice loads in coastal waters (Dempster et al. 2009).

The Norwegian cage ‘Ocean Farm 1’ (Fig. 12.1b) launched in 2017 is a typical semi-submersible cage with the total height of 69 m and the farming volume of 250,000 m^3. The main body of the cage is submerged in the water, and only parts of the cage with accessories are exposed above the water surface.

The Chinese cage ‘Deep Blue 1’ (Fig. 12.1c) launched in 2018 is a submersible cage with a height of 38 m and farming volume of 50,000 m^3. The whole cage is submerged into the water in the hot season and cultures cold water fish using the cold water under the thermocline. When the surface water temperature drops to about 18 °

Fig. 12.2 Aquaculture cages used in coastal (**a**), off-the-coast (**b**), and deeperoffshore (**c**) areas

C at the end of autumn, the cage is floated up to the surface (Dong 2019b). In 2019, the cage was modified and functionally optimized (Fig. 12.2c). In particular, a platform with automatic feeder and power unit was integrated in the cage.

12.1.2.2 Classification Based on Ways of Maintaining the Net Shape

In terms of methods to maintain net shape, aquaculture cages are classified into gravity net cage, anchor tension net cage, semi-rigid net cage, rigid net cage, and so on. Gravity net cage is mainly composed of a floating system, net, counterweight system and mooring system, which maintains the net shape by means of vertical downward tension generated by the counterweight. Anchor tension net cage maintains the net shape and position by means of mooring system. Semi-rigid net cage is composed of rope and rigid steel components to maintain the integrity of cages and the net shape. Frames of rigid net cage are made of steel or other rigid materials to maintain the shape of the net shape.

12.1.2.3 Classification Based on the Distance Away from Seashore

According to the FAO technical book of 2010, mariculture can be divided into coastal mariculture, off-the-coast mariculture, and offshore mariculture according to the distance of the farming waters away from the seashore and water depth (Lovatelli et al. 2013). Coastal mariculture refers to the aquaculture in the sheltered sea area with water depth less than 10 m and less than 0.5 km away from the shore. Off-the-coast mariculture refers to the aquaculture with water depth of 10–50 m and the distance of 0.5–3 km away from the shore as well as tough marine conditions. Offshore mariculture refers to aquaculture with more than 2 km or beyond the visual distance from the shore, water depth of more than 50 m, and tough sea conditions. Off-the-coast mariculture and offshore mariculture can also be collectively called open ocean mariculture.

The slope of the continental shelf and shoreline conditions vary greatly from country to country, so there is no unified standard for the regional division of mariculture in the world. The United States defines mariculture activities that are conducted beyond three nautical miles and in the exclusive economic zone as offshore mariculture (USCOP 2004).

The scale of mariculture in China is much larger than those in other countries in the world. The floating raft farming in some provinces has extended to the open sea areas which is 15 km away from the shore and some fish farming cages are even farther away from the coastline. According to the present situation in China, the food production activity in shallow or sheltered sea areas such as bays within visual range less than 2 km away from the shore and maximum 10 m water depth is defined as coastal mariculture. The activity in open sea areas which is more than 2 km away from the shore with water depth of 10–50 m is called off-the-coast mariculture. The activity using modern equipment in the sea areas with water depth over 50 m or in the exclusive economic zone (12 nautical miles away from the baseline) is called deeper-offshore mariculture (Dong 2019a).

Generally speaking, the cage structure used for coastal mariculture is relatively simple, and most of them are wood and foamed polyester structure or high-density polyethylene floating pipe structure (Fig. 12.2a). The floating frames of off-the-coast mariculture cages, however, are basically made of high-density polyethylene (Fig. 12.2b). Since deeper-offshore mariculture cages are located in the deep-sea area with tough marine conditions, the cage frames made of metal are usually required (Fig. 12.2c).

12.1.2.4 Classification Based on Farming Species

A total of more than 150 fish species and nearly a dozen species of prawn, lobster, crab and other crustacean species have been farmed in cages (Beveridge 2004). Based on the farming species, aquaculture cages can be divided into pelagic fish cage, benthic fish cage, sea cucumber cage, abalone cage and so on. Filter-feeding fish generally do not need additional supply of artificial feeds; therefore, they can be cultured in the cage without feeding apparatus. Benthic fish cage is generally a shallow one. The cage for sea cucumber farming requires water-proof bottom cloth, and the cage for abalone farming requires special structures for delivering macroalgae as feed.

12.1.3 Advantages and Disadvantages of Cage Farming

In 2017, the average production of large off-the-coast mariculture cages in China was 11.1 kg/m^3 while that of small cages with the volume of 1 m^3 for channel catfish was up to 600 kg/m^3 in the United States. The reason for the high yield of cage farming is that aquaculture cages make full use of the environmental hydrodynamics in the farming waters. In spite of the small volume or area of the cage itself, it in fact utilizes the water body hundreds or thousands of times larger than the volume or area of the cage through water exchange. The smaller the volume of the cage, the greater the surface area/volume ratio, the higher the frequency of water exchange in the cage, and the higher yield of the cage. Cage farming is the most economically feasible technology for intensively rearing fish (Beveridge 2004; Angel et al. 2019). In addition to its economic efficiency as aforementioned, cage farming possesses the characteristics as follows:

12.1.3.1 Expansion of Aquaculture Waters and Improvement of Product Quality

The greatest advantage or contribution of cage farming is to expand aquaculture from small land-based waters to large open waters, such as lakes, reservoirs, rivers, bays, and even deeper-offshore areas. As long as the cage farmers obtain governmental permit, they might conduct the farming activities in public waters on the basis of related regulations.

The expansion of aquaculture to large open waters not only increases the aquaculture production, improves the utilization efficiency of water resources, saves a lot of land areas, promotes employment, but also improves the quality of aquatic products accordingly due to better water quality at open areas normally (Beveridge 2004).

12.1.3.2 Easier to Manage

Except the offshore cages, most aquaculture cages have the advantages of mobility and convenient operation. If the environmental conditions where the cages are deployed become unsuitable for farming, the cages might be moved to the water areas with better water quality at any time. Actually, this is just one of the reasons for the better quality of cage-cultured animals. For filter-feeding fish, the cages can be moved to the water areas rich in natural feed organisms. Under the circumstances of typhoon or harmful algal bloom, the cages can also be submerged to certain depths under water surface for a period of time. Frequent cage movement can also avoid the excessive accumulation of organic matter in the local sediment beneath the cages due to the sedimentation of residual feed and feces.

When fingerling release-based aquaculture is carried out in large inland waters, fingerling culture by cages in the same waters can save the cost of transferring fish fingerlings from small waters to large waters and increase the survival rate of the fish released. When the fish fingerlings in cages grow to certain sizes, the cages could be opened to allow the fingerlings to swim into the open water areas. Using the cages with different mesh size in the same waters makes it easier to realize the polyculture of different fish species or different body sizes. In addition, cage farming can inhibit the spawning of certain fish species, such as some tilapia.

12.1.3.3 Reduced Metabolic Activity and Enhanced Growth of Farmed Animals

Caged fish have limited space to swim, so the metabolism and growth of the fish in cages will be changed. The comparisons regarding the metabolic indices of silver carp and bighead carp between the fish individuals farmed in and outside of cages show that the phosphocreatine, hemoglobin and hematocrit of fish inside the cages are lower than those outside the cages, indicating that the movement of the fish within the cages is reduced correspondingly when the space is restricted (Table 12.1). The energy consumed for movement is subsequently decreased and the crude protein and crude fat contents in the muscle are increased for the fish in cages (Table 12.2).

Table 12.1 Metabolism indexes of the silver carp (H) and bighead carp (A) in and out of net cages (from Editing Group for Cage Fish Farming Technology 1982)

	Phosphocreatine (mg/L)		Hemoglobin (g/100 mL)		Haematocrit (%)	
Locations	H	A	H	A	H	A
In cage	7.2	7.4	7.3	6.4	36.6	32.1
Outside of cage	9.9	10.6	7.5	7.1	40.5	33.1
In/outside (%)	72.7	69.8	97.3	90.1	90.4	97.0

Table 12.2 Biochemical composition of the silver carp (H) and bighead carp (A) muscle in and out of cages (from Editing Group for Cage Fish Farming Technology 1982)

	Crude protein (%)		Crude fat (%)		Water (%)	
Locations	H	A	H	A	H	A
In cage	16.90	15.61	3.46	1.59	78.66	81.75
Outside of cage	16.38	15.15	2.86	1.08	79.62	82.32
In/outside (%)	103.2	103.0	121	147	98.79	99.31

The reduced moving space due to the smaller cage size is beneficial to the growth of farmed fish. Long-term lacking of exercise may also cause excessive fat accumulation of farmed fish, which will result in negative effects on the quality of some farmed fish. For instance, large yellow croaker (*Pseudosciaena crocea*) cultured in small cages has a lower market price mainly because of excessive fat content. Therefore, farmers are trying to use cages or pens with large volumes to culture large yellow croaker now in China.

12.1.3.4 Prevent Harm from Predators or Parasites

The fish in cage are defended by cage nets, which can effectively avoid the predation of large carnivorous fish or animals and improve the survival rate of the farmed fish.

The louse (*Lepeophtheirus salmonis*) infestation on cultured Atlantic salmon is a serious disease for fish farming. For example, the economic loss was about 160 million NOK in 1994 in the Norwegian salmon industry. The extent of lice infection is related to the vertical position of cultured fish. Salmon in a 20-m-deep cage had lower levels of lice infection during spring compared to salmon in a 6-m-shallow cage. Therefore, it is an effective measure to prevent the parasitism of sea lice by means of submerging the cages to the deep-water layer (Hevrøy et al. 2003).

12.1.3.5 Convenient to Realize Mechanization and Intellectualization

Cage aquaculture is an intensive farming method, which is more suitable and convenient to carry out mechanization and intelligent operations. At the present, a variety of special equipment for cage culturing has been developed and widely used, such as net washing machine, fish suction pump, feeding machine and specialized vessel. In the future, studies regarding cage facilities will be focused on intelligent farming equipment and management system.

12.1.3.6 Major Problems of Cage Culture

When cage aquaculture is greatly expanded, the residual feed, fece, and metabolic wastes produced by farming activities will cause biodeposition and eutrophication of the farming waters and adjacent waters. The use of chemical medicines may produce potential risks of pollution. The escape of cultured fish may also lead to biological invasion or genetic pollution. Besides, farming of carnivorous fishes consumes large amounts of fish meal and fish oil (Naylor et al. 1998, 2000). In addition, cage culture obstructs water current and might conflict with other industries such as transportation, tourism and fishing. Refer to Chap. 4 for more information with respect to the impacts of cage farming on the environment.

12.2 Carrying Capacity of Cage Farming in Open Waters

The evaluation of the carrying capacity of a water body or area usually requires the understanding of the following four aspects: the factors that determine productivity, the resource consumption and waste produced by aquaculture organisms, the environmental response to aquaculture waste, and the allowable response range. Because the diet of farmed fish in the cage is dominantly artificial feed, the factors that restrict productivity are environmental factors rather than the factors of nutrition or natural feed organisms. Using mathematical model and the data on-site investigated, and referring to relevant current acceptable or allowed standards or thresholds, the carrying capacity of specific farming waters or area can be evaluated. For cage farming of fish, important environmental factors include dissolved oxygen content, un-ionic ammonia, organic matter content in sediment, etc. In contrast to the evaluation of the carrying capacity of closed small waters or bivalve production systems (see Chap. 3), the evaluation of carrying capacity for cages farming of fed fish in open waters should take full account of hydrodynamics. At the present, the evaluating methods that are commonly used include simple models, particle tracking model and numerical models.

12.2.1 Simple Models

Carrying capacity models for aquaculture include simple mathematical expressions, farm-scale models of production, and complex processes involving multiple interactions at the ecosystem scale (Weitzman and Filgueira 2020). Models can define ecological thresholds and indicators and run simulations to depict hypothetical scenarios related to different levels of production or environmental conditions.

Simple models for the evaluation of aquaculture carrying capacity are mathematical expressions that describe the static relationship between aquaculture organisms and surrounding conditions. The limiting factors of carrying capacity might be dissolved oxygen concentration, organic matter content in sediments, etc. The carrying capacity of aquaculture waters can be determined by comparing the relevant parameters of the aquacultural water area obtained by on-site measurement or theoretical calculation with the acceptable values. The carrying capacity of cage-farmed fish and shellfish in Mulroy Bay, Ireland, for example, was evaluated using the dissolved oxygen budget model. The dissolved oxygen budget model is as follows (Telfor and Robinson 2003):

$$OP_{\text{Plankton}} + OP_{\text{Macroalgae}} - OD_{\text{Sediment}} - OD_{\text{Cultured animals}} > 0$$

The limiting factor of the model is that the sum of net oxygen produced by plankton (OP_{Plankton}) and macroalgae ($OP_{\text{Macroalgae}}$) minus the total oxygen consumption by sediment (OD_{Sediment}) and cultured animals ($OD_{\text{Cultured animals}}$) should be greater than zero. The results show that both measured and calculated results are positive (+35,598 kgO_2/d), indicating that there is still the surplus of dissolved oxygen and the overall aquaculture stock in the bay has not exceeded the carrying capacity. Various defects, however, exist in this study, such as the failure to consider the oxygen flux between the atmosphere-water interface. The results can only be regarded as a preliminary qualitative evaluation, but its research idea can be used for reference.

The cage number for fish farming that can be deployed in the area of Zhoushan Sea in China is estimated using the following model (Xu et al. 2005a):

$$N = K \times S \times 10^6/200$$

where N is the number of the standard cages with a surface area of 200 m^2, S is the area (km^2) of the sea area which could be used for aquaculture, and K is the coefficient related to the depth and water quality of the sea area. According to the water depth and water quality of the area and the advice of experts, the value of K ranges from 1/60 to 1/30. The results of 27 survey stations reveal that the carrying capacity (cage number) in Zhoushan Sea is 2385 cages. This model is only a rough empirical model because the boundary and conditions in the model are unclear, such as stocking density, farmed species, etc.

Organic carbon content of surface sediment is used as the limiting index to evaluate the carrying capacity of cage farming of fish at the Dapengao area, Daya Bay in China (Huang et al. 2003). If the organic carbon content of 1.8% is taken as the acceptable maximum threshold, the organic carbon content of the sediment in the farming area has exceeded the limit. It is concluded that the carrying capacity of the farming area is 650 t in spring and 550 t in autumn.

Based on the three examples as aforementioned, it can be seen that the evaluations using simple models belong to the static method and are easy to carry out. The impact factors covered in the model, however, are not comprehensive, resulting in low accuracy and limited information. The complex models described below involve both hydrodynamic information and spatial and temporal variations.

12.2.2 Particle Tracking Model

For the farming waters with shallow depth and weak current, the residual feed and feces produced by farmed fish impose obvious impacts on the sediment environment of the aquaculture waters, which subsequently affects the carrying capacity. Three steps for the assessment of the cage farming impacts on the sediment are usually adopted: firstly, quantification of solid wastes derived from cage farming; secondly, calculation of the distribution of the wastes; finally, generation of waste contour plots using GIS software (Beveridge 2004).

The particle tracking model (DEPOMOD) is recommended to simulate the deposition and accumulation of solid wastes on the sediment from cage farming and the subsequent effects on the benthos (Cromey et al. 2002). The grid generation module in the model provides the user with the grids containing the information of depth of relevant area, number of cages, and location of sampling points. The particle tracking model can predict the initial deposition of residual feed and feces on the sediment based on the information of discharge rate of residual feed and feces as well as the hydrodynamics in the target area. Subsequently, according to the current field near the sediment, the actual distribution of particulate matter and the net accumulation of residual feed and feces in the grid area can be predicted by using the resuspended model. Finally, the influence of aquaculture activities on the benthic community could be predicted according to the quantitative relationship between the benthic community and the quantity of residual feed and feces.

The sedimentation rate of feed is related to various factors such as feed type and density, pellet size, etc. According to the experiment of Cromey et al. (2002), the relationship between the sedimentation rate (y, cm/s) and particle size (x, mm) of pelletized feed for trout conforms to the following equation:

$$y = 5.9775e^{0.0797x}$$

The particle tracking model can be validated by means of sediment trap studies (Cromey et al. 2002). The flux (g/(m^2·d)) predicted by the model is basically consistent with the field data with the accuracy of 20% and 13% for the dispersive and depositional site, respectively.

According to the regulations of the Norwegian government, the species number of benthic animals in the sediments below the fish cage farming areas should not be less than two, which is the limit of carrying capacity for local areas (Stigebrandt 2011). When the biomass of cultured organisms is high, the biomass of benthic animals in the sediments below the cage will increase. The benthic community, however, is usually dominated by single species and in extreme cases, the benthic animals will disappear due to hypoxia.

The DEPOMOD model can be used for site selection of new farms, estimation of carrying capacity, and prediction of feed demand. Although most of the models are used for the studies regarding production carrying capacity, the DEPOMOD model evaluates ecological carrying capacity in the scale of farming areas.

12.2.3 Water Quality Model

As for the farming area with deep water and high flow velocity, it is ideal to evaluate the carrying capacity using water quality numerical models which integrate the relationship between aquaculture activities and water quality. For such models, current field and amount of feed supply impose great effects on the carrying capacity. Waterflow can bring dissolved oxygen inside cages and dilute or take away the metabolic waste produced by farmed animals, and thus create a beneficial environment for the farmed animals. Different farmed animal requires species-specific water quality and the acceptable maximum or minimum threshold of environmental conditions, which can be used as the criteria for evaluating the carrying capacity. When intending to build a fish farm in a specific water area, the first step to take is evaluating the carrying capacity of the area by using mathematical models, combining on-site investigated environmental data and relevant effective standards. For open sea areas, more attention should be paid to eutrophication, while for semi-closed bays, more attention should be paid to indicators which are essential for farmed animals such as dissolved oxygen and ammonia.

The carrying capacity of fish cage farming in Gongwan Bay, Guangdong Province, is studied using the water quality numerical model (Huang and Wen 1998). The phosphorus loading derived from the fish farming of a single cage (3 m × 3 m × 3 m, fish yield 250 kg) is calculated by using the following formula:

$$F_{\mathrm{P}} = E \times E_{\mathrm{P}} - Y \times Y_{\mathrm{P}}$$

where F_{P} is the phosphorus loading produced by the fish in the cage, E is the corresponding amount of the feed required, E_{P} is the phosphorus content in the feed, Y is the amount of fish production, and Y_{P} is the phosphorus content per unit body weight of fish. According to the calculation, the phosphorus loading of each cage is 18.75 kg.

According to the requirement of water quality standard, 0.02 mg P/L is taken as the maximum restriction value of phosphorus, and the mathematical model two-dimensional equation (tide and wave) for shallow waters is used to simulate the current field in the bay, and the on-site investigated data of current and tidal level are used to verify the model. Therefore, the following formula is used to calculate the limitation of the water environment on the carrying capacity of cage farming:

$$\frac{\partial (HP)}{\partial t} + \frac{\partial (HUP)}{\partial x} + \frac{\partial (HVP)}{\partial y} = \frac{\partial}{\partial x}\left(HDx\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(HDy\frac{\partial P}{\partial y}\right) - KPH + SH$$

where P is the concentration of phosphorus; H is the mixing depth of water; U and V are the mean current speed in the x and the y directions, respectively; Dx and Dy are the diffusion coefficients in the x and the y directions, respectively; K is the attenuation coefficient; and S is the content of pollution source. The background value of phosphorus in the bay is 0.006 mg/L, and the limiting element to primary productivity is phosphorus. The calculation results show that the carrying capacity of cage farming in Gongwan Bay is about 65,000 cages. Because only part of residual feed and feces are dissolved into the water environment and the undissolved part will be deposited to the bottom sediment, the above-calculated phosphorus loading will be somewhat different from the actual situation (Zhang et al. 2007a).

The water quality numerical model is adopted to evaluate the carrying capacity of fish cages at the farming area (84.7 km^2) of the South Yellow Sea in China (Zhang et al. 2018). Based on the National Fishery Water Quality Standard of China (GB 11607-1989), dissolved oxygen and un-ionic ammonia (UIA) are selected as the limiting factors to evaluate the production carrying capacity of the farming area. Based on the National Seawater Quality Standard of China (GB 3097-1997), dissolved oxygen, total dissolved inorganic nitrogen, and active phosphate are selected as limiting factors to evaluate the ecological carrying capacity of the farming area.

Firstly, the oxygen consumption and loading of dissolved wastes of steelhead trout (*Oncorhynchus mykiss*) in the cage is estimated using the nutrient budget model as follows:

$$OR = -0.8162T^2 + 33.224T - 28.689$$
$$AER = -0.0711T^2 + 2.1604T - 9.6283$$

where OR is the oxygen consumption rate per unit body weight of steelhead trout [g/(g·h)], AER is the ammonia excretion rate [g/(g·h)], and T is the water temperature. The effective aquaculture volume of a farming cage is 170,000 m^3 with the fish yield capacity of 5000 t. If water temperature is set as the highest value of 19 °C, the total oxygen consumption rate and ammonia excretion rate of the entire fish in the cage are 1540 kg/h and 29 kg/h, respectively. The ratio of UIA (NH_3) to the total ammonia (NH_3 + NH_4^+) is 4%, i.e., the total UIA excretion rate from the cage is 1.16 kg/h. The effects of solid wastes such as residual feed or feces are not considered for the evaluation.

Current speed and the subsequent water exchange are minimum at the slack water period between flood tide and ebb tide; the carrying capacity of the farming area at this period is minimum. As such, a Delft3D hydrodynamics-water quality model is established to simulate the oxygen consumption and UIA excretion of the farming area during the period, subsequently the production carrying capacity is calculated.

The current speed is set at the lowest value at the advection period, i.e., 0.04 m/s, and the model is simulated for 6 h. The background conditional values of the farming area are 7 mg/L for dissolved oxygen and almost 0 for UIA. According to the National Fisheries Water Quality Standard of China (GB 11607-1989), for salmon and trout farming, dissolved oxygen level should be continuously kept higher than 5 mg/L for 16 h and lower than 4 mg/L at any time is not permitted, and maximum concentration of UIA is 0.02 mg/L.

Set 10 cages as a group, in 2 or 3 rows with the distance of 240 m between the cages, along the current direction. With the model simulation during the slack water period, the oxygen consumption or production of UIA will not impose negative impacts on the salmon or trout in the cages. The dissolved oxygen level in the most downstream cage is still above 4.5 mg/L and UIA is less than 0.005 mg/L. Therefore, such deployment of the farming cages will not exceed the production carrying capacity of the specific area.

It should be noticed that the production carrying capacity is related to the aquaculture operations, i.e., it may be elevated with decreasing size of cages and increasing distances between cages. The ecological carrying capacity of a specific farming area is related to the total number of cages, i.e., related to the total oxygen consumption or waste production. In order to evaluate the ecological carrying capacity of the farming area of 84.7 km^2, hydrodynamic models of the middle Yellow Sea, including the farming area, are established and verified. The changes in the dissolved oxygen and total dissolved inorganic nitrogen simulated in respective cases of that 20, 40, or 60 cages are deployed in the farming area. The results reveal that when 60 cages are deployed, although the total dissolved inorganic nitrogen is still less than 0.2 mg/L, lower than the standard of Class I water quality, the dissolved oxygen level will be reduced from 7 mg/L to less than 6 mg/L, i.e., from Class I to Class II. Accordingly, it is considered that the deployment of 60 cages will be beyond the ecological carrying capacity of the farming area. In conclusion, the deployment of less than 40 cages in the evaluated farming area can meet the requirements of ecological carrying capacity of the farming area of 84.7 km^2.

12.2.4 Integrated Numerical Model

In 2004, Stigebrandt and other Norwegian experts developed the MOM (Modelling-Ongrowing fish farm-Monitoring) model system for the carrying capacity evaluation of marine fish cage farming. MOM model system is a comprehensive model including seven sub-models, i.e., fish model, dispersion model, benthic model, fish cage water quality model, water quality (Secchi depth) model of surface waters, water quality (oxygen concentration) model of basin waters, and the model of the natural flow of organic matter (Stigebrandt 2011).

MOM system defines that each of three conditions may determine the carry capacity of a specific fish farming area. The first condition is that beneath the cages there must exist living zoobenthos. The corresponding environmental quality standard (EQS) is that at least two living benthic species could be found beneath the cages. The maximal biomass in the cage fulfilling this condition is considered as the carrying capacity based on benthos (CC_{bent}). The second condition is that the water quality in the cages should be good enough for cultured fish. As for salmon and trout farming, the corresponding carrying capacity based on dissolved oxygen (CC_{O2}) is that the dissolved oxygen content should be higher than 5 mg/L or 60% saturation, and the carrying capacity based on UIA (CC_{UIA}) is that the UIA should be lower than 0.020 mg/L. The third condition is no unacceptable negative impacts on adjacent regional waters. The maximal biomass that fulfills this condition is considered as CC_{reg}. It is suggested that the Secchi depth should not be reduced by $>10\%$ due to anthropogenic eutrophication, and the minimum dissolved oxygen content in the farming basin water should be higher than 3.0 mL/L (Stigebrandt 2011).

CC_{bent}, CC_{O2}, and CC_{UIA} belong to the carrying capacity of local site or specific farming area. Note that such three estimates of carrying capacities are dependent on the farming methods, which means that they may be elevated with decreasing size of cages and increasing distances between cages. In contrast, CC_{reg} is the evaluation of carrying capacity in regional scale, i.e., the carrying capacity of a whole bay. CC_{reg} is related to the total farmed biomass and feed supply in regional scale. All four estimates of the carrying capacity including CC_{bent}, CC_{O2} CC_{UIA}, and CC_{reg} may be increased by means of optimizing feed ingredients and improving feed conversion efficiency.

12.3 Biofoulers and Antifouling of Farming Cage

Biofoulers are the general term for microorganisms such as algae and aquatic invertebrates that live on the surface of objects in water, resulting in biofouling of aquaculture facilities and subsequent impacts on the farmed fish and shellfish. It is estimated that approximately 5%–10% of aquaculture industry value is spent on dealing with biofouling-related problems every year (Dürr and Watson 2010). In addition, biofoulers seriously affect the commercial value of cultured shellfish products. Therefore, understanding biofouling and its effects can help farmers effectively clean up biofoulers on the surface of aquaculture facilities and farmed products, and hence reduce farming costs and improve product quality.

12.3.1 Biofoulers of Net Cages

After the aquaculture facilities are introduced into water, the biofoulers begin to colonize the surfaces of the facilities through succession. There are three alternative models of community succession: facilitation, tolerance and inhibition (Jenkins and Martins 2012). Whether a first arrival or a later biofouler survives in an aquaculture facility, it has some advantage in competing for resources, driving competitors away or eliminating them. In a Scottish sea loch in winter, accrual of extracellular polymeric substance, bacteria and pennate diatoms is followed by increased abundance of pennate and centric diatoms. After 6 weeks, biodiversity and abundance of diatoms is further increased and the first hydroids appeared after 8 weeks (Corner et al. 2007).

The main biofoulers on mariculture facilities include algae and sessile epibenthic organisms such as oysters, mussels, sea squirts, barnacles, hydra and bryozoa. All biofouling communities vary temporally and spatially. Cyanobacteria, diatoms and mosses are the main biofoulers on freshwater cages. In Western Europe, most fouling consists of algae, hydroids, serpulids, mussels, barnacles and ascidians (Dürr and Watson 2010). Allochthonous fouling species brought by waterflow such as the green algae *Enteromorpha* and brown algae *Sargassum*, usually occur on the farming facilities due to the blocking by cage net.

The biofoulers in aquaculture are related to the cultured species, structures and materials of facilities as well as farming site. High variability in types of material and their surface characteristics elevate the habitat diversity for various biofoulers. Hard biofoulers prefer to recruit to harder substrata, such as culture trays for scallops. However, algae and other soft biofoulers, such as ascidians, hydroids and sponges, tend to recruit to ropes and nets (Dürr and Watson 2010). The community structures of biofoulers show quite obvious difference between various farming sites and geographical locations. Even in the same site, the effects of light varying with water depth lead to substantial changes in the community structure of biofoulers. The effect of tide on the biofoulers on the fixed aquaculture facilities is quite significant. The facility parts that are permanently submerged in the water are generally colonized by more biofoulers than those frequently air-exposed. Aquaculture activities, especially feed supply, will increase the nutrients in the water and subsequent the biomass of biofoulers.

The vertical distribution patterns of biofoulers on aquaculture facilities are related to seasons, deploying time, geographical location, distance away from the shore, current velocity and eutrophic status. Besides the sessile species composition occurring in the surrounding water, the predominant factor influencing the vertical distribution patterns of algae on the facilities is the lighting condition. In the photic zone, numerous algae grow on the facilities. The lowest limit of water depth for algae occurrence is related to the water transparency, which is as shallow as only a few meters in coastal areas and up to tens of meters in offshore areas. In Scapa Flow, Scotland, for example, at 5 m depth the extensive biofouling community is dominated by red and green algae, erect hydroids, scallops, mussels, and encrusting barnacles and tubeworms. This community is greatly reduced at 10 m depth. Green algae are virtually absent, red algal cover is reduced, and erect colonial hydroids dominate the community (Dürr and Watson 2010). For the situation of the cage 'Deep Blue 1' in China, under the water depth of 20 m in the summer season, hydroid is the dominant species attaching on the cage net, impeding the water exchange between inside and outside of the cage.

12.3.2 Effect of Biofoulers on Cage Farming

Although biofoulers are beneficial or no harm for aquaculture in some circumstances, they are primarily deleterious to aquaculture (Fitridge et al. 2012). Three major negative effects of biofoulers on fish and shellfish farming include restriction of water exchange, deformation of cages, and disease risk.

12.3.2.1 Restriction of Water Exchange

For farmed aquatic animals, some degree of water exchange is required to achieve a sellable product. If fouling is high, costs of production increase due to reduced growth rate of farmed animals and increased cleaning and maintenance costs.

Biofoulers on the surface of the cage net impede the water exchange between outside and inside of cages and thus inhibit the growth of cultured fish and shellfish. The water exchange rate can be reduced by half or even more in case of the occurrence of abundant biofoulers (Gormican 1989). Because the surface/volume ratio of large net cage is relatively smaller, the impacts of biofoulers on its water exchange are more serious.

Water exchange efficiency of the farming cages or lantern nets directly affects the replenishment of dissolved oxygen and the elimination and dilution of metabolic wastes inside the cages and lantern nets. For Atlantic salmon farming, it is better to keep the farming water quality as dissolved oxygen higher than 7 mg/L. Dissolved oxygen lower than 5 mg/L will lead to the reduction in the feed intake rate and growth rate of the fish. In the worse cases, dissolved oxygen level below 2 mg/L will threaten the fish survival. Frequent net cleaning to prevent the mesh blocking by biofoulers is one of the most important routine management measures for cage or lantern net farming.

12.3.2.2 Deformation of Cages

The degree of deformation of the cages is related to current velocity, cage structure, counterweights, cage type and the biomass of biofoulers. Drastic weight increase of net cages is one of the most important issues with biofouling in finfish and shellfish farming. Biofoulers can increase the net weight up to 200 times (Beveridge 2004), which significantly affects the routine management of the cage. The presence of mussels and hydroids on the net increases the horizontal drag forces on cage netting up to three-folds or the drag coefficient by up to 900% (Swift et al. 2006).

Strong currents can significantly cause the deformation of net cages. The effective volume of the cage will be reduced by 45%–80% at a flow velocity of 0.5–1.0 m/s unless the counterweights are substantially increased (Fitridge et al. 2012). A highly deformed net cage can increase structural stresses at specific points of the cage and lead to material fatigue of cage systems. Therefore, when designing the floatation and mooring systems of farming cages, the increased load due to biofoulers should be considered.

12.3.2.3 Disease Risk

Pathogens that live with biofoulers on cages raise the disease risk of the farmed fish. Parasites which temporarily perch with biofoulers might infect farmed fish when the fish is not healthy enough. *Neoparamoeba pemaquidensis* which causes gill disease of salmon, for example, lives on bryozoa and sea squirt. If any farmed fish is not in a healthy condition it will be susceptible to disease. There are many viruses that are isolated from bivalves and identified as finfish pathogens (Fitridge et al. 2012). In addition, a number of bacterial agents that cause disease in finfish are common in bivalve tissues (Dürr and Watson 2010).

Some biofoulers associated with farming cages are also the intermediate hosts of a part of fish parasites, such as *Gilquinia squali* and *Cardicola forsteri*. The former implicates in the deaths of Chinook salmon smolts (Kent et al. 1991), and the latter is a major blood fluke pathogen of southern bluefin tuna (Cribb et al. 2011).

12.3.3 Antifouling of Net Cages

Biofoulers lead to poor water exchange between outside and inside of cages, increased cage deformation and disease risk, etc. Therefore, antifouling is extremely important to improve the safety and efficiency of fish and shellfish farming. Aquaculture is an industry which produces aquatic food products for human, thus, the prevention of biofoulers in aquaculture must be based on food safety. Commercially used approaches for antifouling include net changing and cleaning, chemical antifoulants and biological antifouling.

12.3.3.1 Net Changing and Cleaning

Cage farming needs to change or clean the netting frequently. However, frequent net changing and cleaning increase the damage or loss of farmed animals, and disturb their feeding regimes. The frequency of cleaning and changing netting is from a few days to a few weeks depending on numerous factors such as water quality, materials of netting, mesh sizes, cage depth, farmed species and sizes. The larger the mesh size is, the longer the time it takes for biofoulers to clog the meshes, and hence the lower frequency for net cleaning. Cleaning methods which commonly used include scrubbing manually by divers, washing by high-pressure water hoses or automatic washing machines. If biofoulers are only distributed on the upper part of the cage for a few meters, the upper part of the cage could be lifted out of the water for a period of time to kill the biofoulers.

In addition, the season and timing of cleaning netting are also very important. It is necessary to adjust the frequency and intensity of net cleaning according to the reproductive peaks of dominant fouling species and the seasonality of larval settlement in different marine areas. For instance, in temperate sea areas including northern China, the peak of reproduction and larval settlement of most marine invertebrates is concentrated in spring. Therefore, it is necessary to increase the frequency of net cleaning from March to June. Effective management for anti-settlement in spring will reduce the corresponding workload for antifouling in summer. In autumn, there will be a smaller peak of reproduction from October to November in some temperate zones than that in spring. During this period, management for anti-settlement of biofoulers should hence be strengthened appropriately.

12.3.3.2 Chemical Antifoulants

Copper is toxic, even at moderately low concentrations, particularly to the larval stages of invertebrates. As such, net coated with copper can effectively prevent the settlement of larval biofoulers. Treated nets provide a measure of protection for many months although the degree of protection declines rapidly after 6 months or so. In temperate regions nets may have to be treated each year, newly treated nets being installed in April–May to give protection over the summer months when larval settlement is greatest. The cost of treatment can add from 20% to 25% to the cost of a knotless nylon cage net (Beveridge 2004). Copper leaching from impregnated nets into the water column elevated copper concentrations of inside treated salmon pens have been recorded after net installation (Thomas and Brooks 2010).

Although it is believed that copper cannot be accumulated in the muscle or liver of some farmed fish, it is desirable that fish fingerlings are released a month after farming cages are deployed if copper-coated net is used. In addition, copper-coating net also imposes influences on benthic organisms in cage farming area. In recent years, copper alloy net is adopted for cage construction whereas the ecological effects of copper alloy net are not well understood to the present.

Based on the consideration of clean production and green products, the use of net with copper coating is decreasing, especially in European Union (Fitridge et al. 2012). Copper or zinc coating for aquaculture facilities has been prohibited in numerous countries which have called for the development of non-toxic coating materials. Before non-toxic, economical and efficient coatings are widely utilized, mechanical cleaning and biological antifouling should be the first choice for antifouling in cage farming.

12.3.3.3 Biological Antifouling

Co-culture of herbivorous or omnivorous fish or species predating pest as antifouling species in farming cages can effectively remove fouling organisms attached on the net. The antifouling animals can be introduced into finfish and shellfish farming cages for antifouling (Dürr and Watson 2010; Fitridge et al. 2012). Due to the food preference or selectivity of antifouling animals, the fouling organisms that are not edible for the animals will not be removed from the nets effectively. Therefore, only the antifouling animals with a broad dietary spectrum can be used as successful control agents. Co-culture of such fish and invertebrates can only reduce the frequency of net cleaning or changing, but cannot completely solve the problem of the biofouling of the net.

New antifouling products with a focus on non-toxic coatings, non-leaching biocides, and fouling-release technologies based on low-surface energy coatings, texturing, and surface-bound compounds could be developed (Dürr and Watson 2010).

Brief Summary

1. Aquaculture net cage is usually a kind of box-shape facility for holding or farming aquatic animals in marine or fresh waters. The use of simple cages made of cotton, linen and bamboo for fish farming in China has a history of more than 2000 years, while modern cages with the nets made of artificially synthetic fibers and/or metal alloys originated from Japan, Norway and the United States in 1950s and 1960s. Since the introduction of modern cages in China in the 1970s, cage farming has been rapidly promoted in reservoirs, lakes, rivers and bays in China, which greatly expands the aquaculture water areas in China.
2. Based on the floating status of the cages in the water column, aquaculture cages can be classified into fixed cages, floating cages, semi-submersible cages and submersible cages. Based on the methods to maintain the net shape, the cages can be classified into gravity cages, anchor tension cages, semi-rigid cages, rigid cages and so on. Based on the distance away from the seashore and water depth,

the cages can also be classified into coastal cages, off-the-coast cages and offshore cages. Based on the farming species, the cages can be classified into pelagic fish cages, benthic fish cages, sea cucumber cages, abalone cages and so on.

3. Advantages of cage farming include expansion of the aquaculture water areas, improvement of product quality, easier to manage, reduction in the metabolic rate of farmed animals and subsequent elevated growth rate, avoidance of harm from predators or parasites, and convenience to realize mechanization and intellectualization.
4. Different from the carrying capacity evaluation for small-scale inland waters, the evaluation of carrying capacity for farming cages of fish in open sea areas should take hydrodynamics into full consideration. Because the diet of farmed fish in the cage is dominantly artificial feed, the factors that restrict productivity are environmental factors rather than the factors of nutrition or natural feed organisms. For cage farming of fish, important environmental factors include dissolved oxygen content, un-ionic ammonia, organic matter content in sediment, etc. At the present, the evaluating methods widely adopted include simple models, particle tracking models and numerical models. Evaluation with simple models is a static method which is easy to use with relatively lower accuracy and limited information provided. Complex models involve not only hydrodynamic information but also spatial and temporal variations.
5. CC_{bent}, CC_{O2} or CC_{UIA} belong to the carrying capacity of local waters, i.e., those of a specific site or farming area, which are also dependent on the farming methods, such as cage size and distances between cages. In contrast, CC_{reg} is the evaluation of carrying capacity in regional scale, i.e., the carry capacity of a whole bay. CC_{reg} is related to the total farmed biomass and feed supply in regional scale. All four estimates of the carrying capacity including CC_{bent}, $CC_{O2,}$ CC_{UIA} and CC_{reg} may be increased by means of optimizing feed ingredients and improving feed conversion efficiency.
6. Biofoulers are the general term for microorganisms such as algae and aquatic invertebrates that live on the surface of objects in water, resulting in biofouling of aquaculture facilities and subsequent impacts on the farmed fish and shellfish. Biofoulers in aquaculture are related to the farming species, materials and structure of farming facility as well as farming site.
7. The vertical distribution of biofoulers on the aquaculture facilities is related to seasons, cage deploying time, geographical location, distance away from seashore, current velocity and the eutrophic status. The deepest limit of algal occurrence is related to the water transparency of the farming area, which might be as shallow as few meters in nearshore waters and up to tens of meters in offshore waters. Below the photic zone the dominant marine biofoulers are often colonial hydroids.
8. Although there are circumstances where biofoulers are beneficial, or at least, do not affect production, biofoulers are primarily harmful to cage farming, such as blocking net meshes of cages and hence impeding water exchange, consuming

dissolved oxygen in water column, increasing the disease risk and deformation of cages.

9. Antifouling in aquaculture must be based on food safety. Commercially used approaches for antifouling include net changing and cleaning, chemical antifoulants, and biological antifouling.

13 Health Maintenance and Welfare of Aquatic Animals

Shuang-Lin Dong and Yan-Gen Zhou

Given the positive correlation between the environmental quality and the health of the farmed animals in aquaculture waters, one of the core tasks of aquaculture management is to enhance the health of cultured aquatic animals by improving water quality, to reduce, alleviate, or even eliminate the occurrence of certain diseases for higher breeding efficiency and safer aquatic products.

13.1 Health Maintenance of Aquaculture Animals

Health maintenance is a concept in which animals are cultured under conditions that optimize the growth rate, feed conversion efficiency, reproduction, and survival while minimizing problems related to infectious, nutritional, and environmental disease, all within an economical context (Plumb and Hanson 2011). Health maintenance does not simply target infectious diseases; instead, it involves the entire process of aquaculture activities for the purpose of improving the health of cultured aquatic animals and efficient production of healthy aquatic products through production management. As culture becomes more intensive, need for intervention increases accordingly, and principles of health maintenance become of greater importance.

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13.1.1 Environment Degradation in Relation to Disease Occurrence

Aquaculture animals' diseases are often attributed to the hostile water environment, particularly the low dissolved oxygen which causes fish infection. In the process of pond culture, the outbreak of the algal bloom often deteriorates water quality, as represented by the decline of dissolved oxygen (DO) and pH, and rise of NH_3 and CO_2. For example, when DO falls below 1 mg/L channel catfish will suffocate successively. In beginning, no bacteria are isolated from internal organs or skin–muscle lesions of these fish, but 2 days later and for several days thereafter, *Aeromonas hydrophila* is isolated from both. When freshwater is added to the pond, mortality ceases and clinical signs of infectious disease abate (Plumb and Hanson 2011). This disease is called low dissolved oxygen syndrome (LODOS), which well illustrates how the disease is caused by the interaction among culture environment, host, and pathogen. Therefore, when investigating the cause of a disease in farmed animals, one should not simply look for the pathogen, but also for environmental triggers.

$D = H(P + E^2)$ describes the relationship of environment (E), host (H), and pathogen (P) in disease occurrence (D) (Plumb and Hanson 2011). Under the preconditions of pathogen existence and host's low immunity, disease outbreak is often triggered by the bad aquaculture water environment (Fig. 13.1).

The pathogenicity of pathogens is related to the infectiousness, virulence, and viability of the pathogen. Host susceptibility is related to species, age, nutritional status, stocking density, etc. The main environmental factors that trigger disease include temperature, DO, CO_2, pH, NH_3, salinity, etc.

The synergistic effect of environmental factors often aggravates the effect of a particular environmental factor on farmed animals, such as that of DO, CO_2, pH, NH_3, and other factors working together on the hypoxia syndrome that causes the death of farmed fish. With sufficient DO, channel catfish can tolerate CO_2 at 20–30 mg/L. But when the DO is low, fish cannot excrete CO_2; and sublethal CO_2 concentration can cause fish coma and death (Boyd 1990).

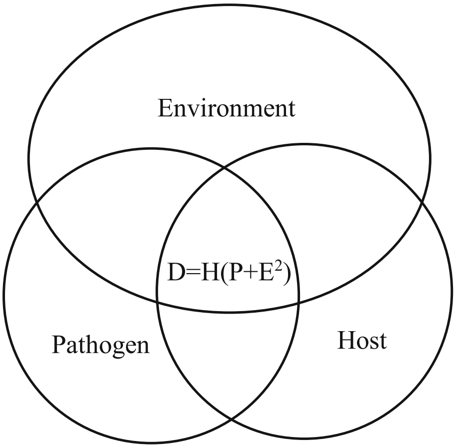

Fig. 13.1 Infectious agents (P), host (H), and environment (E) in relation to disease occurrence (D)

13.1.2 Environmentally Induced Diseases

Aquaculture animals can neither live in chemically pure water, nor in water filled with debris. Fish can adapt to a wide range of water quality parameters, of which, however, only a narrow range is optimal for its health or growth, varying with species and strains (Table 13.1). Fish exposed to extreme water conditions will either gradually adapt or become diseased and die. Environmentally induced diseases are diseases that occur in farmed organisms exposed to extreme water quality conditions.

Native fish can normally adapt to the water quality parameter changes caused by seasonal change in local aquaculture. Some favorable changes can promote fish growth by promoting its growth and gonad development. However, a rapid change in the water conditions, which the farmed fish are unable to adapt, may cause environmentally induced diseases. For instance, heavy rainstorms may dilute the salinity of mariculture ponds, and an abrupt drop of the salinity can lead to the death of farmed stenohaline animals. In China, there have been reports of mass mortality of sea cucumbers in mariculture ponds after heavy rains. The suspended matters brought by the rainstorm can also damage the gill filaments of farmed fish. In addition, seawater intrusion caused by storm surges often result in the death of farmed fish in freshwater ponds.

13.1.2.1 Water Temperature

Almost all aquaculture animals are ectothermic, subject to the temperature changes of the aquaculture water in metabolic intensity, growth rate, reproduction, and even survival. The temperature range favoring reproduction is narrower than that for

Table 13.1 Water quality criteria for optimum health management of cold-water and warm-water fish (mg/L except for pH) (from Plumb and Hanson 2011)

Criteria	Cold water fish	Warm water fish
Dissolved oxygen	5–saturation	5–saturation
pH	6.5–8.0	6.5–9.0
Un-ionic ammonia	0–0.125	0–0.02
Calcium	4–160	10–160
CO_2	0–10	0–15
H_2S	0–0.002	0–0.002
Total iron	0–0.15	0–0.5
Manganese	0–0.01	0–0.01
Nitrate	0–3.0	0–3.0
Phosphorus	0.01–3.0	0.01–3.0
Zinc	0–0.05	0–0.05
Total hardness ($CaCO_3$)	10–400	10–200
Total alkalinity ($CaCO_3$)	10–400	10–400
Nitrogen (gas saturation)	$<100\%$	$<100\%$
Total solids	0–80	50–500

growth and survival (Table 5.4). The natural distribution of aquatic animals is primarily governed by their reproductive or hatching temperatures, that is, the temperature at the boundary of their natural distribution is usually their critical temperature for reproduction or hatching. The impact of water temperature on the growth of farmed animals is introduced in Sect. 5.2 of this textbook. The temperature threshold that causes disease in aquatic animals is close to the threshold of survival or tolerance. The same is true for other water quality parameters.

The temperature tolerance of carps ranges from nearly 0 °C to more than 30 °C. It is common that different geographic populations of the same species are varied in temperature tolerances, and long-term exposure to given temperatures is harmful, though not immediately lethal. For instance, the fancy carp that are exposed to extreme temperature changes chronically show signs of thermal stress, such as a thin body with a concave outline to the dorsal surface (Hoole et al. 2001).

Fish that are exposed to high temperatures may suffer respiratory stress and nervous activity. Warmer water contains less DO, however, the fish in it require more DO for their metabolism. In addition, with the increasing of water temperatures the toxicity of certain pollutants, such as heavy metals and ammonia, is also increasing.

Low temperature may compromise fish's immune system, making it more susceptible to certain bacteria and fungi, like overwintering cyprinids to pseudomonas infection. Low temperatures can directly cause respiratory stress and coma. Behavioral signs associated with hypothermia include lowered respiratory rate and loss of swimming co-ordination.

13.1.2.2 Dissolved Gases

The atmosphere is composed of nitrogen (78%), oxygen (21%), and other gases (1%), but their concentrations in water are 1/20 or 1/30 of those in the air, varying greatly with the temperature, salinity, altitude, and biological activities of local waters (see Sect. 2.3 for detail).

Oxygen requirements vary greatly among fish species and size. Normally, the species are accustomed to high DO in cold water, streams, and seawater environments. For instance, common carp are tolerant to low DO and can survive at DO levels as low as 0.7 mg/L in organically rich waters. DO requirements of warm-water fishes are >2 mg/L, while those of cold-water fishes are >5 mg/L (see Table 4.1). More attention should be paid to the problem of hypoxia in the aquaculture waters in summer, especially when water temperature is maintained by heating equipment. Overcrowding of fish and over-feeding or high levels of organics can also cause hypoxia in the water.

Fish have developed its own regulating mechanism for hypoxia tolerance by increasing their efficiency in utilizing oxygen from the blood, by increasing the density of mitochondria within their red muscles (Hoole et al. 2001). When the DO in the water drops rapidly below the critical point, fish will gulp at the water surface. Chronic hypoxia is not necessarily lethal to farmed fish but may affect growth and increase the susceptibility to diseases.

The dissolved gas in the water may also become supersaturated. Fish exposed to this supersaturated water are at risk of ‘gas bubble disease’ (GBD). GBD of fish occurs sometimes at noon in summer when the pond is supersaturated with DO due to the intensive photosynthesis of aquatic plants or phytoplankton. It is also common when nitrogen is oversaturated at waterfalls, discharged water at hydropower stations, and sudden decompression of water in deep wells. Sometimes gas supersaturation occurs in ponds or tanks when aerators work vigorously and the sudden heating of gas-saturated cold water. It is generally believed that gas saturation over 110% is likely to damage the health of fish.

In acute cases of GBD, the fish may exhibit impaired or unnatural swimming behavior. In severe cases, GBD can lead to death within a few minutes. In both acute and chronic cases, gas bubbles may be observed within the eyes of exposed fish (Hoole et al. 2001). Fish affected with GBD are not treatable, however, recovery is possible in chronic situations where the cause of gas supersaturation is removed.

13.1.2.3 pH

The pH is generally 4–10 in natural inland water and 8–8.5 in seawater, lower or higher in special water bodies. The pH is 5.6 in normal rainwater, but can be as low as 4.0 in heavily polluted areas where the rain is known as acid rain. The pH of rainwater remains acidic after the acid rain flows over the basin poor in buffering capacity (poor in alkaline salts, such as granite), forming an acidic stream. The toxicity of various pollutants may be influenced by pH.

Farmed aquatic organisms usually adapt well to the water environment of pH 6.0–8.5. Pond water is mostly acidic in coastal areas rich in humus and pyrite (FeS_2) or other sulfide soils (see Sect. 8.1). The enclosed aquaculture waters also tend to be weakly acidic as a result of the metabolic activities of the aquaculture organisms and the decomposition of organic matter. The fish suffering chronic low-pH (acidosis) do not show obvious symptoms except retarded growth. Typical of the acute acidosis are hyperactive and nervous, and there is hyperproduction of gill mucus in response to the acid conditions, causing the fish respiratory problems. Low pH also increases the toxicity of some heavy metals.

The pH is higher in some aquaculture waters, such as the ponds in saline-alkali soil area (see Sect. 11.2.1), the newly constructed concrete tanks, and the ponds in which quicklime has been lately applied. Intensive photosynthesis of aquatic plants or phytoplankton can significantly promote the pH of aquaculture waters, especially in the pond poor in buffering capacity. A fish that is exposed to a pH higher than its tolerance range may exhibit clinical disease (alkalosis), which may take the form of rotten fins, blindness, muscle ulcers, and gangrene. In cases of acute alkalosis, the fish’s skin and gill epithelia will be damaged and become cloudy in appearance. High pH will also boost the proportion of highly toxic un-ionic ammonia (NH_3) in total ammonia.

13.1.2.4 Nitrogen-Containing Metabolites

Ammonia is the most toxic of the nitrogenous wastes and can be acutely lethal to fish under certain conditions. Aquaculture waters often contain a certain amount of ammonia excreted by farmed animals. In an aerobic environment, the nitrifying bacteria can turn the ammonia into low-toxic nitrite and nitrate. Ammonia can be highly concentrated in aquaculture waters contaminated by domestic sewage. The tolerance of farmed animals to ammonia varies with species and individuals (see Sect. 3.2).

Fish exposed to toxic levels of NH_3 may develop osmotic regulation problems and respiratory difficulties. Fish are sensitive to NH_3 toxicity at low DO content and high pH. Exposure to chronic sublethal levels of NH_3 can hinder the growth of farmed fish and increase their susceptibility to diseases. Typical of the acute intoxication are loss of balance and higher frequency of respiration. The solution to NH_3 toxicity is reducing NH_3 concentration by exchanging water, improving biofiltration, reducing the level of organic wastes, and so on.

When aquaculture water is not well nitrified, NO_2^- will accumulate, which may poison the farmed animals in severe cases. NO_2^- at high concentration in the water environment may cause hypoxia as it enters blood through gills and affects the oxygen-carrying capacity of hemoglobin. Affected fish may show behavioral symptoms of increased gill beat rate and gulping at the water surface. Chronic exposure to sublethal NO_2^- levels has been linked with increased susceptibility to bacterial infections. Changing water or improving the efficiency of biofilters is the best solution to such problems. Adding 100 mg/L salt to the water can somewhat alleviate NO_2^- toxicity (Hoole et al. 2001).

Under aerobic conditions, NO_3^- is the final metabolite of nitrogenous compounds widely present in waters and groundwater contaminated by agricultural fertilizers. Although NO_3^- is not very toxic to farmed fish, high concentration of NO_3^- can slow down fish's growth, impair immunity, and make it more susceptible to infectious diseases. High concentration of NO_3^- is common in circulating aquaculture systems poor in denitrification.

13.1.2.5 Other Pollutants

There are more pollutants affecting farmed animals, like domestic sewage, fertilizers, pesticides, petroleum, heavy metals, and sometimes harmful algal blooms. Please see Sect. 4.2 for their impact on aquaculture and farmed animals.

13.1.2.6 Water Quality Standard for Fisheries

Many countries and regions have formulated water quality standards for fisheries. The US Environmental Protection Agency (EPA) publishes National Recommended Water Quality Criteria for aquatic life, human health, and nutrients. EU Water Directive 78/659/EEC sets out the water quality standards for freshwater fisheries and shellfish culture. China has developed the *Water Quality Standard for Fisheries* (Table 13.2) to prevent and control water pollution in fisheries waters for the growth, reproduction, and quality of aquaculture products such as fish, shrimp, mollusks, and algae. This standard is applicable to both seawater and freshwater bodies for fisheries and aquaculture, such as spawning grounds, feeding grounds, overwintering grounds, migration channels, and stock enhancement zones. The values of the

Table 13.2 Water quality standard for fisheries of China (GB 11607–1989)

List	Items	Standards	List	Items	Standards
1	Color, odor, taste	Must not cause fish, shrimp, shellfish, algae to different color, odor, or taste	18	Fluoride (as F)	≤1
2	Floatable substance	No visible oil film or foam on the water surface	19	Un-ionic ammonia	≤0.02
3	Suspended matter	Artificially increased amount must not exceed 10, and the suspended matter must not harm the fish, shrimp, and shellfish after depositing on the bottom	20	Kjeldahl nitrogen	≤0.05
4	pH	Freshwater 6.5–8.5, seawater 7.0–8.5	21	Volatile phenol	≤0.005
5	DO	In consecutive 24 h, it must be greater than 5 for more than 16 h, and not less than 3 at any time during the rest of the period; for the salmonid habitat it must not be less than 4 at any time during the rest of freezing period	22	Yellow phosphorus	≤0.001
6	BOD	No more than 5, during freezing period no more than 3	23	Petroleum	≤0.05
7	Total coliforms	No more than 5000 ind./L (no more than 500 ind./L for shellfish aquaculture waters)	24	Acrylonitrile	≤0.5
8	Hg	≤0.0005	25	Acraldehyde	≤0.02
9	Cd	≤0.005	26	666 (C-type)	≤0.002
10	Pb	≤0.05	27	DDT	≤0.001
11	Cr	≤0.1	28	Malathion	≤0.005
12	Cu	≤0.01	29	Santobrite	≤0.01
13	Zn	≤0.1	30	Dimethoate	≤0.1
14	Ni	≤0.05	31	Methamidophos	≤1
15	As	≤0.05	32	Methylamine parathion	≤0.0005
16	Cyanide	≤0.005	33	Carbofuran	≤0.01
17	Sulfide	≤0.2			

Note: The units of parameters in the table are mg/L except for pH and the total quantity of *Escherichia coli*

criteria in Table 13.2 refers to the highest allowable one measured for a single item. Exceeding the standard value of a single item means that the normal growth and reproduction of fish, shrimp, and mollusks cannot be guaranteed.

The standard stipulates that any enterprises, institutions, and self-employed persons that discharge industrial wastewater, domestic sewage, and hazardous waste must take effective measures to ensure that the water quality of the nearest fisheries and aquaculture waters meet this standard. For details of these factors, please refer to the *Chemistry in Aquaculture Water Environment* edited by Lei (2004).

13.1.3 Health Maintenance of Farmed Fish

Health maintenance of farmed fish involves the entire process of aquaculture: the location and construction of a culture facility; selection and introduction of culture species; and reproduction, culture, and harvesting of the final product (Plumb and Hanson 2011). Efficient production of safe aquatic products depends on the health of the farmed animals improved by maintaining good water quality, staying away from infectious pathogens, and feeding complete formula feed.

13.1.3.1 Site Selection of Fish Farms

Successful aquaculture depends to a large extent on the site selection which mainly includes land topography, soil quality, water quality and abundance, and proximity to the market. To maintain a healthy fish stock, farmed species, soil quality, and water quality must be compatible. Indigenous fish species should be preferred, and farming an introduced species sometimes entails additional costs. For example, cultivating tropical fish in the north or cold-water fish in the south requires heating or cooling water, which can increase the cost in aquaculture unless the source of warm or cold water from the industries, geothermal water, or underground water is available.

Pond soil quality not only affects pond water seepage conditions but also water quality. Acid is typical of the pond water in coastal soil rich in humus, pyrite (FeS_2), or other sulfide; and alkalinity is typical of the pond water in salt-alkali soil (see Chaps. 8 and 11). Too acidic or too alkaline water has some effect on farmed animals. In the perspective of disease prevention, both spring water and well water are better than surface water (river, lake, reservoir, etc.). But sometimes readjustment has to be made on the inappropriate indexes of spring and well water such as carbon dioxide, nitrogen, pH, iron content, temperature, etc. The water quality of aquaculture waters should meet the requirements for fish health and fisheries (see Tables 13.1 and 13.2). If the water is sourced from the surface water, effort must be made to prevent pathogens, harmful organisms, and pollutants from entering the aquaculture waters.

13.1.3.2 Avoiding Exposure to Infectious Pathogens

The ideal way to control infectious fish disease is to prevent exposure to pathogenic agents whenever possible, thus avoiding most devastating health problems through biosecurity. To avoid farmed fish stock exposure to certain infectious diseases, it is necessary to start with ensuring that the water source and the stocked fry are free of specific pathogens (SPF) and destroying fish stocks that have become infected with specific pathogens. All Nordic countries have established coordinated surveillance and monitoring systems for fish diseases of concern to the fish farming industry. The ultimate goal of the program is to eradicate or keep the level of disease to a minimum. Diseases included in the surveillance are viral hemorrhagic septicemia, infectious hematopoietic necrosis, infectious pancreatic necrosis, viral nervous necrosis, bacterial kidney disease, and furunculosis. According to the authors, due to these surveillance systems coupled with good management practices the fish disease situation in the Nordic countries is generally good compared to other countries of the world (Plumb and Hanson 2011).

The imported aquatic products are required to be quarantined in more and more countries, of which some developed ones have made laws and regulations to restrict the free transfer of fish to secure its health. Quarantine is an approach to disease avoidance when fish are moved from one area to another. Fish should be isolated for a specific period of time before contact with a resident stock. If disease develops in newly arrived animals, it can be dealt with more effectively and without exposing resident stocks.

In 1989, an attempt was made to prevent establishment of viral hemorrhagic septicemia virus (VHSV) in the United States by destroying adult salmonids as they returned to spawn at two sites in the Pacific Northwest where the virus had been found. This constituted the first confirmed VHSV occurrence outside Europe and so these drastic measures appeared to be justified. Unfortunately, in subsequent years, the virus was found in different areas of the northwestern United States (Plumb and Hanson 2011). Some viruses, such as infectious pancreatic necrosis virus (IPNV), have an intermediate host of waterfowl, and the virus infects fish after passing through the digestive tract of the bird. Therefore, the measures to prevent some infectious diseases should not be limited to water alone.

Some pathogens are facultative and opportunistic pathogens, and can coexist without disease unless the fish’s immune system or other defensive mechanisms are compromised. *Aeromonas hydrophila*, the pathogen of motile *Aeromonas* septicemia (MAS), exists in freshwater rich in organic matter worldwide. MAS only occurs when fish have suffered some mechanical or biophysical injury, and when the bacterial numbers overwhelm the fish’s resistance.

Epidermal and gill parasitic diseases also usually develop when the environment has deteriorated to a certain extent. Therefore, the most effective way to prevent them is exchanging water so as to reduce organisms and pathogens in the water bodies. Prophylactic treatments after fish are handled will aid in healing superficial wounds and in reducing bacterial populations on the skin. For diseases caused by facultative and opportunistic pathogens, ecological and nutritional disease prevention should be the top priority.

In managing obligate pathogen-induced aquatic diseases (viruses, some bacteria, and most parasites), initial consideration is given to the pathogen source in the culture system. To deal with these pathogens, a strategy of quarantine and segregation should be adopted. Diseased fish can transmit the disease to fish in contact with them through epidermal mucus; therefore, controlling the stocking density can reduce the extent of such diseases. Fish can also become ill by ingesting intermediate hosts containing pathogens or fresh bait fish with bacteria or parasites. For some parasitic diseases in which waterfowl are the intermediate hosts, covering the culture ponds and tanks with nets can effectively prevent the occurrence of the disease. It is very important to select SPF brood stock for hatchery as some pathogens can be transmitted vertically through eggs or milt in reproduction. Pathogens are often brought into the farm by means of carriers or visitors; therefore, vehicle disinfection and disinfection of the soles of visitors' shoes should be institutionalized.

Some pathogenic bacteria are host-specific, such as *Aeromonas salmonicida*, meaning that they are not pathogenic to aquatic animals of all species and all ages. In that case, quarantine and segregation can reduce the spread of such diseases. The reduction can also be achieved by cultivating the species or strains that are not or less sensitive to specific pathogens in the epidemic areas. Salmon and trout younger than 3 months are susceptible to infectious hematopoietic necrosis virus (IHNV), especially at 10–17 °C. Thus, if fish can be cultured in water above 17 °C, effects of disease are minimized.

In the past, growth rate was the main consideration for new fish breed selection traits, but now people are also starting to consider disease resistance as an important or major indicator for breed selection and genetic manipulation of hatchery, with some success.

13.1.3.3 Nutritional Diseases

Proper nutrition is essential for survival, growth, and reproduction of farmed fish. Fed fish in an aquaculture system obtains all or most of its nutrition from feed, therefore, feeding a complete formula feed is the basis for healthy farmed fish. A deficiency of any type of nutrients can affect fish health and reduce the resistance of farmed fish to disease. Injury to the spinal column of channel catfish (broken-back syndrome) results from a vitamin C deficiency. Insufficiency of riboflavin may cause eye cataract in rainbow trout. A niacin deficiency increases sensitivity to ultraviolet irradiation and 'sun burn' on fish in clear water. Nutritional gill disease of trout is caused by a pantothenic acid deficiency and can progress into bacterial gill disease if the deficiency is not corrected. Also, severe anemia in channel catfish is linked to dietary deficiency of folic acid or presence of the folic acid antagonist pterotic acid (Plumb and Hanson 2011). Lack of some elements in the feed makes fish more susceptible to diseases.

It has been found that fish fed to satiation are more susceptible to diseases than those lightly fed. For example, the susceptibility of channel catfish to virus disease (CCVD) is decreased following starvation for 2 weeks. Taking channel catfish off feed when enteric septicemia of catfish (ESC) occurs has been practiced throughout the catfish industry in the United States. To what degree nutrition affects disease resistance in fish remains unclear. When water quality becomes critical with high organic fertility and low DO, reduced feeding can hasten a reversal of this trend; therefore, flexibility in feeding can be a valuable tool in aquaculture management (Plumb and Hanson 2011).

13.1.3.4 Prevention Outweighs Treatment

Fish health maintenance program should be started in parallel with aquaculture production, even at the time of facility establishment, not just when disease outbreaks occur. Often a chemical can be added to water and/or an antibiotic incorporated into feed, which will result in a positive response and cessation of mortality. However, the effect of these treatments may be temporary and disease may reoccur unless a commitment is made to seek and eliminate all predisposing disease factors.

Pond patrol (mainly observing fish feeding, movement behavior, and water color) is the daily routine for health care of fish. When you find a sudden decrease in fish intake, it means that there is something wrong with the fish themselves; if you find a sudden change in the water color of the pond, it means that there is something wrong with the water quality. At this point, you should be highly alert, as soon as possible to identify the cause, and take appropriate measures. Real-time monitoring of dissolved oxygen in farmed water and determination of trends is also a daily task of fish health care.

Based on food safety considerations, it has become a consensus that every effort should be reached to reduce the use of antibiotics in aquaculture production. Therefore, maintaining a clean environment and good water quality has become the most important aspect of fish health maintenance, for example, frequent water changes, continuous maintenance of dissolved oxygen in the water, timely removal of dead fish, annual dredging and lime disinfection of ponds, and keeping the environment clean and production tools hygienic.

13.2 Regulation of Bacterial Community in Aquaculture Waters

The quantity of bacteria in farmed water is related to its organic load, and the quantity of bacteria is often higher when the organic load is higher, such as applying organic fertilizers and feeding large amounts of feed. In the practice of aquaculture, people often want cleaner water with less microorganisms, so whether it is a closed recirculating aquaculture system or a pond, people often use various methods such as water exchanges and disinfecting to reduce the quantity of bacteria in the water. In fact, these methods are also a double-edged sword.

Activities such as water change and disinfection in aquaculture production systems are a disturbance to the microbial community, which can cause a rapid decrease in the quantity of bacteria in the water. After water exchange, the quantity of bacteria will gradually recover with the residual feed and feces accumulated during feeding. After water disinfection, the bacteria will also gradually increase after a sudden drop until they reach a level compatible with the organic load of residual feed and feces.

Some bacteria in the aquaculture water are harmless, some are beneficial, to farmed organisms, and others are pathogenic, and can infect the farmed organisms. Bacterial species can be classified as *r*-selective strategy species and *K*-selective strategy species. Nutrient-rich, resource-competitive, and variable environments favor species with rapid population proliferation and high capacity for resource utilization, i.e., *r*-selective species, also called opportunity species. Conversely, nutrient-poor, resource-competitive, stable environments are more favorable to species with slow population proliferation *K*-selective species. It can be seen that

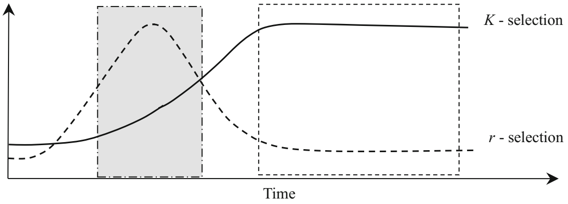

Fig. 13.2 Microbial succession in aquaculture water and solutions to minimize exposure of animals to opportunist bacteria (from Schryver and Vadstein 2014; Sorgeloos 2018)

aquaculture water bodies with frequent water exchanges and disinfection or those that have just started feeding are more favorable to *r*-selective bacterial species.

Figure 13.2 shows the succession pattern of bacterial communities in aquaculture waters. It can be seen that after disturbance, the bacterial community first develops rapidly with *r*-selective strategy species, followed by *K*-selective strategy species, and finally forms a stable community with a high quantity of *K*-selective species and a low quantity of *r*-selective species. The pathogenic bacteria are mostly *r*-selective strategy species, and they have a strong impact on juvenile fish and individuals of farmed organisms under environmental stress (Schryver and Vadstein 2014).

According to the *r*/*K* selection theory and the succession law of bacterial community in aquaculture waters, the larvae and fingerlings should be stocked when the *K*-selection bacteria approach or reach the peak in the water (the right box in Fig. 13.2), rather than soon after water exchange or disinfection (the left shaded box of Fig. 13.2) to avoid infecting pathogenic *r*-selection strategy bacteria. In addition, minimizing disturbances in the culture water, such as minimizing the frequency of disinfection and water exchanges, is also an effective way to reduce bacterial disease.

To reduce risks of infecting pathogenic *r*-selection strategy bacteria, the new water should be matured or incubated in the pretreatment tank or pond for a period of time to allow the *K*-selection species to develop first before being pumped into the aquaculture waters. Some experiments have shown that water exchanges using pre-matured water maintain stable microbial community in the aquaculture water and increase the survival rate of Atlantic cod juveniles by 65% to 70% (Attramadal et al. 2014). The relationship between changes in microbial diversity caused by water exchange, disinfection, and the occurrence of disease still deserves further in-depth study.

13.3 Ecological Prevention of Diseases in Shrimp Aquaculture

Ecological prevention of disease refers to the way to prevent and control the occurrence of diseases in aquaculture through ecological means, such as blocking pathogen transmission routes to avoid contact between farmed organisms and pathogens, and keeping good environmental conditions to improve the disease resistance of farmed organisms, and to reduce the pathogenicity of pathogen. This section will only briefly introduce the ecological prevention of white spot disease (WSS) of shrimps.

The white spot disease, also known as the white spot syndrome of shrimps, has spread to almost all shrimp farming countries worldwide since its appearance in 1991, and an annual loss of about one billion USD caused by the disease to the aquaculture industry (Verbruggen et al. 2016). The pathogen is white spot syndrome virus (WSSV). Quarantine and elimination are the best strategies for dealing with this highly infectious disease, but WSSV is prevalent in coastal aquaculture areas in many countries and is difficult to eradicate. Taking some ecological preventive measures can effectively alleviate the occurrence of the disease and reduce the loss caused by the disease.

13.3.1 Transmission Routes of White Spot Syndrome Virus

White spot syndrome (WSS) is still incurable due to the incomplete immune system of the shrimp and the economic cost to treat. At present, some ecological methods can effectively prevent and control the occurrence and intensity of the disease. The host of white spot syndrome virus (WSSV) and some major transmission routes will be introduced for a better understanding of the principles of ecological prevention and control of the disease. WSSV was found to be present and infective in the dormant eggs of rotifers and copepods, indicating that the dormant eggs of zooplankton may be the host of WSSV (Yan et al. 2004, 2006), which provides a new route to gain insight into the overwintering transmission mechanism of WSSV.

Seawater crustaceans are generally susceptible to WSSV, and almost all farmed shrimps are susceptible hosts to WSSV (Wang et al. 1998a; Rajendran et al. 1999; Lei et al. 2002). WSSV can naturally or artificially infect some crustaceans which, however, show no obvious pathological symptoms or significant mortality after infection. They are the potential hosts of WSSV, such as *Callianssa harmandi*, red swamp crayfish (*Procambarus clarkii*), etc. (Maeda et al. 1998; Rajendran et al. 1999; Zhang 2007; Verbruggen et al. 2016). WSSV can infect shrimp in several ways. Healthy shrimps can be infected with WSSV by cannibalizing infected shrimps, also by physical contact with sick shrimps (Tuyen et al. 2014). Some scholars found that there are a lot of WSSV virion in the oocytes of Chinese shrimp (*Fenneropenaeus chinensis*). It is also found that brood stock of giant tiger prawn (*Penaeus monodon*) infected with WSSV can produce eggs with WSSV. Therefore, it is inferred that the virus can be transmitted vertically through germ cells (Bao et al. 1997; Jiang et al. 2000). Silva et al. (2016) also reported that there is a vertical transmission route for infectious muscle necrosis virus (IMNV) in whiteleg shrimp (*Litopenaeus vannamei*), which, however, is not supported by other scholars (Liu et al. 1999b; Lo 1997).

Free WSSV can infect shrimp through phytoplankton adhesion. Studies have shown that microalgae can adhere WSSV excreted from infected shrimp and then become a carrier of WSSV. As shown in the PCR detection in an experiment, WSSV is found in four phytoplankton which can carry it for a certain period of time (Table 13.3). WSSV is found in all the four phytoplankton for 96 h, among which the *Isochrysis zhanjiangensis* and *Platymonas subcordiformis* are WSSV positive

Table 13.3 PCR detection of four phytoplankton for carrying adhering WSSV at different time

	Time (hours)												
Species	0.5	1	2	4	8	12	24	48	72	96	120	144	168
Isochrysis zhanjiangensis	+	+	+	+	+	+	+	+	+	+	+	+	−
Platymonas subcordiformis	+	+	+	+	+	+	+	+	+	+	+	+	−
Dunaliella salina	+	+	+	+	+	+	+	+	+	+	+	−	−
Skeletonema costatum	+	+	+	+	+	+	+	+	+	+	−	−	−

Note: + WSSV positive, − WSSV negative

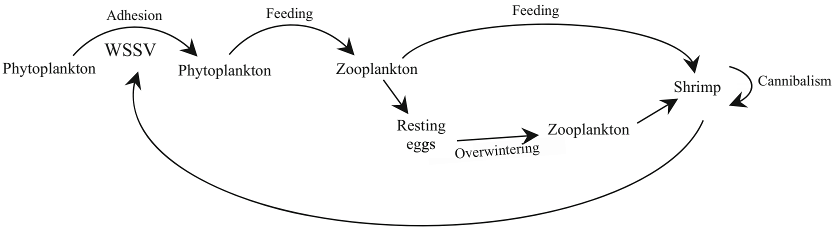

Fig. 13.3 Several transmission routes of white spot syndrome virus (WSSV) through adhesion and food chain

within 144 h, and the *Dunaliella salina* is positive within 120 h. Then, the above algae become WSSV negative one after another, probably due to the decomposition of WSSV DNA (Zhang et al. 2007d).

The zooplankton in shrimp ponds has been found WSSV positive for many times in epizootiological surveys (e.g., Yan et al. 2004; Zhang 2007). Four common zooplankton species in shrimp ponds, i.e., *Brachionus urceus*, *Acartia clausi*, *Nitocra* sp., and *Neomysis awatschensis*, are tested for WSSV infection by both immersion and virus-phytoplankton adhesion methods. The results of nested PCR detection show that these zooplankton and nektons are effectively infected with WSSV (Zhang et al. 2007c) (Fig. 13.3).

Overwinter dormant or resting eggs of zooplankton collected from the sediment of shrimp farming ponds in spring are sometimes WSSV positive after rigorous surface disinfection of the eggs in both copepod and rotifer (Yan et al. 2004; Zhang and Dong 2006). The larvae hatched from the virus-positive dormant eggs are also WSSV positive (Zhang and Dong 2006). *Nitocra* sp. is effectively infected with WSSV through the virus-phytoplankton adhesion method. The larvae of Kuruma prawn (*Marsupenaeus japonicas*) fed with the WSSV-positive *Nitocra* sp. for 15 days are also infected with the WSSV (Zhang and Dong 2008). Therefore, the *Nitocra* sp. can be a vector in WSSV transmission.

In summary, free WSSV can adhere to phytoplankton, which can increase its activity time by more than 4-folds. The WSSV adhered to the surface of the phytoplankton can be ingested by rotifers and copepods, and infect zooplankton; the rotifers or copepods infected with WSSV can produce dormant eggs with virus, and the hatched larvae can transmit WSSV to shrimp larvae (Fig. 13.3).

13.3.2 WSS Outbreak in Relation to the Environment

13.3.2.1 WSS in Relation to the Physical Factors of Aquaculture Water

It is found that the outbreak of WSS in farmed shrimps is closely related to heavy rain. It has become a pattern of shrimp disease occurrence after typhoon and rainstorm in Fujian Province every year (Zeng et al. 1998). He and Mo (1999) have conducted a statistical analysis of about 667 ha of shrimp farming ponds in Guangdong Province, and found that heavy rain generally can induce the disease in giant tiger prawn farmed over 20 days. The incidence rate is 7% for shrimps farmed for 20–30 days, 30% for shrimps farmed for 30–50 days, and as high as 80% for shrimps farmed for more than 50 days.

The outbreak of WSS is also related to the cold air current attack. According to He and Mo (1999), WSS often break out in Guangdong Province when the temperature of the pond water drops as a result of the cold air currents moving southward in April and May. WSS outbreak is also related to the depth of the pond and water exchange rate daily. The shallower the pond water and the greater the water exchange rate is, the more intense the pond disturbance is.

The aforementioned changes involving the salinity, temperature, and amplitude of variation affect the pathogenicity of WSSV and the susceptibility of shrimps. The infectious activity of WSSV remains for 1 h in pure water, but loses its infectivity in 3 mol/L salt solution after 1 h (Xie et al. 2000). The cumulative mortality of whiteleg shrimp and the quantity of virus in the shrimp will both increase after abrupt changes in salinity from medium salinity (23 ± 1) to either high salinity (32 ± 1) or low salinity (14 ± 1). Therefore, for shrimps with WSSV, inappropriate changes in salinity will turn WSSV from potential infection to acute infection (Sun et al. 2004; Xiang et al. 2014b).

Temperature also affects the mortality of shrimps infected with WSSV. The median lethal time (LT_{50}) of Kuruma prawn artificially infected with WSSV is 16.0d, 4.5d, 4.5d, and 9.0d at the temperature of 15 °C, 23 °C, 28 °C, and 33 °C, respectively. The shrimp is most severely infected with WSSV at 28 °C with the lowest total blood cells, and least infected at 15 °C with the highest total blood cells (Guan 2003). The cumulative mortality of whiteleg shrimp infected with WSSV is less than 11.1% at the end of the 45-day experiment at 19 ± 1 °C, while the mortality of the shrimps reaches 63.3% at 48–96 h at 25 ± 1 °C (Sun et al. 2004).

When the proliferation rate of WSSV is the highest at the temperature of 21–30 ° C, all the infected red swamp crayfish die after 6 to 8 days. However, the proliferation of the virus is inhibited by both higher (33 °C) and lower (15–18 °C) temperatures. The virus proliferation is significantly inhibited when the temperature drops to 12 °C or 8 °C (Li et al. 2013b). The proliferation rate of WSSV in whiteleg shrimp at 29 ± 1 °C is also significantly higher than that at 19 ± 1 °C.

Studies have also shown that the susceptibility temperatures of giant tiger prawn, whiteleg shrimp, Chinese shrimp, Kruma prawn, and red swamp crayfish to WSSV are 30C, 27 °C, 23 °C, 25 °C, and 24 °C, respectively (Rahman et al. 2006; Xie et al. 2005; Yao and He 2002; Zhou et al. 2001a). That is a key reason why some shrimps develop disease twice a year. Certainly, the susceptibility temperature is related to the size and physiological condition of the shrimps, as well as the condition of pathogen in the experiment.

Abrupt change of temperatures also affects the WSS of farmed shrimps. The patterns of temperature change of 24 → 27 °C/6 h and 24 → 30 °C/6 h do not cause the death of healthy Kruma prawn, but can accelerate the death of infected ones. Compared with 27 °C, the water temperature of 33 °C can inhibit the proliferation of WSSV in whiteleg shrimp. Temperature fluctuations between 27 and 33 °C also affect the proliferation of WSSV with different WSSV strains performing differently (Rahman et al. 2007).

Studies on two freshwater crayfish (*Pacifastacus leniusculus* and *Astacus astacus*) show that after 45 days of injection or oral administration of WSSV, the crayfish did not die at the temperature of 4 ± 2 °C or 12 ± 2 °C, but they died 100% after transferred to 22 ± 2 °C. The dying crayfish at 22 ± 2 °C were alleviated when transferred again to water below 16 °C. Being no more than the carrier of WSSV, these crayfish do not develop disease at low temperatures, but they do become ill when temperature increases (Jiravanichpaisal et al. 2004).

Previous studies have shown that abrupt changes in the salinity and temperature of aquaculture waters may increase the pathogenicity of WSSV or/and the susceptibility of shrimps. Therefore, moderately increasing the water depth of shrimp ponds and controlling the frequency and percentage of water exchanges are effective measures to reduce drastic fluctuations in temperature and salinity in pond water and prevent outbreaks of the disease.

In the practice of sea cucumber farming in ponds in North China, a large number of deaths occur after heavy rainstorms sometimes due to abrupt drop in salinity. Therefore, Professor Chang Ya-qing from Dalian Ocean University develops the ‘sluice gate for sea cucumber aquaculture pond’ that timely discharges the newly added low-salinity water in the upper layer of the pond when it rains to avoid an abrupt drop in salinity, which is also applicable to shrimp aquaculture.

13.3.2.2 WSS in Relation to the Chemical Factors of Aquaculture Water

A good and stable chemical environment in aquaculture waters is very important for the health of aquaculture organisms. Poor chemical environment can reduce the ability of farmed organisms to resist pathogens and can even lead to the outbreak of diseases. The main chemical factors that affect the health of aquaculture organisms in aquaculture systems include mainly pH, DO, ammonia, nitrite, COD, etc.

When the pH of the water is below 5 or above 12.6, WSSV will lose its infectious activity in about 1 h (Xie et al. 2000). The average survival time of whiteleg shrimp infected with WSSV will be prolonged by 28.4 h for every unit decrease in the water pH range of 5.0–9.5 (Chen et al. 2010). Similarly, the infectivity of Monodon-type baculovirus (MBV) increase with increasing pH (Li et al. 1996b). Therefore, WSS can be effectively prevented by keeping the pH of the aquaculture waters within an appropriate range.

The effect of DO content in water on disease resistance of shrimp and crabs has been reported extensively. Cloudy and rainy days reduce the DO in aquaculture waters due to weakened photosynthesis of phytoplankton. The massive death of plankton can also reduce the DO of the water. Low DO conditions can reduce the disease resistance of farmed shrimps and lead to the outbreak of WSS (Wang et al. 1998c).

Ammonia is an important product of protein metabolism of farmed animals in aquaculture waters. Massive accumulation of ammonia in the water is detrimental to the farmed animals' excretion of nitrogenous waste, causing blood ammonia poisoning if ammonia enters their tissue fluid from the water environment. Shrimp is somewhat tolerant of ammonia, and whiteleg shrimp is more tolerant than giant tiger prawn and Chinese shrimp. The safe concentration of un-ionic ammonia is 0.201 mg/L for the 5 cm whiteleg shrimp (Sun et al. 2002), 0.104 mg/L for post larvae of giant tiger prawn (Zhou 1991), and 0.097 mg/L for 2.61 cm Chinese shrimp (Zang et al. 1993). Ammonia can also reduce the ability of disease resistance of farmed animals, particularly in Chinese shrimp exposed to high concentration of ammonia for a long time.

Nitrite is an intermediate product of multiple processes such as nitrification and denitrification. It is highly toxic to farmed animals and can cause disorders in such physiological and metabolic activities as respiration, ion regulation, cardiovascular pressure regulation, endocrine, excretion, etc. The safe concentration of nitrite is 5.55 mg/L for whiteleg shrimp. Higher nitrite concentration in aquaculture waters reduces the immunity and disease resistance of the shrimp, and even cause its massive mortality (Tseng and Chen 2004). Nitrite can convert the oxygenated hemocyanin in the hemolymph of shrimp to deoxygenated hemocyanin, reducing the affinity for oxygen and increasing the susceptibility of shrimp to pathogens. Changes in the concentration of nitrite nitrogen from the initial concentration (0.05 mg/L) to medium (10 mg/L) and high concentration (20 mg/L) show that whiteleg shrimp with WSSV are more sensitive to concentration changes of nitrite, which is more likely to cause potential infection to acute infection. The cumulative mortality of whiteleg shrimp in the initial, medium, and high concentration groups are 52.2%, 70.0%, and 76.7%, respectively, in the test of abrupt changes of nitrite nitrogen (Xiang et al. 2014a).

COD is a key index of water quality in shrimp ponds. Higher COD demonstrates the high concentration of organic matter and deterioration of water quality. WSS is less likely to break out in shrimp ponds where COD concentration is lower than 10 mg/L, but more likely to break out in ponds with higher COD (Li et al. 2008).

Some disinfectants, such as alkalis, halogens, and oxidants, are often used as compounds to kill WSSV. A 60 min-acting of chlorine dioxide at an effective concentration of 50 ppm can well degrade the structural protein of WSSV and deprive its infectious activity. Potassium permanganate at 25 ppm acting for

15 min, or 50 ppm acting for 5 min, can completely deprive the infectious activity of WSSV (Li 2014).

13.3.2.3 WSS in Relation to the Biological Factors of Aquaculture Water

Aquatic environment organisms related to WSS include hosts or carriers of WSSV and the organisms impacting on the quality of aquaculture water. WSSV hosts involve many species like farmed shrimps, most crabs, and wild shrimps. WSSV is also found to be carried by planktonic crustaceans and even rotifers in aquaculture waters. WSSV-negative shrimps may be infected with the virus if feeding on or contacting with animals infected with WSSV. Please refer to Sect. 13.3.1.

Another group of organisms related to WSS are those that can affect the quality of aquaculture water, such as phytoplankton and planktonic microorganisms. As an integral part of the shrimp pond ecosystem, phytoplankton plays an indispensable role in maintaining the normal functions of the pond ecosystem and stabilizing the pond environment. The photosynthesis, respiration, and decomposition of phytoplankton can alter the DO, CO_2, pH, and redox potential of the water, and in turn affect the existing forms of ammonia and sulfides in the water. These changes of water chemistry can directly or indirectly affect the pathogenicity of WSSV and/or disease resistance of farmed shrimp.

Phytoplankton in aquaculture waters has a positive effect on the suppression of shrimp WSS. For example, when *Heterosigmaak akashiwo* was added to the water and co-cultured with Chinese shrimp infected with WSSV, less virus was detected in the shrimp than in the unadded group, and mortality peak of the shrimp was delayed (Li et al. 2003b). Recently, better results have been achieved in greenhouse shrimp farming, a system in which phytoplankton dominated the biological environment. Green algae in the ponds can prevent shrimp WSS, such as the chlorella in 10^6 cells/mL is more effective in disease prevention in shrimp ponds in the Philippines. When shrimp ponds are dominated by *Nannochloropsis* and chlorella, the density of 10^5 cells/mL is also effective (Tendencia et al. 2011), because chlorella itself is antibacterial and capable of improving water quality.

There is a side to the transmission of WSSV that is aided by phytoplankton. Phytoplankton is not the host of WSSV, however, WSSV can adhere to the phytoplankton, making WSSV survive longer in seawater, transmitting WSSV to the shrimps via zooplankton (Fig. 13.3).

Bacteria play an extremely important role in the farmed shrimp ecosystem by decomposing and utilizing the organic matters effectively to reduce the concentration of certain harmful substances in the pond. Studies have shown that the scientific use of bacteria in the culturing process can not only effectively purify the water environment (Li et al. 2007), but also reduce the incidence of WSS. In the Philippines, feeding with planktons and high mangrove to pond area ratio can reduce the risk of WSS (Tendencia et al. 2011).

Integrated some species with shrimp in aquaculture pond, such as seaweeds, filter-feeding fish, and filter-feeding shellfish, are also environmental organisms of the shrimp. If these organisms are reasonably integrated, they all can effectively prevent the occurrence of WSS or alleviate the symptoms of the disease. Please refer to Chap. 7 for more details on their mechanisms. In addition, the co-culture of shrimps and pufferfish can also prevent outbreaks of WSS (see Sect. 9.2 for detail).

13.3.3 Comprehensive Prevention of WSS

Since the epidemic of shrimp WSSV, researchers and shrimp farmers in many countries around the world have done a lot of systematic and in-depth studies on pathogen, epidemiology, immunity, and ecological prevention of this disease, and some progress has also been made. However, no economical and 100% effective method has been developed to prevent WSS in epidemic areas of WSS. The production of shrimp (excluding crayfish) farming in China increased to 2.314 million tons in 2021 compared with 63,900 tons in the tough period of 1994, mainly due to the introduction of whiteleg shrimp, the expansion of shrimp farming to low-salinity ponds, and the application of integrated ecological technologies for disease prevention.

Whiteleg shrimp is more suitable species for intensive farming for its stronger disease resistance and less cannibalism than other shrimp species. Since the large-scale aquaculture of whiteleg shrimp started in China in 1998, its production has gradually exceeded that of Chinese shrimp that had dominated China's production of farmed shrimps, accounting for 85% in the production of farmed shrimps in China in 2021. China has extended its shrimp farming from seawater ponds to low-salinity even freshwater ponds in non-WSS epidemic areas far from the coast, and has successfully applied the integrated ecological technologies for disease prevention in some epidemic areas.

Based on the previously described WSSV transmission routes and the relationship between WSS outbreak and the environment, some ecological technologies to prevent WSS can be deduced or generalized in the perspectives of physics, chemistry, and biology. Some of these technologies focus on blocking WSSV transmission, some on killing WSSV hosts or carriers, and some on improving habitat environment of shrimp and increasing their resistance to the disease. However, more comprehensive prevention technology is used in practice, including:

13.3.3.1 Pre-Treatment of Shrimp Farming Water

Shrimp farming is best carried out in non-WSS epidemic areas, but if in the epidemic areas, water source and ponds should be well treated first. If a water of pH is <7.0, an appropriate amount of lime should be applied to raise the pH. If shrimp is cultured in salt-alkali pond, attention should be paid to adjusting the Na^+/K^+ (See Sect. 11.4 for details). If the water is sourced from open waters, the water should be filtered and disinfected before pump into shrimp farming ponds (Li et al. 2004; He and Sun 2004).

13.3.3.2 Blocking WSSV Transmission during Shrimp Culture

The stocking of shrimp juveniles of specific pathogen free is the most important physical isolation measure in both infected and non-infected areas. In addition, effective measures to block WSSV transmission in the infected areas are closed management and killing WSSV:

1. Shrimp ponds need to be drained and exposed to the sun after harvest to kill WSSV (Hernandez-Llamas et al. 2014).
2. Dormant eggs of zooplankton are the intermediate hosts of WSSV that can overwinter with the virus in pond sediments (Fig. 13.3). Therefore, water should be thoroughly disinfected at least twice to kill the zooplankton larvae hatched from the dormant eggs before stocking shrimp juveniles.
3. If possible, the pond can be covered with waterproof mulch, which allows the ponds to be completely dredged after harvesting. The dormant eggs of zooplankton in the sediment of the pond can be completely removed after harvest of the shrimp. One reason why some traditional intertidal shrimp ponds are diseased year after year is that they cannot be thoroughly dredged and there may be residual pathogens overwintering in the sediments of the ponds (Yan et al. 2004).
4. Enclosing farming ponds with polyethylene film enclosure to prevent wild crabs that may carry WSSV from entering the pond (Li et al. 2004; He and Sun 2004). Closed or semi-closed management is adopted to prevent WSSV from entering the farming ponds (Hu et al. 2011; Suo et al. 2015).

13.3.3.3 Keeping Good Environmental Conditions of Farming Ponds

Stable and good water quality can improve the disease resistance of farmed organisms and reduce the pathogenicity of WSSV. The main ways to maintain stable and good water quality include disturbance reduction, green water farming, and probiotic applications.

13.3.3.3.1 Disturbance Reduction

Disturbance reduction refers to maintaining the stability of water quality through physical and biological measures, aiming at improving the disease resistance of farmed prawn and reducing the pathogenicity of WSSV. Major measures to reduce the disturbances include: the use of pre-mature water to change the water, which can maintain the stability of microbial community in aquaculture water (Attramadal et al. 2014); continuous aeration to avoid drastic daily fluctuations of DO (He and Sun 2004); timely discharge of the pond sediments (residual feed and faces) to avoid the accumulation of organic matter; increase the depth of shrimp farming pond appropriately to avoid drastic drop of water temperature and salinity (He and Mo 1999).

13.3.3.3.2 Green Water Farming

Shrimp farming practices show that co-culture of shrimp with macroalgae, filter-feeding fish, and filter-feeding shellfish can maintain a good and stable water quality and improve the success rate of shrimp farming. Foreign scholars call this kind of farming technology as green water technology (Tendencia et al. 2011). Co-culture of shrimp with puffer fish can also effectively prevent outbreaks of WSSV. The principles can be found in Sect. 9.2 of this book.

13.3.3.3.3 Probiotic Applications

Probiotics are live microorganisms that can produce beneficial effects on physiological health or/and their ambient environment of farmed animals. The probiotic bacteria commonly used in aquaculture include *photosynthetic*, *pseudomonads*, *bacillus* bacteria, and so on. Probiotics have been applied on a large scale in the actual production of shrimp farming, with certain effects in improving the water quality, improving the disease resistance of farmed shrimp (Shan 2013). Bacillus can inhibit heterotrophic bacteria and vibrio in shrimp farming waters to a certain extent, which is beneficial to maintain stable phytoplankton biomass, enhance non-specific immunity of farmed shrimp, and improve the survival rate and yield of the shrimp (Gatesoupe 1999; Ninawe and Selvin 2009; Li et al. 2006; Cao et al. 2013b). Others, such as *Vibrio alginolyticus*, may be beneficial to farmed animals. Since 1992, *Vibrio alginolyticus* has been used as probiotic bacteria in shrimp seedling production in Ecuador (Garriques and Arevalo 1995).

In recent years, biofloc technique has been considered to be a model of high-density shrimp farming with zero water change (Zhang 2012b; Shan 2013; Xu 2014). The mechanism of disease prevention of farmed shrimp in the biofloc model can refer to the Sect. 10.4 of this book.

13.4 Welfare of Farmed Fish

More and more people are aware of the compliance with the rules on care and use the laboratory animals, such as 3Rs principles, that is, if animals were to be used in experiments, every effort should be made to replace them with non-sentient alternatives, to reduce to a minimum the number of animals used, and to refine experiments which used animals so that they caused the minimum pain and distress (Macrina 2005).

Scholars believe that fish, like mammals and livestock, are entitled to animal welfare as they can feel the pain and show the fear though in a degree and way different from higher animals.

In Europe, the human use of fish is regulated by specific directives and recommendations based on the assumption that vertebrates should be regarded as sentient beings and that their use in the scientific process must be limited to the areas of research that may ultimately benefit human or animal health or the environment (Nuffield Council on Bioethics 2005). Given their significant impact on future aquaculture, here is a brief introduction about the concept of fish welfare and some research in fish welfare.

13.4.1 Welfare Indicators of Farmed Fish

Animal welfare means that animals adapt to the environment and the satisfaction of their basic natural needs. The 'Five Freedoms of Animal Welfare' were developed by the UK Farm Animal Welfare Council (FAWC) in 1979 following an investigation into the welfare of intensively farmed animals. The five freedoms are: freedom from hunger and thirst, freedom from discomfort, freedom from pain, injury or disease, freedom to express normal behavior, and freedom from fear and distress. More than 100 countries have enacted laws and regulations on animal welfare, especially EU countries and Norway which highly value fish welfare by making regulations on the welfare of farmed fish.

Fish welfare is a part of animal welfare. In 1986 the United Kingdom listed fish as one of the animals protected. A detailed recommendation concerning farmed fish has been provided in 2006 by the Standing Committee of the European Convention on the Protection of Animals kept for Farming Purposes (Council of Europe 2006).

There are over 25,000 species of teleost fishes in the nature and nearly a hundred species of fishes are farmed. Ensuring the welfare of farmed fish is a complex issue because so many species-specific factors or aspects must be considered, such as physical–chemical parameters of water, environmental complexity, stocking density, foraging and social behaviors of the farmed animals, and so on.

13.4.1.1 Welfare Indicators

Welfare indicators of fish are used to judge the state of their welfare, which are observations or measurements that provide information about the extent to which the animal's welfare needs are met.

In order to ensure the welfare of housed or farmed fish, there must be good indicators that are easily identifiable, reliable, and minimally invasive. When stress is a long-term and long-term response that leads to maladaptive consequences, stress indicators can be considered a measure of poor welfare. Thus, health and stress avoidance contribute to welfare assessment, but positive welfare conditions are in turn a prerequisite for physical health and stress avoidance (Tonil et al. 2018).

Hunger, pain, discomfort, and fear of farmed fish can be assessed by their performance, anatomical, behavioral, and physiological indicators. Assessment of animal welfare levels based on blood and tissue parameters must be done using minimally invasive capture and sampling methods. Physical and behavioral health status should also be assessed using non-invasive methods whenever possible. For example, farmed fish is least disturbed by remote-controlled underwater cameras from which the information obtained is more credible.

Physical indicators of fish welfare include color and changes of eye and skin, morphological alterations, altered body posture, mucus production and opercular beat frequency, and so on (Tonil et al. 2018).

Behavior indicators of fish welfare may consider the following main categories: (1) space use, habitat selection, and structural complexity of the rearing environment; (2) foraging behavior and altered food consumption; (3) aggression to conspecifics, especially in relation to stocking densities; and (4) spatio-temporal patterns of behavior, changes in the use of the water column, swimming activity, shoaling to escape predators, and disruption of circadian rhythm (Tonil et al. 2018).

The indicator mostly used to assess fish welfare is cortisol content that characterizes its physiological performance. Some indicators of biological non-invasion have also been used to study fish welfare. For example, the cortisol content in farming water can be used as an indicator of biologically non-invasive welfare assessment (Li and Liu 2014). With further research on fish welfare, it is believed that more and more representative and scientific indicators will be explored.

13.4.1.2 Water Physical and Chemical Parameters

The physical and chemical properties of aquaculture water have a direct and important impact on farmed fish, such as water temperature, DO concentration, pH, ammonia concentration, heavy metals, and pesticides from human activities. Other factors like noise and vibration also have impact on fish welfare. Compared with fish in natural environment, farmed fishes have limited space for activities, therefore it is necessary to provide as much as possible an environment with physical and chemical parameters required for fish welfare.

13.4.1.3 Complexity of Environment

Complexity of environment is a factor that needs to be considered in designing aquaculture system. The environmental complexity of aquaculture waters can improve the welfare of farmed fish because the complexity can reduce stress and make fish feel safe. The structural complexity can alter the behavior of fish, and play a positive role to promote recovery and ameliorate adverse effects following a stressor (Pounder et al. 2016). For example, introduction of shelters in the waters can reduce stress as well as the competitive and aggressive behavior among individuals of European catfish (*Silurus glanis*) (Slavík et al. 2012). In addition, the complexity of environment can promote the foraging ability of farmed fish.

The density and territorial characteristics of farmed fish should be comprehensively and balanced considered for determining whether to set up shelters. The absence of shelters may lower the welfare level by intensifying competitive and aggressive behavior among individuals. On the other hand, more shelters may also lower welfare levels by occupying the space of the waters which intensifies competitive and aggressive behavior among individuals at high density. The appropriate substrate can improve fish welfare, especially the appropriate substrate color. Blue and brown-green substrates can reduce the aggressiveness in juveniles of gilthead seabream (*Sparus aurata*) (Batzina and Karakatsouli 2014).

It is important to assess the enrichment of living environment of each farmed species, including the behavioral characteristics of different developmental stages, as well as the territoriality and aggressiveness, to prevent fish from developing abnormal behavior in monotonous environment.

13.4.1.4 Stocking Density, Foraging Behavior, and Social Behavior

Foraging behavior varies greatly among species, so it is difficult to develop a universal feeding strategy, such as feeding rhythm, for all farmed fish. In this regard, autonomous feeding systems improve the welfare of farmed fish by allowing them to choose the optimal feeding time on their own. Stocking density is often related to the spatial pattern of fish behavior. Swimming activity status may be a reliable indicator of stress and overcrowding.

There is an interaction among stocking density, foraging behavior, and social behavior of farmed fish, which in turn determine the aggressive intensity. Aggression is a key factor in determining territoriality and spatial behavior, contributing to the inter-individual distance and the occurrence of physical contact and potential associated injuries (Tonil et al. 2018). Aggressive behavior costs much energy and may affect metabolism and immunity if it is too violent.

Less aggressive behavior can be achieved by stocking appropriate quantity and weight of farmed fish in aquaculture waters. Social behavior of fish is often based on its social hierarchy and the fish density related to food availability. Therefore, foraging behavior and stocking density can be used to assess fish welfare as they affect the social behavior of fish.

13.4.2 Methods for Assessing Fish Welfare

Welfare of farmed fish can be evaluated by conventional or comprehensive method (Li and Liu 2014). The conventional method adopts the fish welfare indicators including fish physiology, biochemistry, behavior, and the water quality of aquaculture waters. However, single welfare indicators, such as cortisol content, food intake, energy consumption, mortality, swimming behavior, etc., can only represent a certain aspect of fish condition and are not equivalent to welfare status. A high level of fish welfare is supposed to be the ability to cope with certain stresses and diseases, and well maintain internal homeostasis and health. If fish welfare is viewed comprehensively in the perspective of physiological function and behavior changes, the variation of one single indicator such as cortisol cannot be used to evaluate the general level of welfare.

Overall welfare assessment (OWA) is the model based on observations of the animals, their biological and physical environments. There are two approaches to form OWA models, i.e., risk analysis and semantic modeling. The objectives of the former are to identify hazards, consequences, and probabilities of occurrence, and to find critical control points in the production process to avoid stress, injuries, disease, and mortality. The latter focuses on the indicators of the degree of fulfillment of the animal's welfare needs and the effects on the animals' wellbeing.

A scoring semantic model for OWA (SWIM 1.0) of Atlantic salmon in sea cage is successfully developed by Stien et al. (2013) to enable fish farmers to make a formal and standardized assessment of fish welfare using 17 welfare indicators, such as water temperature, salinity, oxygen saturation, stocking density, lighting, daily mortality rate, appetite, sea lice infestation ratio, etc. Given the variability of fish living environments under different culture practices, a comprehensive and accurate evaluation of fish welfare levels is not an easy task.

With more in-depth researches being done on fish welfare, how to improve it has become a hot topic, especially on the control of stocking density, timely grading in case of cannibalism and coercive behavior, optimizing farming environment, safe transportation, and humane slaughter.

Maintaining higher welfare in farmed fish means higher survival rate of farmed fish, higher quality of aquatic products, stronger international competitiveness of products, and also means higher investment in farming. Improving the welfare of farmed fish is often not contradictory to increasing the benefits of farming, but there is still more research work to be done to understand this.

Brief Summary

1. Health maintenance is a concept in which animals are cultured under conditions that optimize the growth rate, feed conversion efficiency, reproduction, and survival while minimizing problems related to infectious, nutritional, and environmental diseases, all within an economical context. Health maintenance does not simply target infectious diseases; instead, it involves the entire process of aquaculture activities for the purpose of improving the health of cultured aquatic animals and efficient production of healthy aquatic products through production management.
2. The relationship between culture environment (E), host (H), pathogen (P), and disease occurrence (D) is $D = H(P + E^2)$. Under the preconditions of pathogen existence and host's low immunity, disease outbreak is often triggered by the bad aquaculture water environment.
3. Environmentally induced diseases are diseases that occur in farmed organisms exposed to extreme water quality conditions. Common environmental inducers in aquaculture include water temperature, dissolved oxygen, dissolved nitrogen, pH, NH_3, etc. The temperature threshold that causes disease in aquatic animals is close to the threshold of survival or tolerance. The same is true for other water quality parameters.
4. After disturbance, the bacterial community in aquaculture waters first develops rapidly with *r*-selective strategy species, followed by *K*-selective strategy species, and finally forms a stable community with a high quantity of *K*-selective species and a low quantity of *r*-selective species. The pathogenic bacteria are mostly *r*-selective strategy species, and they have a strong impact on juvenile fish and individuals of farmed organisms under environmental stress. To reduce risks of infecting pathogenic *r*-selection strategy bacteria, the new water should be matured or incubated in the pretreatment tank or pond for a period of time to allow the *K*-selection species to develop first before being pumped into the aquaculture waters.
5. Ecological prevention of disease refers to the way to prevent and control the occurrence of diseases in aquaculture through ecological means, such as blocking pathogen transmission routes to avoid contact between farmed organisms and pathogens, and keeping good environmental conditions to improve the disease resistance of farmed organisms, and to reduce the pathogenicity of pathogen.
6. Animal welfare means that animals adapt to the environment and the satisfaction of its basic natural needs. EU countries and Norway highly value fish welfare by making regulations on the welfare of farmed fish.

7. Ensuring the welfare of farmed fish is a complex issue because so many species-specific factors or aspects must be considered, such as physical–chemical parameters of water, environmental complexity, stocking density, foraging and social behaviors of the farmed animals, and so on.

Aquaculture Mapping in the Context of Climate Change

14

Yun-Wei Dong

With increasing food demand and declining wild capture of fisheries, aquaculture as a key component of food supply becomes more and more important for providing high-quality proteins (Froehlich et al. 2018a). Since the 1980s, world aquaculture production has kept increasing at an annual growth rate of 6%. Although the rapid expansion of aquaculture has brought immense food supply, the development of aquaculture is facing unprecedented pressures from climate change, resource constraints, environmental pollution, energy consumption, and other factors as mentioned in Chaps. 3 and 4.

For coping with these challenges and ensuring sustainable development of aquaculture, spatial planning for aquaculture (aquaculture mapping) and improving management in aquaculture activities become more and more important. Timely and proper aquaculture mapping becomes one of the most important decisions and is fundamental for the profit, sustainability, and longevity of the industry. Otherwise, improper aquaculture management may lead to serious environmental problems and costly socio-economic conflicts, even causing biodiversity loss and dysfunction of natural ecosystems.

Aquaculture activity is also one of the potential major activities in the marine protected areas (MPAs), even in the full protected MPAs, and so it is important to design the aquaculture activities with the consideration of marine protected areas under the United Nations Sustainable Development Goal (Grorud-colvert et al. 2021). Thus, an ecosystem-based approach for aquaculture mapping is needed to strategically and comprehensively balance the location, aquaculture type, and stakeholders' interests as mentioned in Chap. 1.

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14.1 EAA-Based Aquaculture Mapping

14.1.1 Ecosystem Approach to Aquaculture

Ecosystem approach to aquaculture (EAA), defined as a strategy for integrating aquaculture within broader ecosystems, is a framework currently implemented by Food and Agriculture Organization (FAO) for aquaculture mapping to promote sustainability, equity, and resilience of interconnected social and ecological systems (Willot et al. 2019). Three principles govern the implementation of the EAA (see Sect. 1.3.4 for detail). Violating the three criteria can undermine the benefits derived from aquaculture development which can be defined as inappropriate spatial planning. Even more, it may exacerbate conflicts in the use of space and cause loss of functions and services of ecosystems. Fish disease, environmental issues (like eutrophication, biodiversity decline, and ecosystem service loss), production issues (low growth rate), social-economic issues (equity issues and lack of public confidence), poor risk resistance, and lack of resilience (to climate variability, climate change, and other external hazards) would be common problems in an inappropriate aquaculture area (Aguilar-Manjarrez et al. 2017). Therefore, for a successful aquaculture industry, it is essential to make appropriate spatial mapping and select a suitable aquaculture area. Because of this realization, FAO has produced guidance for aquaculture spatial planning (FAO and World Bank 2015) which can be divided into four processes (Table 14.1):

Scoping: It aims to establish the objectives of aquaculture, determine general areas that may be suitable for various types of aquaculture, determine national priorities for ecosystem conservation and conversion, and determine who may be the relevant stakeholders involved in decision-making. All decisions must comply with the relevant laws.

Zoning: It aims to place criteria for aquaculture and other activities together to identify broad zones suitable for different activities or a mix of activities.

Site selection: It aims to identify the most suitable locations within the zone for individual farm development to reduce risk and optimize production.

Table 14.1 Main characteristics of the processes for scoping, zoning, site selection, and area management for aquaculture

Characteristics	Scoping	Zoning	Site selection	Area management
Scale	Global to national	Subnational	Farm or farm clusters	Farm or farm clusters
Data	Environmental data, biological information, political, technical, and economic feasibility	Environmental data, biological information, socio-economic factors	All available data	Data for risk assessment and carrying capacity
Resolution	Coarse	Moderate	Fine	Fine

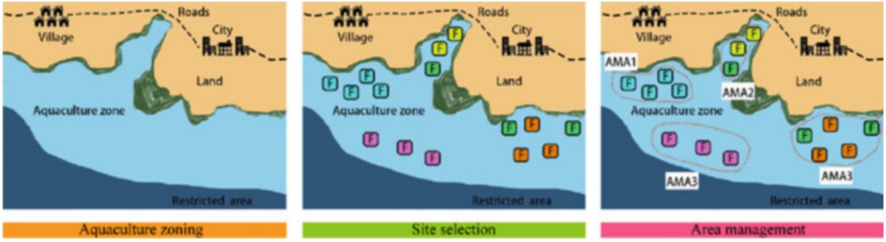


Fig. 14.1 Potential steps in the spatial planning and management process for aquaculture

Aquaculture management areas (AMAs): It aims to manage individual farms collectively to protect the environment, reduce risk, and avoid potential conflicts.

The processes for scoping, zoning, selecting, and managing aquaculture areas usually carry out the following steps within the EAA framework (Aguilar-Manjarrez et al. 2017):

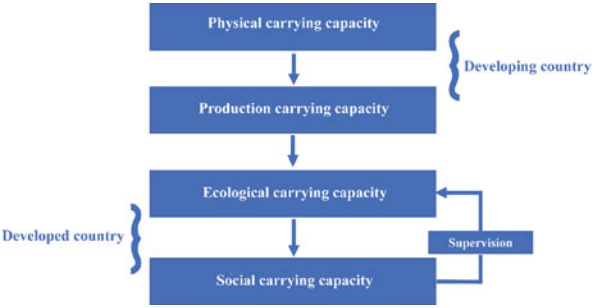
1. Scoping to understand the issues in the multi-stakeholder context in which aquaculture might develop.
2. Identifying opportunities and risks for aquaculture.
3. Evaluating carrying capacity for aquaculture development in setting the upper limits of aquaculture production given the environmental limits and social acceptability of aquaculture.
4. Allocation of user/area access and/or management rights.
5. Developing management plans for the zone/site/AMA.
6. Monitoring of the plan and adjustment over time.

With downscaling of processes for scoping, zoning, site selection, and area management for aquaculture, the research purpose becomes more specific, spatial scale becomes smaller, and more high-resolution data are required (Fig. 14.1).

14.1.2 Carrying Capacity Estimation

Estimation of carrying capacity for aquaculture development is usually considered as the primary criterion for ecosystem-based management, and then for aquaculture mapping (Ross et al. 2013). As mentioned in Chap. 3, carrying capacity estimations are multifaceted approaches, and are important for setting the upper limits of aquaculture production given the environmental limits and social acceptability of aquaculture (Ross et al. 2013), which are divided into four categories: physical, production, ecological, and social. Physical carrying capacity is based on the physical factors of the environment and the farming system. Production carrying capacity estimates the maximum aquaculture production. Ecological carrying capacity is defined as the magnitude of aquaculture production that can be supported

Fig. 14.2 The rank of carrying capacity in the developed and developing countries. Developing countries usually pay more attention to the physical and production carrying capacity, and developed countries usually pay more attention to the ecological and social carrying capacity



without leading to significant changes to ecological processes, services, species, populations, or communities in the environment. Social carrying capacity is defined as the amount of aquaculture that can be developed without adverse social impacts (see Chap. 3 for details).

Different countries have different priorities of carrying capacities defined by national or local purposes and policies, depending on the development stages of the socio-economic growth, civilization level, environmental conscientiousness, and other factors. This means that some aspects are more important than others in all multi-criteria decision processes of carrying capacity estimation (Fig. 14.2). In the developed countries there usually has considerable social pressure to regulate all aquaculture productive activities, while in the developing countries there usually has greater deregulation and political flexibility to maximize productivity (Telfer et al. 2013). In some developed countries, the stakeholders have applied spatial planning to minimize negative impacts as a prerequisite. For example, the 'Aquaculture Mapping Atlas' (https://coastalscience.noaa.gov/project/aquaculture-mapping-atlas-farm-model) has been proven to be a valuable tool, which is capable of assessing potential use conflicts and environmental interactions, for Connecticut resource managers in the United States (Bricker et al. 2016). However, in most developing countries, the main challenges of aquaculture expansion are the initial industrial site selection and subsequent expansion of aquaculture operations.

14.2 Aquaculture Zoning

In this section, we focus on the aquaculture mapping in the scale of national and subnational; in other words, we aim to describe aquaculture zoning here emphasizing the importance of ecology in this process of aquaculture mapping.

14.2.1 Factors Should be Considered for Aquaculture Zoning

Socio-economic, legal, and environmental factors that contribute to the success or failure of aquaculture activities should be considered for aquaculture zoning. At the socio-economic level, aquaculture is limited by liquidity, land availability, operator

Table 14.2 Environmental factors associated with aquaculture zoning

Classification	Parameters
Climatology	Temperature, wind, precipitation, evaporation, solar radiation, humidity
Geology	Granulometry, organic matters/nutrients, special habitats, bathymetry, soil suitability
Hydrology	Dissolved oxygen, temperature, salinity, pH, redox potential, chlorophyll a, water turbidity, nutrients (nitrates, nitrites, and phosphates), suspended solids, water supply, toxic, pollutant, discharge, yield, floods, water elevations, swell, hydrodynamic, currents, scattering, significant wave height and return period

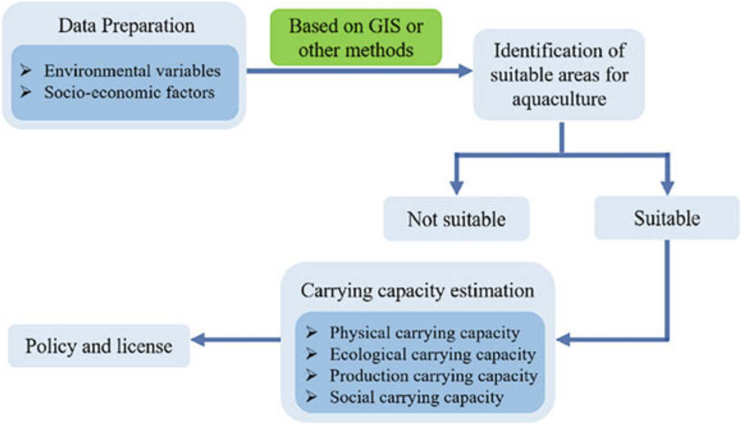


Fig. 14.3 The process of aquaculture zoning identification

skill levels, labor requirements, operating costs, and other considerations. At the legal level, the site plan should contain an analysis of local, state, and national legal requirements. Environmental constraints and factors are also essential for aquaculture spatial planning, and the environmental factors associated with aquaculture mapping are emphasized in Table 14.2.

Suitable zoning also highly depends on the mariculture species, culturing regions, culturing modes, and the surrounding environments. Ecosystem-based aquaculture mapping is focused on the impacts of the marine environment on cultured organisms. It is constantly evolving in order to accommodate changing developments, suitability of aquaculture zoning will be vital to ensure a sustainable future for the environment, ecosystems, and aquaculture activities.

14.2.2 Key Steps for Aquaculture Zoning

For aquaculture zoning, the key steps can be listed as follows (Fig. 14.3):

14.2.2.1 Identification of the Areas Suitable for Aquaculture

At present, most zoning for aquaculture carries out on a scale of subnational. As same as the scoping stage, it is hard for zoning to identify aquaculture areas exactly. It may only be possible to define in broad terms where aquaculture would most likely prosper. Some details are needed at the zoning stage: (1) define boundaries by local knowledge, field exploration, property maps, and hydrographical parameters; (2) the fundamental factors that determine the viability of a zone (Table 14.2); (3) define candidate aquaculture area following these criteria: few existing residents, abundant water supply, have basic production infrastructure (e.g. electricity, roads) and transportation, and off ecologically sensitive sites; (4) experience: pre-existing aquaculture also has an impact on the identification of aquaculture zoning. The existence of successful aquaculture farms suggests more general applicability, the failed aquaculture farms suggest more general unsuitability. But identification of aquaculture zoning should be dealt with differently under different situations and should not rely too much on experience; (5) suitability criteria: the stakeholders should formulate specific suitability criteria because those thresholds would be different according to culture mode, surrounding environment, aquaculture scale, and species. Based on the five points above, zones with potential for aquaculture and the most suitable aquaculture species can be identified.

14.2.2.2 Identification of Issues and Risks in Zoning

For identifying a suitable aquaculture zoning, it is better to know the issues and risks that those failed aquaculture zoning faced. There are a variety of issues and risks for zoning, among those factors related to the environment, diseases, climate-related risks, and users' conflicts. Firstly, identifying the type of risks is a key part of aquaculture zoning. Secondly, it needs to understand the risk impacts on the aquaculture production process, focus on the different steps (upstream and downstream aspects), and evaluate the likelihood of occurrences. Ultimately, according to actual conditions, experts would draw a risk mapping, which can be used to avoid the threat.

14.2.2.3 Broad Carrying Capacity Estimation for Aquaculture Zones

The first two steps are mainly considered the constraints on aquaculture by external factors, but ignore the environmental and socio-economic impacts that aquaculture can pose to other sectors and on itself (see Chap. 4 for more details of negative impacts). Carrying capacity estimation is in demand. Within the frame of EAA, it is more focused on ecological carrying capacity and social carrying capacity (see Chap. 3 for more details). Based on carrying capacity models, stakeholders can define the actual carrying capacity for specific species in a specific area.

14.2.2.4 Biosecurity and Zoning Strategies

Disease is probably the main threat and cause of a disaster to aquaculture everywhere and requires planning at all scales. Because of the fluidity of water, if effluents or diseases occurred from one farm, it must ensure those cannot flow onto another farm. It is a sensible approach to adopt biosecurity strategies that are known for a set of practices to minimize the introduction, establishment, and spread of pathogens. At the zoning stage, a zone may comprise one or more water catchments from the source of a river to an estuary or a lake, or only part of a water catchment from the source of a river to a barrier that effectively prevents the introduction of specific infectious agents.

14.2.2.5 Legal Designation of Zones for Aquaculture

For sustainability of aquaculture, regulations and/or restrictions should be assigned to each zone in accordance with their degrees of suitability for aquaculture activities and carrying capacity limits. Firstly, the government should develop site-specific guidelines for the areas allocated to aquaculture activities, which can be classified as 'suitable areas' 'unsuitable areas' and 'suitable areas with limits' Secondly, individual license application for aquaculture space needs to meet the standards zoning guidelines. Finally, the stakeholders carry out effective management over time. The whole management process should include implementation, enforcement, monitoring, evaluation, research, public participation, and financing.

14.2.3 Aquaculture Zoning in the Context of Climate Change

In the face of climate change, aquaculture species have also encountered dramatic changes in temperature, pH, dissolved oxygen, sea level, and extreme events. The surface temperature has risen by about 1 °C from 1850–1900 to 2010–2019, and global warming of 1.5–2 °C will be exceeded during the twenty-first century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades (IPCC 2021). The ocean has absorbed fully half of all the fossil carbon released to the atmosphere, and the pH in open ocean surface water has changed by a range of -0.017 to -0.027 pH units per decade since the late 1980s (IPCC 2019). Global subsurface pH has decreased over the past 20–30 years, with signals observed to at least 1000 m depths (Lauvset et al. 2020). Dissolved oxygen levels in the global upper 1000 m of the ocean have decreased by 0.5–3.3% during 1970–2010, alongside an expansion of oxygen minimum zones (OMZ) by 3–8% (IPCC 2019). The global mean sea level (GMSL) rose by ~0.20 m between 1901 and 2018. GMSL rise has been accelerated since the late 1960s, with an average rate of ~1.3 mm/year between 1901 and 1971 and ~3.7 mm/year between 2006 and 2018 (IPCC 2021). The frequency and intensity of extreme events are also changing. For example, the frequency and intensity of hot extremes have increased and those of cold extremes have decreased on the global scale since 1950. If global warming increases, some compound extreme events with a low likelihood in past and current climates will become more frequent, and there will be a higher likelihood that events with increased intensities, durations, and/or spatial extents unprecedented in the observational record will occur (IPCC 2021).

Climate-driven changes in global warming, ocean acidification, hypoxia/anoxia, sea level rising, and extreme events will have serious impacts on aquaculture sectors at scales ranging from individual, to farming system, to national, and global.

14.2.3.1 Global Warming

Temperature increase in an appropriate range can improve growth, and shorten the production cycle, thereby increasing the production yield. On the other hand, the original sites may not be suitable for the original species if the aquaculture species have already lived near their thermal limits, especially for those with narrow thermal ranges. The FLOW module of the Delft3D numerical model was used to analyze global warming effects in the Rías Baixas, and the results indicated that mussels became less comfortable in the context of ocean warming at the northwestern Iberian Peninsula (Des et al. 2020). A study also showed that the mortality of reared aquatic animals infected by bacterial diseases increased with increasing temperature (Reverter et al. 2020). In a study of the potential for open-ocean finfish aquaculture on a global scale, three common aquaculture species (Atlantic salmon, gilthead seabream, and cobia) representing different thermal guilds across species and regions had heterogeneous responses across species and regions to global warming (Klinger et al. 2017), implying aquaculture zoning for target species needs to consider the spatio-temporal dynamics of climate changes to reduce the climatic risks faced by long-term production and ensure the sustainability of aquaculture.

14.2.3.2 Ocean Acidification

Bivalves are particularly vulnerable to ocean acidification because the increase of $p\mathrm{CO}_2$ in seawater will reduce the CaCO_3 saturation of aragonite and calcite, which has negative impacts on the bivalves' aquaculture (Kroeker et al. 2010, 2013). The study of Pacific oysters on the Oregon coast showed that there was a negative correlation between Pacific oyster production and the naturally rising carbon dioxide levels. Growth, development, and aerobic performance of fish can also be adversely affected by ocean acidification (Franke and Clemmesen 2011; Frommel et al. 2014; Munday et al. 2009). However, some fleshy algae will be more competitive in the condition of rising CO_2 (Hepburn et al. 2011).

14.2.3.3 Hypoxia and Anoxia

Hypoxia and anoxia can negatively affect the performance of aquaculture species (Li et al. 2019a, b). Based on the theory of oxygen- and capacity-limited thermal tolerance (OCLTT), it is suggested that the biochemical and physiological capacities of aquatic ectotherms have evolved such that aerobic scope is maximized within a given temperature range in order to optimize fitness-related performance, while performance degrades as aerobic scope decreases at unfavorable temperatures (Pörtner 2010; Pörtner and Farrell 2008; Pörtner and Knust 2007). Most fishes have some capability to tolerate hypoxia, but if severe hypoxia persists, fishes are very likely to die (Cook and Herbert 2012; Fitzgibbon et al. 2007). Studies examining the impact of hypoxic conditions on fish production have shown that even partial periods of hypoxia could lead to a decline in fish growth (Pichavant et al. 2000, 2001).

14.2.3.4 Sea Level Rising

Sea level rising will allow saltwater to invade coastal farming areas, especially in lowland regions (Kibria et al. 2017). Local farming industries have to move to inland or upstream. From another point of view, it also offers new opportunities for coastal aquaculture, because of the suitable areas for the brackish water culture of high-value species (Kibria et al. 2017). Coastal aquaculture zoning should fully assess the opportunities and risks of sea level rising.

14.2.3.5 Extreme Events

Extreme events such as hurricanes, heat waves, cold snaps, and heavy precipitation can be devastating to aquaculture farming. Hurricane Katrina struck the U.S. Gulf Coast on August 29, 2005, causing widespread flooding and significant property and infrastructure damage to the fishing and aquaculture industries (Buck 2005). Acute temperature changes that exceed the thermal tolerance limits of organisms can lead to mass death of aquaculture species. Since 2013, extreme high temperatures have led to large-scale deaths of sea cucumber cultured in northern China as what will show in the section of the case study. Heavy precipitation can change salinity and can trigger flooding events. Predicting and forecasting the occurrence of extreme events are very important to guide emergency planning, and reduce the risk of aquaculture.

14.2.3.6 Impacts from Multiple Stressors

The impacts of climate changes on aquaculture are often multi-factorial. In the process of aquaculture regionalization, the joint effects of various environmental factors in the context of climate change should be considered to ensure industrial safety. Guiding aquaculture zoning requires a comprehensive assessment of aquaculture vulnerability and potential productivity under climate change. The vulnerability of global aquaculture-related livelihoods to changing climate indicates the locations where the vulnerability may occur and where further research is likely warranted. The vulnerability of freshwater aquaculture is greatest in Asia, which has a large aquaculture industry. For brackish water production, Viet Nam and Ecuador have the highest vulnerability scores. With regard to marine aquaculture, Norway and Chile are the most vulnerable due to the relative size of their respective industries (Handisyde et al. 2017). Based on heat tolerance and growth data of 180 mariculture species (finned fish and bivalves), the estimation of the potential production for global marine aquaculture under climate change showed that the suitable waters for finfish would increase, but would decrease for bivalves worldwide over the next century. Within the suitable areas for finfish aquaculture, the decline in average production gradually became more widespread over time, especially in tropical and subpolar regions. Similar trends would be observed in bivalves (Froehlich et al. 2018a).

Global climate is seriously damaging and will continuously threaten the sustainable development of aquaculture. Along with the innovation of sustainable aquaculture technology and artificial breeding, aquaculture mapping, as an important part of industry management, is urgently needed.

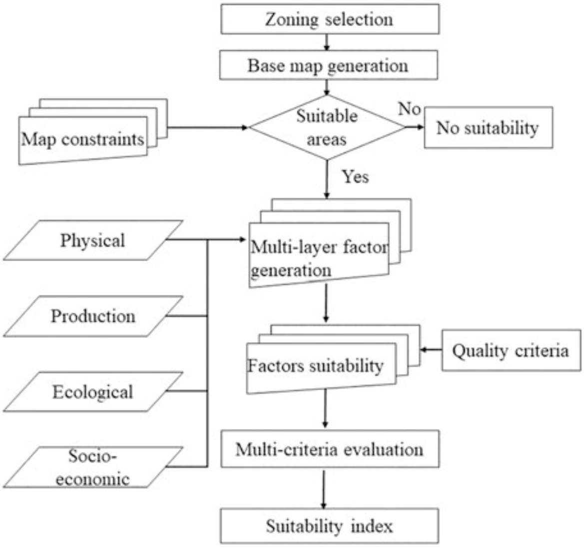
14.2.4 Methods for Aquaculture Zoning

14.2.4.1 Geographic Information Systems-Based Multiple-Criteria Evaluation

Geographic information systems (GIS) are commonly used for aquaculture site selection (Falconer et al. 2016). The GIS-based multi-criteria evolution (MCE) combines multiple variables into a structured model and can provide a holistic overview of multiple criteria (Fig. 14.4). MCE has been commonly applied for aquaculture zoning. For example, Micael et al. (2015) applied GIS-based MCE to assess suitable areas for the fish-cage farming in the Azores Archipelago (36°55′–39°43′N; 24°46′–31°16′W) and a total area of 17.1 km^2 was identified as suitable for mariculture in São Miguel Island. Radiarta et al. (2008) use GIS-based MCE to identify the suitable sites for hanging culture of Japanese scallop (*Mizuhopecten yessoensis*) in Funka Bay, Japan. In this study, remote sensing data were applied, and seven thematic layers were grouped into two basic requisites for scallop aquaculture, namely biophysical (sea temperature, chlorophyll, suspended sediment, and bathymetry) and social-infrastructural (distance to town, pier, and land-based facilities). And then a series of GIS models was developed for identifying the potentially suitable culture areas.

Sustainable development of aquaculture needs to keep the balance between aquaculture, biodiversity, and other human uses co-occurring in the region, including coastal and maritime tourism, transportation, fisheries, infrastructure for energy, and industry. To keep the balance, multiple-objective marine spatial planning approaches have been developed (Grantham et al. 2013; Yates et al. 2015). For example, to evaluate multi-objective prioritization for aquaculture and biodiversity, a systematic planning approach that develops and tests six planning scenarios

Fig. 14.4 Information flow, and framework adopted in the multi-criteria evaluation (MCE) (modified from Brigolin et al. 2017; Silva et al. 2011)



(single-objective scenarios S1–S4 and multi-objective scenarios S5–S6) in the Emilia-Romagna region of Italy was carried out, and new locations for aquaculture were prioritized by using decision support tool 'Marxan' and its advanced version 'Marxan' with zones (Venier et al. 2021).

14.2.4.2 Ecological Models for Aquaculture Zoning

Physical carrying capacity focuses on the effect of physical factors of the environment and the farming system on aquaculture and is the primary criterion for aquaculture mapping. Therefore, physical carrying capacity estimation is usually the first stage for aquaculture mapping, and it is important to quantify potential adequate and available areas for aquaculture in the ecosystem.

For evaluating the relationship between species distribution patterns and environmental factors, the species distribution model (SDM) is widely applied for assessing the suitability of habitat for site selection. For example, SDM was applied to investigate whether the Gulf of Maine is suitable for the edible brown algae *Alaria esculenta*, and these regions identified as environmentally suitable provided fundamental information for the next socioeconomic analysis (Resnick 2020). Falconer et al. (2016) found that the method combining SDM with MCE models would be more reliable. For examining the potential suitable habitats of Manila clam (*Ruditapes philippinarum*) in Moon Lake, China, an ensemble-modeling approach was implemented in the biomod2 platform. The distribution data of Manila clam with oceanographic and sediment data were applied to analyze potentially suitable areas using nine single-algorithm species distribution models. These results indicated that species distribution models are useful tools to identify suitable aquaculture sites for Manila clam farming (Dong et al. 2020).

Mechanical models can combine functional traits of cultured species with environmental data. Among the mechanical models, the dynamic energy budget (DEB) model, a robust ecophysiological model, has been widely applied to evaluate habitat suitability. As an aquaculture siting tool, DEB-based life-history trait approaches can provide quantitative information for local management and can also translate complex results into useful visual representations for stakeholders (Mangano et al. 2019). In order to assess the potential shellfish aquaculture areas and to evaluate the carrying capacities in these areas, responses of the blue mussel (*Mytilus edulis* L.) to the spatio-temporal fluctuation of the environment in Mont Saint-Michel Bay, France, were analyzed using a generic growth model based on DEB. This study confirmed that DEB was a suitable approach to evaluating the environmental effects and habitat suitability for shellfish aquaculture (Thomas et al. 2011). For selecting suitable aquaculture areas for the Pacific oyster (*Crassostrea gigas*) in shallow Mediterranean lagoons, the DEB model was also used to identify and rank the suitability of habitats to culture Pacific oysters and found that among 12 of the lagoons investigated, 11 lagoons were potentially suitable for Pacific oyster farming, indicating DEB was a powerful tool for site selection for stakeholders, policymakers, and farmers (Grantham et al. 2020).

14.3 Case Studies of Aquaculture Mapping in China

Because the production, ecological, and social carrying capacity estimations have been well described in Chap. 3, in this section, we mainly focus on three case studies about the physical carrying capacity estimation for site selection with the ecophysiological models and species distribution models (SDMs). These three case studies, including heat sensitivity of common aquaculture species in China, salmon aquaculture in the Yellow Sea, and impacts of high temperature on sea cucumber pond aquaculture, were presented.

14.3.1 Heat Sensitivity of Common Aquaculture Species in China

Global warming has caused a huge loss of mariculture in China. To make matters worse, the warming condition is deepening and it is predicted that the loss situation will be deteriorating if nothing is done to change current practices. Thus, a scientific and comprehensive assessment of the impacts of global warming on China's mariculture is urgent and important.

Using the thermal safety margin (TSM), a proxy, which is defined as the differences between the maximum environmental temperature and upper thermal-tolerance limit for each species across its aquaculture region, Ma et al. (2021) assessed the thermal sensitivity of mariculture species in China with the consideration of culturing region and production modes in use. The authors collected the upper thermal limits of 42 commercially important culturing species as well as the information on culturing modes in production practice, extracted the maximum environmental temperatures along China's coast under the current situation and two RCP scenarios (RCP4.5 and RCP8.5), and calculated TSMs with these data (Fig. 14.5). There are significant differences in heat tolerance among species cultured in different regions by comparing different species' upper thermal limits, and the southern species are more heat-tolerant than the northern species. According to the different species' TSMs calculated, ten species, particularly the abalone (*Haliotis discus hannai*), the scallop (*Patinopecten yessoensis*) and the pufferfish (*Takifugu rubripes*), fat greenling (*Hexagrammos otakii*) are considered as the most sensitive aquaculture species, which means the production of these species may be affected seriously under current warming situation. By comparing the averages of all species' TSMs cultured in the same region, some culturing regions, especially locations in 31–34°N (Jiangsu Province) and 38–39°N (Tianjin Municipality, Hebei, and Shandong Provinces) may meet catastrophic influences caused by high temperature and potential extreme heatwave and require additional attention during culturing process. Under RCP4.5 and RCP8.5 scenarios, it is predicted that the situation will become even worse in 2050. To compare the sensitivity of various mariculture modes in China, the authors calculate the TSMs in different production modes and find that pond farming and mudflat ranching are more vulnerable mariculture systems among different mariculture modes as the species cultured in these modes has lower TSM values compared to other mariculture modes.

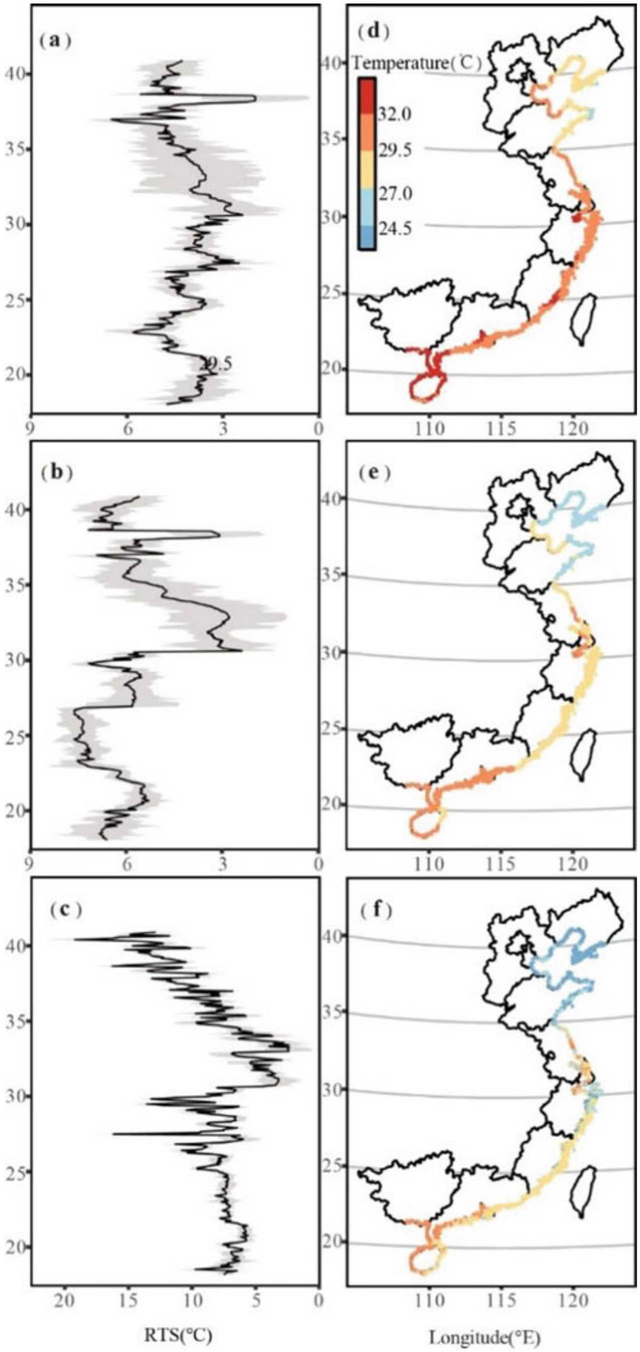


Fig. 14.5 Thermal sensitivity of different species, culturing regions, and models. (**a**, **d**) Culturing models coastal land models (CLMs); (**b**, **e**) sea-surface models (SSMs), and (**c**, **f**) sea-bottom models (SBMs). (**a**–**c**) Regional thermal sensitivity (RTS) along China's coast; (**d**–**f**) maximum temperature at each grid cell (from Ma et al. 2021)

This study implies that similar to what happens in other countries, the mariculture industry in China is under great threat from high temperatures in the future under present environmental conditions and will be even more vulnerable to heat in the future. Therefore, it is necessary to formulate and adopt timely and effective measures to minimize the impact of warming on aquaculture. Additionally, a much more precise evaluation project on the effect of global warming on the future development of China's mariculture industry needs to be launched, and a timely and effective risk assessment model in the aquaculture regions is crucial for the sustainable development of aquaculture, which both are crucial for future policy designation and spatial distribution in mariculture industry under the constant warming situation.

14.3.2 Offshore Aquaculture of Salmon in the Yellow Sea

The high density of mariculture, the frequent occurrence of diseases, and the deterioration of the environment have become increasingly prominent in coastal aquaculture. For keeping the balance between economic development and environmental protection, aquaculture space expansion has been encouraged recently. To alleviate the problems of environmental pollution and resource constraints on coastal and land, offshore mariculture has been encouraged by central and local governments in recent years. The pioneer program of offshore aquaculture is the net pen aquaculture of salmon and trout, 'Deep Blue 1', in the Yellow Sea Cold Water Mass (YSCWM). Because most salmons are cold-water fish species, and are sensitive to high temperature, it is crucial to figure out the appropriate locations for allocating net pens of salmon and trout culture with high spatio-temporal resolutions in the temperate regions. The YSCWM is a seasonal water mass, with extremely high seasonal and vertical variations. It extends from the Liaodong Peninsula to the East China Sea, covering one-third of the deep Yellow Sea, and has three cold centers. It usually forms in May and June, peaks in July and August, and dissipates completely in December (Yu et al. 2006). For culturing cold-water fish species in YSCWM, the spatio-temporal heterogeneity of the thermal environment at meso- and micro-scale needs to be fully considered to avoid the damage from high temperature.

For predicting the potentially suitable culture regions of Atlantic salmon (*Salmo salar*), one of the most commonly commercially farmed salmonids, species distribution models (algorithms including maxent, random forests, support vector machines, and boosting regression tree) of *S. salar* were constructed and the suitability index for culturing *S. salar* was estimated, with the global distribution data of *S. salar* from Global Biodiversity Information Facility (GBIF, https://www.gbif.org/) and environmental data from Bio-ORACLE (https://www.bio-oracle.org/) and World Ocean Atlas 2018 (https://www.ncei.noaa.gov/access/world-ocean-atlas-2018/). The results showed that the suitable aquaculture areas for *S. salar* are highly dynamic in different water layers. At the layers of 0–15 and 15–30 m, the suitability index is low from June to November, but the suitability index in most areas of the Yellow Sea

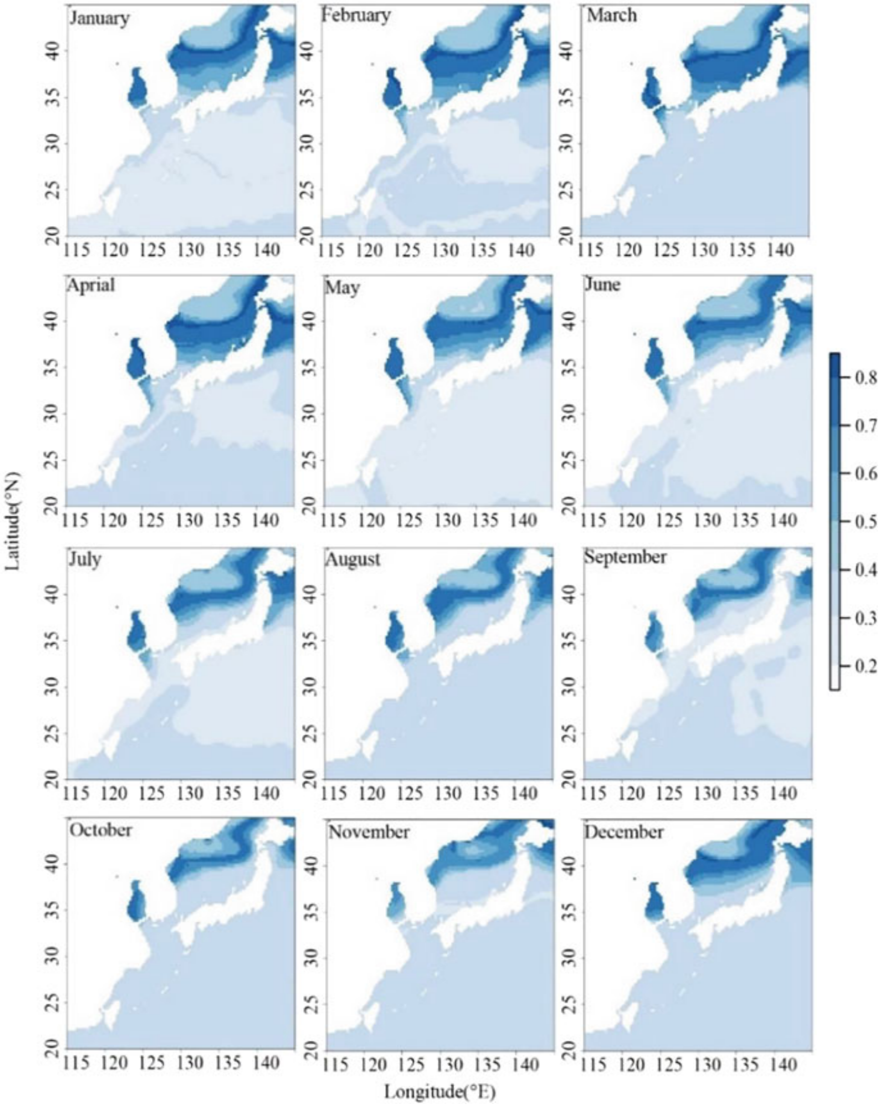


Fig. 14.6 The suitability index for culturing Atlantic salmon (*Salmo salar*) in the water layer of 45–60 m in the Yellow Sea

is high in the other seasons. On the other hand, at the water layer of 45–60 m, high suitability index for culturing *S. salar* occurs throughout the year (Fig. 14.6).

These results provide useful information for offshore aquaculture of salmon. For adapting to the temperature environments in the YSCWM, in summer, the cage can be sunk into the water layer of 45–60 m to avoid damage from high temperatures. In the other seasons, the cage can be adjusted to the appropriate water layer to reduce the farming cost and risks from high temperatures. Overall, it is feasible to farm *S. salar* and other cold-water fish in the Yellow Sea with the consideration of the highly heterogeneous temperature environments. Furthermore, species distribution models that consider the spatio-temporal heterogeneity of the meso- and micro-scale thermal environment are helpful for identifying the potential offshore mariculture regions for improving aquaculture production in the context of global warming.

14.3.3 Impacts of Extreme High Temperature on Pond Aquaculture of Sea Cucumber

Sea cucumber (*Apostichopus japonicus*) is an important aquaculture species in northern China. As a typical temperate species, sea cucumber is sensitive to high temperature. When the temperature exceeds its upper thermal tolerance limit, there are a series of complex physiological responses in sea cucumber, even leading to large-scale death. Nowadays, pond culture is the important mode of sea cucumber aquaculture in China. Due to the shallow water of pond aquaculture, the water temperature is closely related to the local air temperature. High temperature and extreme heat events in summer are notorious environmental factors damaging the sea cucumber pond aquaculture. Since 2013, there has been continuous high-temperature weather during summer in the sea cucumber aquaculture areas, and the high temperature has brought a devastating blow to the pond aquaculture industry of sea cucumber, especially in 2018, the main production areas of sea cucumber were affected by extreme high-temperature with a total economic loss of ~2.3 billion dollars.

For evaluating and predicting the effect of high temperature on sea cucumber pond aquaculture and selecting suitable aquaculture areas, hourly summer temperature data (July to August) in 2011–2020 were collected and the 99th percentile high temperature value (T_{99}) of each grid point was defined as the intensity of extreme high temperature in each year. The relationship between temperature and survival rate in the literature was also collected as a physiological proxy of the sea cucumber and then used as a thermal performance curve which was simulated by a three-parameter logistic model. The semi-lethal high temperature of the sea cucumber is ~32 °C, thus the ambient temperature that is higher than 32 °C is defined as a disaster-causing temperature, and whenever the ambient temperature exceeds the disaster-causing temperature is recorded as a disaster-causing event. The vulnerable areas of the sea cucumber pond aquaculture to high temperature were ranked based on the disaster-causing event frequency.

From 2011 to 2020, the pond aquaculture areas of sea cucumber in northern China encountered the disaster-causing temperature. The total disaster-causing event frequency has shown a clear increasing trend from 2011 to 2018, and the affected areas have also kept increasing, 10% of areas for sea cucumber pond aquaculture suffered from the disaster-causing temperature in 2011 while more than 40% of the area experienced disaster-causing temperature in 2018. In 2019 and 2020, 20% of areas suffered from the disaster-causing temperature. The high frequency of disaster-

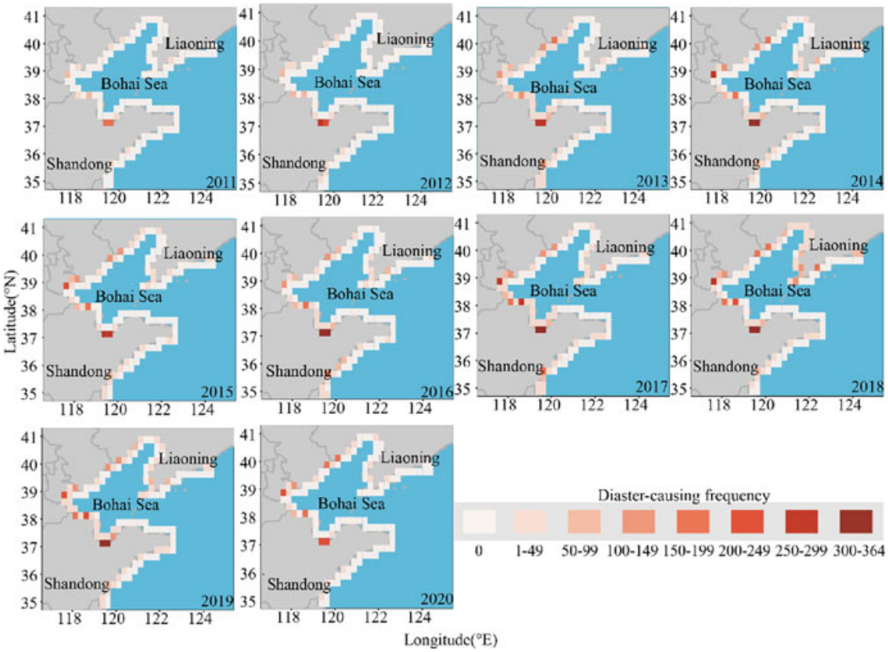


Fig. 14.7 The disaster-causing event frequency of sea cucumber pond aquaculture in northern China from July to August 2011–2020

causing events mainly occurred in the southwest Bohai Sea and the Liaodong Bay (Fig. 14.7). Under the scenarios of RCP2.6 and RCP8.5, T_{99} will continue to rise in most coastal areas in northern China, and can even reach 40 °C in some regions. Under the impacts of global warming, those previous aquaculture areas would possibly no longer be suitable for the culture of sea cucumber, and the risk of high temperature will increase throughout the bays of the Bohai Sea.

This study implies that sea cucumber pond aquaculture in China is sensitive to extreme high temperature in the past and will be even more vulnerable to the extreme high temperature in the future. Therefore, in the context of intensified extreme high temperature events and global warming, the establishment of micro- and meso-scale risk assessment models are in demand. The development of the sea cucumber pond aquaculture needs to fully consider the local temperature conditions and establish an adaptative management plan for coping with the increasing extreme high temperature in the future.

Brief Summary

1. Aquaculture mapping, including process of scoping, zoning, site selection, and aquaculture management areas, is important for balancing aquaculture, biodiversity, and other human uses activities.

2. The Ecosystem Approach to Aquaculture (EAA), defined as a strategy for integrating aquaculture within broader ecosystems, is a framework currently being implemented by FAO for aquaculture mapping to promote sustainability, equity, and resilience of interconnected social and ecological systems.
3. Socio-economic, legal, and environmental factors should be considered for aquaculture zoning. Ecosystem-based aquaculture mapping is focused on the impacts of the marine environment on cultured organisms, especially in the context of climate change. It is constantly evolving in order to accommodate changing developments, suitability of aquaculture zoning will be vital to ensure a sustainable future for the environment, ecosystems, and activities.
4. For aquaculture zoning, the key steps include identification of areas suitable for aquaculture, identification of issues and risks in zoning, broad carrying capacity estimation for aquaculture zones, biosecurity, and zoning strategies, and legal designation of zones for aquaculture.
5. Global climate change, including global warming, ocean acidification, hypoxia and anoxia, sea level rising, and extreme events, seriously threatens the sustainable development of aquaculture. The impacts of climate changes on aquaculture are often multi-factorial. In the process of aquaculture regionalization, the joint effects of various environmental factors under climate change should be considered.
6. Geographic information systems (GIS) were commonly used for aquaculture site selection. The GIS-based multi-criteria evolution (MCE) combines multiple variables into a structured model and can provide a holistic overview of multiple criteria.
7. Ecological models, including correlation and mechanical models, for aquaculture zoning, have been applied recently.
8. Species distribution model (SDM) as the representative of the correlation model is useful to quantify the potential suitable areas for aquaculture in the view of physical carrying capacity.
9. Among the mechanical models, the dynamic energy budget (DEB) model, a robust ecophysiological model, has been widely applied to evaluate habitat suitability.

Sustainability of Aquaculture Production Systems

15

Shuang-Lin Dong and Yun-Wei Dong

To alleviate the constraints of factors such as land and freshwater resources on aquaculture development, there is a trend worldwide toward the intensification of aquaculture systems. However, the agricultural practice of the world in the last decades has proved that simplistic intensification of agriculture systems has paid high prices while increasing crop production and production efficiency, such as land degradation, loss of soil organic matter and nutrients, depletion of water resources, and water pollution. Therefore, the concept of sustainable intensification of agriculture is proposed by some scholars, seeking to increase crop yields and associated economic returns per unit time and land without negative impacts on soil and water resources or the integrity of associated non-agricultural ecosystems (Tilman et al. 2011; Cassman and Grassini 2020). In view of this, sustainable intensification should also be a pattern for the development of aquaculture.

The goal of sustainable development of aquaculture systems can be achieved through ecological intensification, that is, integrating anthropogenic inputs with aquaculture ecosystem services. This chapter will introduce the multidimensionality of aquaculture systems, and the relationships of intensification degree with economic efficiency and ecological footprints, so that we can better understand the sustainability of aquaculture systems and the future development pattern of the aquaculture industry.

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15.1 Multidimensionality of Aquaculture Systems

With the intensification and scaling up of aquaculture systems, modern aquaculture systems have become more than just food production and economic value proliferation; their interactions with other systems have gradually intensified, and the multidimensionality of their functions or roles has become increasingly clear (Fig. 15.1). This strengthening of the multidimensionality of aquaculture systems will inevitably influence the future development pattern of the aquaculture industry.

The sustainability of aquaculture systems is related to numerous factors about economy, society, resources, and environment. Economic and social factors (e.g., economic development, food security, employment, etc.) may promote aquaculture development, resource constraints (e.g., land, freshwater, fishmeal) may constrain aquaculture development, and environmental factors (e.g., ecological footprints, water footprint, etc.) as well as policy are also fatal factors. This section will briefly introduce the driving effect of economic and the influence of some resource factors on aquaculture.

15.1.1 Economic Functions of Aquaculture Systems

There is no way to prove who was responsible for the earliest aquaculture activities at the Jiahu site in China 8000 years ago, but it can be assumed that the earliest aquaculture systems were established for food production. It was not until the Warring States Period or earlier that aquaculture developed to a certain scale and produced a surplus of farmed fish for their own consumption, and it became natural to buy and sell these surplus farmed fish 'commodities'. According to the book 'Fish Farming' written by FAN Li in 460 BC, the farmed carp had been traded. Thus, during the Warring States Period at the latest, aquaculture was no longer a mere food production activity, but also an economic activity.

In the 1950s and 1960s, with the application of aerators, floating PE or PVC net cages, and pelleted feed, aquaculture began to expand to a larger scale rapidly, open water began to be used for aquaculture, and apparent economic benefits (economic

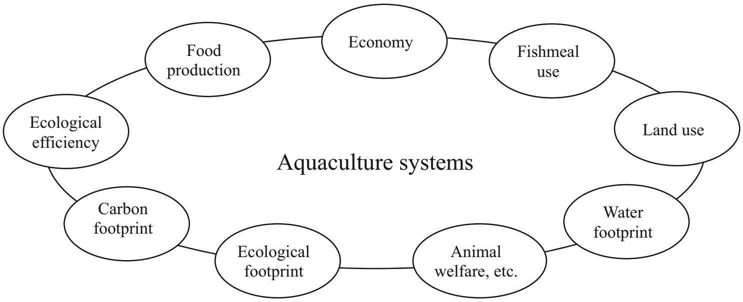

Fig. 15.1 The multidimensional natures of aquaculture systems (modified from Dong 2019a)

Table 15.1 Annual economic accounting of six aquaculture systems in China (from Dong 2019a)

Systems	Stocking density (kg/hm^2)	Total economic input (CNY/hm^2)	Total economic output (CNY/hm^2)	Income (CNY/hm^2)	Output-input ratio
Extensive monoculture of sea cucumber in pond	4.60×10^2	1.10×10^5	1.81×10^5	7.02×10^4	1.65
Intensive monoculture of grass carp in pond	1.51×10^3	4.81×10^4	5.65×10^4	0.85×10^4	1.17
Intensive polyculture of carps in pond	1.56×10^3	3.97×10^4	5.95×10^4	1.98×10^4	1.50
Semi-intensive monoculture of shrimp in pond	7.92	1.60×10^4	2.94×10^4	1.34×10^4	1.84
Flow-through for turbot	–	1.355×10^6	2.511×10^6	1.156×10^6	1.85
Indoor intensive monoculture of sea cucumber	1.25×10^4	6.53×10^6	8.00×10^6	1.48×10^6	1.23

benefits regardless of environmental costs) increased significantly. The economic nature of aquaculture systems can lead to a commitment to maximize economic profits and to improve (economic) input-output ratios. This can undoubtedly push up quickly the level of research and technology in aquaculture, such as the selection of the most appropriate species for culture, the use of economically efficient feeds, and the exploration of optimal stocking densities. The income per unit area in the highly intensive culture systems is substantially higher than in the extensive culture systems, rising from ~10,000 CNY/hm^2 to more than a million CNY/hm^2 (Table 15.1). This is the main intrinsic driver of the enthusiasm for aquaculture intensification. However, the negative impacts of simplistic intensification on wild fish resources and the environment are too serious to be ignored.

Aquaculture system is both a subsystem of natural ecosystem and a subsystem of socio-economic system, and its development is governed by both natural endowments and economic laws, therefore, it would be biased to study it solely by ecological or economic methods.

15.1.2 Linkages between Aquaculture and Wild Fish Resources

Aquaculture is closely linked to wild fish resources. The development of aquaculture can relieve fishing pressure on wild resources. Meanwhile, aquatic seedling breeding facilities can also be used to proliferate fishery resources in natural waters and marine ranching. If done properly, aquaculture may be beneficial to the restoration of wild fish resources and biodiversity conservation in the natural waters. On the contrary, aquaculture has been mainly concerned in terms of its consumption of fishmeal and fish oil, which was ever called 'fishmeal trap' (Naylor et al. 1998).

The production proportion from fed species in total global aquaculture production is increasing, rising from about 59% in 2000 to 69.5% in 2016 (FAO 2018). About 41% of China's aquaculture production was obtained from fed species in 2008 (Dong 2009b), rising to 47% in 2016 (Dong 2019a). The production proportion from fed species in China is significantly lower than the world average due to the large-scale culture of the filtering-feeding species, including marine bivalves and freshwater carps. Considering production and species, China's aquaculture industry is one of the most ecologically efficient animal food production systems in the world (Gui et al. 2018; Larsen and Roney 2013).

Aquafeeds contain a certain amount of fishmeal and fish oil from wild fish resources. Four major advances along the aquaculture supply chain have been developed to reduce the consumption of wild fish resources over the last 20 years: rapid growth in omnivorous species production; improved feed conversion ratios for fed species; increased use of alternative protein and oil ingredients in feed; and increased production and use of fishmeal and fish oil from fish-processing wastes and bycatch (Naylor et al. 2021). However, it cannot be ignored that the share of global fishmeal used by the aquaculture industry increased to 69% in 2016 from 33% in 2000, while the share of global fish oil increased to 75% from 55%.

International fishmeal production capacity is in the range of 5–7 mt, and its production fluctuates largely affected by the oceanic phenomena, e.g., El Niño (Boyd and McNevin 2015). The limited and unstable international supply of fishmeal and rapid increases of the demand for fishmeal has triggered the general upward trend in world fishmeal prices.

The use of plant-based ingredients from terrestrial systems has been increasing steadily. Therefore, land and freshwater are needed to grow the crops used as aquafeed ingredients, so the land use and water consumption of farmed aquatic products will increase accordingly when plant protein replaces fishmeal (see following sections for details). Therefore, fishmeal substitution remains an issue that requires in-depth, systematic research (Powell 2003; Jennings et al. 2016; Mente et al. 2019).

15.1.3 Food Production Functions of Aquaculture Systems

In terms of trophic level, aquaculture production systems can be divided into three categories: the systems that directly cultivate aquatic plants, such as kelp cultivation; the systems that convert plant proteins into animal proteins, such as feeding grass carp with grass; and the systems that convert low-value animal proteins into high-value animal proteins, such as culturing Mandarin fish using diet fish. While the first two types of systems are essentially net food-producing systems, the third type of system is diverse in net food-producing. For example, the system that primarily cultures zooplankton-feeding fish such as bighead carp has the function of net

Table 15.2 Mean feed conversion ratios (*FCR*) and retention values of farmed animals (from Jillian et al. 2018)

Species	*FCR*	Feed/edible weight	Protein retention values[a]	Calorie retention values[b]
Common carp	1.7	3.78	0.15	0.09
Grass carp	1.7	3.78	0.18	0.09
Channel catfish	1.4	2.87	0.18	0.11
Pangasius catfish	1.4	3.02	0.17	0.09
Atlantic salmon	1.3	1.77	0.28	0.25
Rainbow trout	1.3	2.14	0.22	0.16
Giant tiger prawn	1.7	4.25	0.14	0.06
Whiteleg shrimp	1.7	2.68	0.22	0.09
Tilapia	1.7	4.17	0.18	0.07
Weighted average	1.6	3.08	0.19	0.10
Beef cattle	8.0	14.0	0.13	0.07
Pigs	3.9	5.34	0.21	0.16
Chicken	1.9	2.57	0.37	0.27

[a]Protein retention value = (protein in edible portion)/(protein in feeds); [b]Calorie retention value = (energy in edible portion)/(energy in feeds)

protein producing, while the systems that culture fed species are generally not net protein producing systems.

The feed conversion ratios (FCR) of the world's nine most important aquaculture species are 1.6 in average, but their average protein and energy retention values are only 0.19 and 0.10, respectively (Table 15.2). In terms of material balance, there is no net increase in protein production from fed species culture; rather, more protein resources are consumed while producing these aquatic products. However, fed species culture economically achieves protein appreciation function. Of course, most of these fed aquaculture systems take the 'feed' that people can't or don't like to eat, and use farmed animals to convert it into more economically valuable and edible aquatic products.

In terms of FCR, aquaculture animals have higher utilization of feeds than livestock, but in terms of feed protein retention values, there is little difference between aquaculture animals and livestock (Table 15.2). By reducing fishmeal and fish oil inclusion ratios and increasing the use of fishmeal from trimmings, the ratio of wild fish inputs to farmed fish output (FIFO) has been lowered to 0.28 in 2017 for the fed species groups in aquaculture (Naylor et al. 2021). Currently, the production share of fed species in aquaculture in China and the world is still increasing, which indicates that the economic function of aquaculture systems is strengthening.

15.1.4 Land Use by Aquaculture

Globally, 37.8% of the land, or 49.12 million km^2, is used for agriculture including aquaculture. The surface area of aquaculture ponds is about 117,000 km^2, and together with ancillary land and other land-based aquaculture facilities, the areas for aquaculture are a total of about 224,000 km^2, which is 0.17% of the land area (Boyd and Mcnevin 2015). Aquaculture land is mainly converted from agricultural land, mudflats, freshwater wetlands, mangroves, etc. Aquaculture requires a large amount of land for producing plant meals of aquafeeds, in addition to constructing ponds, embankments, water supply and distribution systems, etc.

In 2018, the area of seawater ponds in China was 400,000 hm^2, the area of freshwater ponds was 2.667 million hm^2, and the area of paddy field aquaculture was 2.028 million hm^2, and their production accounted for 4.9%, 44.3%, and 4.7% of the total aquaculture production in China, respectively. In terms of production, pond aquaculture that takes up land resources accounts for half of China's aquaculture. Urbanization in China is squeezing the space occupied by pond aquaculture, while at the same time, the area of waterlogged salt-alkali land aquaculture and paddy field aquaculture is still expanding.

The efficiency of land use varies considerably among aquaculture species because of differences in food habits. For example, the production of 1 t of carnivorous rainbow trout uses only 0.081 hm^2 of land area for plant meals, while the production of 1 t of omnivorous tilapia requires 0.402 hm^2 of land (Table 15.3). This is mainly due to the fact that tilapia feed contains a large amount of plant meals that need to be grown on land, while the 1350 kg of diet fish needed by rainbow trout is from marine capture. So, farmed tilapia is more dependent on land, while farmed rainbow trout is more dependent on wild fish resources.

The average productivity of pond aquaculture of the world is about 2.04 t/hm^2 (including the land for plant meal ingredients in feed), while the productivity of land (including pasture and plant meal) for livestock is 0.23 t/hm^2 (Boyd and Mcnevin 2015). It is evident that aquaculture uses land more efficiently than livestock and poultry. The results of the scenario analysis by Froehlich et al. (2018b) showed that increasing the consumption of farmed aquatic food product over land-raised animal meat could potentially reduce the amount of land required for growing feed crops for a global population expected to reach nine billion people by 2050. Although the development of the aquaculture industry relies more on market, government guidance and social advocacy can also play an important role in better food security and gradual change in people's dietary habits.

Table 15.3 Land required to produce plant meals and live fish needed for fish meal in feed to produce 1 t of some common aquaculture species (from Boyd and Mcnevin 2015)

Species	Land area for plant meals (hm^2)	Live fish for fish meal (kg)
Atlantic salmon	0.074	1350
Trout	0.081	1350
Shrimp	0.220	1710
Tilapia	0.402	486
Channel catfish	0.388	198

There is limited land for aquaculture in general, about 0.17% of the global land surface (Boyd and Mcnevin 2015), however, the land used for aquaculture is originally from the land for agriculture, mangroves, and other coastal or freshwater wetlands. There is a great deal of public concern about the damage to mangroves caused by aquaculture and the impacts of some concentrated ponds on the environment in local areas.

15.1.5 Use of Waters by Aquaculture

70.8% of the earth's surface is covered by water, of which inland waters cover 4.578 million km^2. A total of 201 km^3 of freshwater, mainly in China, was used for inland aquaculture globally in 2010 (Boyd and Mcnevin 2015). In 2018, 746,000 hm^2 of inland lake area and 1.442 million hm^2 of reservoir area were used for aquaculture in China, mainly for fish farming. The area of nearshore mariculture in China was 1.14 million hm^2, the area of mudflat mariculture was 596,000 hm^2, and the area of seawater pond culture was 400,000 hm^2. 60.7% of the mariculture area was used for mollusk culture, 14.4% for crustacea culture, and 11.7% for sea cucumber culture in China.

The total area of available nearshore and mudflats for mariculture is about 2.4 million hm^2 in China, most of which has been utilized, and overload phenomena have appeared at some local areas. However, China has 34 million hm^2 of sea area between -20 m isobath and -40 m isobath (Han and Wang 2013), so there is still a lot of space for the development of offshore aquaculture, especially deeper-offshore aquaculture.

15.1.6 Impacts of Aquaculture on the Environment

The interaction between aquaculture and the environment, focusing on the direct impact of the farming activity on the environment, is introduced in Chap. 4. In fact, the impacts of aquaculture on the environment include all aspects of the process (from 'cradle to grave'), i.e., obtaining raw materials and energy from the nature, producing aquatic products, storing, transporting, and marketing the products until it is consumed.

The environmental impacts of aquaculture activities are multifaceted, including eutrophication, pressure on natural resources (water, energy, and wild fish), loss of biodiversity, biological invasions, genetic risk, disease transmission, carbon emission, acidification, etc. Therefore, we need methods or tools, like ecological footprints to assess the environmental impacts of aquaculture activities comprehensively.

15.2 Ecological Footprint of Aquaculture

15.2.1 Ecological Efficiency and Ecological Footprint

The ecological efficiency of aquaculture systems (the conversion efficiency of input materials and energy in the systems) has long been a central concern. The aim of constructing stable and efficient aquaculture ecosystems with balanced decomposition, production, and consumption is to increase the effective accumulation of useful substances in the aquaculture systems during the circulation of materials. For example, we optimized the structure of integrated aquaculture of shrimp, clam, and seaweed in ponds (Table 9.3), which resulted in a 6.75-fold increase in photosynthetic energy conversion efficiency, a 1.45-fold increase in input N utilization, and a 2.39-fold increase in input P utilization over the monoculture system. Nowadays, people have begun not only to look at the ecological efficiency, but also to pay attention to the relationship between aquaculture and its surrounding environment. Especially with the development of shrimp and Atlantic salmon farming, their negative impacts on the environment have attracted extensive attention from international scholars (Naylor et al. 1998, 2000). There is also an urgent need to quantify the full range of environmental impacts of aquaculture activity. The ecological footprint is one of the theories and approaches for a more comprehensive understanding of the environmental impacts of aquaculture.

The ecological footprint is the metric to measure how much nature we have and how much nature we use. The ecological footprint of aquaculture is a measure of the environmental impact of resource consumption and waste discharge from aquaculture operation. The common methods used to quantitatively study the ecological footprint include life cycle assessment (LCA), input-output analysis, etc. LCA assesses all the environmental impacts associated with a product as described in the following.

15.2.2 Life Cycle Assessment

15.2.2.1 The Concept of LCA

Life cycle assessment is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use stages, to waste management (Hauschild et al. 2018). The concept of LCA helps to break the end-of-pipe management concept of 'pollution only comes from a chimney'. LCA framework is mature, the analysis process is standardized, and the quantitative results are reliable, so it has become a conventional method for the calculation of footprint indexes.

15.2.2.2 The Methodological Phases of LCA

The methodological phases of an LCA typically include major four interrelated components: goal and scope definition, inventory analysis, impact assessment, and interpretation of results (Hauschild 2018).

15.2.2.2.1 Goal and Scope Definition

An LCA starts with a well-considered and deliberate definition of the study goal. The scope definition, on the other hand, describes the functional units of the product system in the study, system boundaries, data distribution procedures, data requirements, and raw data quality requirements.

The goal definition and the ensuing scope definition are very important to consider when the results of the study are interpreted since these definitions involve choices that determine the collection of data and the way in which the system is modeled and assessed. They therefore have a strong influence on the validity of the conclusions and recommendations that are based on the results of the LCA.

15.2.2.2.2 Inventory Analysis

Inventory analysis is the process of creating an inventory of the input and output data in the system under study. Inventory analysis consists mainly of data collection and computation to quantify the relevant inputs and outputs in the product system. The first step is to prepare the data collection by building a life cycle model based on the scope of the study identified. Then data collection is performed and calculations are made based on the collected data to aggregate the inventory results of the product life cycle.

15.2.2.2.3 Impact Assessment

The purpose of impact assessment is to evaluate the environmental impact of the product life cycle based on the results of the inventory analysis phase, which is the central part of the LCA process and also the most difficult part. It is the process of qualitative analysis and quantitative assessment of the environmental impact of various waste discharge obtained in the inventory analysis phase, that is, determining the environmental impact caused by the use of energy and resources.

Rather than focusing on the environmental impacts that actually occur, LCA applies the resource and energy input data and waste discharge data to the impact potentials through a series of characterization methods in order to quantitatively assess the contribution of various input and output items to the environmental impact potential. Assessment of aquaculture systems can include climate change, eutrophication, acidification, energy use, and so on (Table 15.4).

15.2.2.2.4 Interpretation of Results

This is the final phase of the LCA and is to identify the main issues in the product life cycle and assess the results, including integrity, sensitivity, uncertainty, and consistency checks, and thus give conclusions, limitations, and recommendations.

Each of the first three phases of the LCA can be interpreted independently of the analysis results, or an interpretation of unified life cycle results can be made after the completion of the first three phases. For example, interpretation of the results of the inventory analysis stage can clarify the quantitative relationships of various input items in the production process and determine the total amount of energy and resources consumed per unit of product. The interpretation of the whole LCA results can identify the main problems of the system, including the source of the data

Table 15.4 Impact categories commonly used in aquacultural LCAs (from Cao et al. 2013a)

Impact category	Characterization factor	Category indicator	Equivalency unit	Interpretation	Spatial	Temporal
Climate change	Global warming potential (GWP)	CO_2	$kgCO_2$	Atmosphere absorption of infrared radiation	Global	Decades/ centuries
Eutrophication	Eutrophication potential (EP)	PO_4	Kg PO_4	Nutrient enrichment	Regional/ local	Years
Acidification	Acidification potential (AP)	SO_2	Kg SO_2	Acid deposition	Regional	Years
Energy use	Energy use potential (EUP)	MJ	MJ	Depletion of non-renewable energy resource	Regional/ local	Centuries
Biotic resource depletion	Biotic resource depletion potential (BDP)	NPP	Kg C	Depletion of renewable resources	Regional/ local	Years
Abiotic resource depletion	Abiotic resource depletion potential (ADP)	Sb	Kg Sb	Depletion of non-renewable resources	Local	Centuries
Human toxicity	Human toxicity potential (HTP)	1,4-DB	Kg 1,4-DB	Toxic to humans	Local	Hours/days/ years
Ozone depletion	Ozone depletion potential (ODP)	CFC	Kg CFC	Stratospheric ozone breakdown	Global	Decades/ centuries
Photochemical oxidant	Photochemical oxidant potential (POP)	C_2H_4	Kg C_2H_4	Photochemical smog	Regional/ local	Hours/days

Note: *1,4-DB* 1,4-dichlorobenzene, *CFC* chlorofluorocarbon, *NPP* net primary productivity inventory (e.g., resource consumption, energy consumption, waste discharge, etc.), the selection of environmental impact indicators (e.g., global warming potential, eutrophication potential, acidification potential, human toxicity potential, etc.) and the contribution analysis (e.g., the contribution of various resources, energy, and discharge to environmental impact).

15.2.3 Ecological Footprint of Different Aquaculture Systems

In order to identify the environmental impacts of different intensification levels of aquaculture systems, three farms for sea cucumber with intensive, semi-intensive, and extensive culture models in Qingdao, China, were studied in 2013 (Wang et al. 2015b).

15.2.3.1 Goal and Scope Definition of the Systems

In order to compare the differences in energy consumption and environmental impact of the three farming systems, the scope of this study is defined as the energy consumption and waste discharge from seedling stocking to commercial products of the sea cucumber departure from the farm gate, including farm construction and farming processes. The raw materials used for farm construction include mainly concrete, steel, polyethylene, PVC, and bricks or tiles; the energy sources include electricity, coal, and diesel; and the waste discharged includes CO_2, CO, NO_x, SO_2, COD, CH_4, N, and P. Since there are no differences in the subsequent wholesale and retail, handling, and processing of the products from the three farming systems, they are not included in the scope of this study. The study assumes no differences in the seedling and feed used in the three systems. The production of 1 t of fresh sea cucumber by each system is defined as the functional unit of the study.

15.2.3.2 Inventory Analysis of the Systems

The data collected are listed in Table 15.5. In the indoor intensive farming system, the infrastructure materials include concrete, steel, PVC, PE, and bricks, while the construction of the two semi-intensive and extensive farming systems in ponds is relatively simple, using a small amount of concrete, steel, PE, and bricks. In this study, it is assumed that the service life is 10 years for concrete, steel, and bricks, and 4 years for PVC and PE.

Electricity use in the intensive system is mainly from water pumps and aerators. Coal is primarily for cold season warming. Auxiliary power generators use diesel. In the semi-intensive system there are no inputs of PVC or coal inputs, and in the extensive system there are no inputs of PVC, feed, electricity, or coal. The transport radius of materials used for construction and farming processes is assumed to be 50 km for all the three culture systems.

Table 15.5 Inputs and outputs for the production of 1 t of fresh sea cucumber from three farming systems (from Wang et al. 2015b)

Note item	Units	Intensive system indoor	Semi-intensive system in pond	Extensive system in pond
General system parameters				
Total culture volume	m^3	500	40,000	40,000
Average stocking density	Kg/m^3	1.250	0.050	0.046
Inputs				
Concrete	Kg/t	1840	57.1	66.5
Steel	Kg/t	57.8	1.90	2.22
Polyvinylchloride	Kg/t	20.0	0.00	0.00
Polyethylene	Kg/t	556	28.6	27.7
Bricks or tiles	Kg/t	111	3.81	4.43
Feed	Kg/t	1146	53.5	0.00
Electricity	kWh/t	10,000	2857	0.00
Coal	Kg/t	8340	0.00	0.00
Diesel	L/t	97.0	3.53	3.75
Outputs				
Harvests	Kg	1000	1000	1000
N discharge to water	Kg/t	80.6	−105	−125
P discharge to water	Kg/t	90.4	−830	−1106

15.2.3.3 Impact Assessment and Interpretation of Results of the Systems

Based on the relevance of the life cycle inventory data to the environment, global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), photochemical oxidant potential (POP), human toxicity potential (HTP), and energy use (EU) are used as environmental impact indicators to assess the magnitude of potential impacts caused by each indicator for the three farming systems. The results of the life cycle impact assessment for the three systems are presented in Table 15.6.

The global warming potential (GWP) is a metric for weighting the climatic impact of emissions of different greenhouse gases such as CO_2, CH_4, and N_2O in the atmosphere, and is expressed in kgCO_2 equivalent. As seen in Table 15.6, energy consumption is the dominant factor for GWP in intensive system, accounting for 65%, followed by infrastructure materials (27%) and feed (9%). Coal is the dominant energy consumption. In semi-intensive systems, energy consumption, infrastructure materials, and feed contribute 90%, 8%, and 2% to GWP, respectively. However, the total GWP value of the intensive system is 5.32-fold higher than that of the semi-intensive system. The GWP values of extensive system are 1/64 of the intensive system because there are no inputs of feed, coal, and electricity into the extensive system. This is also the reason why the extensive system has the largest proportion of infrastructure materials, 96%, and only 4% of energy consumption.

Table 15.6 Environmental impacts of 1 t of fresh sea cucumber from three systems (from Wang et al. 2015b)

Items	GWP/kgCO_2	EP/kg PO_4	AP/kg SO_2	POP/kg C_2H_4	HTP/kg 1,4-DB	EU/MJ
Intensive system indoor						
Infrastructure materials	5.00×10^3	2.45×10^{-2}	26.6	5.25×10^{-2}	0.648	3.04×10^4
Feed	1.60×10^3	57.3	14.3	0.00	0.55	2.06×10^4
Energy sources	1.20×10^4	9.17	1.52×10^2	0.182	1.27	2.84×10^5
Total	1.86×10^4	66.5	1.93×10^2	0.235	2.47	3.36×10^5
Semi-intensive system in pond						
Infrastructure materials	2.24×10^2	1.07×10^{-3}	1.26	2.60×10^{-3}	0.491	1.28×10^3
Feed	74.9	2.68	0.669	0.00	2.57×10^{-2}	9.63×10^2
Energy sources	3.15×10^3	2.41	41.4	5.20×10^{-2}	0.163	1.04×10^4
Others		-2.59×10^3				
Total	3.45×10^3	-2.58×10^3	43.3	5.46×10^{-2}	0.68	1.27×10^4
Extensive system in pond						
Infrastructure materials	2.24×10^2	1.11×10^{-3}	1.23	2.52×10^{-3}	0.491	1.31×10^3
Feed	0.00	0.00	0.00	0.00	0.00	0.00
Energy sources	12.1	1.13×10^{-2}	6.33×10^{-2}	4.04×10^{-6}	1.27×10^{-5}	1.73×10^2
Others		-3.44×10^3				
Total	2.36×10^2	-3.44×10^3	1.30	2.53×10^{-3}	0.491	1.48×10^3

Note: *AP* acidification potential, *EP* eutrophication potential, *EU* energy use, *GWP* global warming potential, *HTP* human toxicity potential, *POP* photochemical oxidant potential

Eutrophication potential (EP) is a metric for weighting the impact of all biogenic elements, including N and P, that contribute to elevated nutrient levels in the environment, normally is expressed in kgPO_4 equivalent. Eutrophication can lead to the structure changes and biomass increase of planktonic communities in the water column. Excessive plankton biomass in aquatic ecosystems can lead to lower DO levels in the water column. In intensive system, feed is the main contributor to EP. In contrast, the other two culture systems show lower EP. The levels of total nitrogen and total phosphorus in the outlet water of extensive system are lower than those in the inlet water (Li et al. 2011a, 2013a), indicating that parts of the total nitrogen and total phosphorus are retained in the extensive system. Therefore, the extensive system of pond is not only a production system of aquatic products, but also a purification system of coastal water, and an environmentally friendly aquaculture system.

Acidification potential (AP) is a metric for weighting the negative effects of acidification pollution on soil, groundwater, surface water, etc., and is expressed in kgSO_2 equivalent. Acidification gases are mainly SO_2 and NO_x. SO_2 discharge in the study is mainly from the inputs of concrete, PE, PVC, coal, and electricity; NO_x is mainly from the inputs of coal, electricity, and diesel. The largest contributor to AP in the intensive and semi-intensive systems is energy consumption, accounting for 79% and 87%, respectively. In contrast, the AP of the extensive system is 1/33 and 1/8 of the former two systems, respectively, because the system has no inputs of coal and electricity.

Photochemical oxidant formation, also known as secondary air pollution, refers to a mixture of primary pollutants such as NO_x and hydrocarbons in the atmosphere and the secondary pollutants produced by their exposure to ultraviolet light. Photochemical oxidant potential (POP) is expressed in kgC_2H_4 equivalent. The major photochemical pollutant in the study is CH_4, whose emissions are mainly from PE, PVC, diesel, and electricity use. The contribution of energy consumption to POP is overwhelmingly dominant in the intensive and semi-intensive systems, accounting for 77% and 95%, respectively. In extensive system, since there is almost no input from energy use, the main contributor to POP is infrastructure materials with a proportion of 99%. Therefore, it is recommended that pond culture systems for sea cucumber should minimize the use of PE materials and replace them with stone, waste concrete to further reduce the impact of POP.

Human toxicity potential (HTP) covers the impacts of toxic substances on human health and is expressed in kg 1,4-dichlorobenzene (DCB) equivalents. The major HTP are smog and CH_4 in the study. The smog is mainly caused by the suspended particulate matters of coal combustion and power generation. The CH_4 emission is mainly from the use of PVC, PE, diesel, and electricity. In the study, the ratio of HTP of intensive, semi-intensive, and extensive farming systems is 5.0:1.4:1.0, respectively.

Energy use (EU) is an important impact factor in ecological footprint. In this study, EU in intensive system is 26-fold and 225-fold higher than those in semi-intensive and extensive systems, respectively. The EU of intensive system contributes 65%, 78%, 77%, 52%, and 85% to GWP, AP, POFP, HTP, and EU, respectively, with absolute dominance relative to both infrastructure materials and feed inputs.

Cao et al. (2011) also studied the ecological footprint of intensive and semi-intensive systems of shrimp farming in China, and showed that the values of AP ($kgSO_2$ equivalent), EP ($kgPO_4$ equivalent), GWP ($kgCO_2$ equivalent), cumulative energy use (CEU/GJ), and biological resource use (BRU/kgC) for intensive systems are 43.9, 63, 5280, 61.5, and 60,700, respectively, while the corresponding values for the semi-intensive system are 19.4, 32.3, 2750, 34.2, and 36,800, respectively. It can be seen that the environmental impact of the intensive system is almost twice as high as that of the semi-intensive system, despite the fact that the land use of the intensive system is significantly less than that of the semi-intensive system. This is mainly due to the fact that the former uses more electricity and feeds, and produced higher concentrations of nutrients in the discharge water.

15.2.4 Ecological Footprint and System Sustainability

Cao et al. (2013a) compared the ecological footprints of aquatic food product, livestock, and poultry, and the results showed that aquaculture typically generates much less environmental cost than animal husbandry (Table 15.7). With the exception of chicken, livestock produces more CO_2 than aquatic food product, and can lead to more severe acidification and eutrophication. Cattle and their manure produce the most greenhouse gases and, therefore, beef has the greatest GWP. In addition, beef has the highest AP and EP. Aquatic food product uses more electricity than livestock, but EP of wild-caught aquatic food product is much less than that of farmed aquatic food product. Overall, aquatic food products are not only high-quality animal proteins, but also better eco-friendly products.

The high quantity of land (sea area) use for wild-caught aquatic food product is due to the low density of fish in the ocean and the large area of the seafloor per

Table 15.7 Environmental impacts of 1 t of agri-animal foods and aquatic food products (from Cao et al. 2013a)

Product	Location	GWP ($kgCO_2$ eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	CEU (GJ)	Land use (1000 m^2)
Beef	UK	25,300	708	257	40.7	38.5
Pork	UK	6360	395	100	16.7	7.4
Chicken	UK	4570	173	49	12	6.4
Farmed shrimp	Asia	5250	31	37	54	2.2
Farmed salmon	Europe	2450	22.4	51.7	43.3	6
Farmed trout	France	2270	15.2	38.5	58.8	–
Wild-caught cod	Europe	3000	–	–	81.3	1390
Wild-caught tuna	Spain	1800	24	3.7	–	–

Note: *CEU* cumulative energy use

trawled fish. Fishmeal used for the products in Table 15.7 is not included, i.e., it is not converted into land area, which would be very different if it was included, as some aquaculture products use huge amounts of fishmeal. Wild-caught fish has less land use impacts than farmed fish.

RAS performs better than open aquaculture system in terms of EP and biotic resource use (BRU); however, its performance in terms of GWP and energy consumption is poor (Table 15.8). The channel catfish in Vietnamese pond farming has an unusually high GWP due to the use of rice in its feed. Large amount of greenhouse gases is released during rice cultivation.

Pelletier et al. (2009) compared the ecological footprint of Atlantic salmon farming in Norway, the UK, and Chile, and showed that the environmental costs of farmed salmon are the lowest in Norway and the highest in the UK mainly due to the differences in feed formula and feed utilization. There are more fishmeal and fish oil in the feeds used in the UK. The BRU of salmon farming in the UK, Norway, and Chile are 137,000, 111,000, and 56,600 kg C, respectively.

The AP, GWP, and EU of shrimp farming in the United States are higher than those in China and Thailand, but its EP is less than those in China and Thailand (Deng and Wang 2003). This is primarily due to the fact that there are more energy inputs in the shrimp farming systems in the United States.

Although a large number of papers have been published on the evaluation of aquaculture systems by LCA, great care should be taken in comparing and interpreting the results of these studies, as their research contexts may differ greatly, as may the scope (boundary) definition, methodology, etc. A more accurate analysis is only possible when comparing research subjects from the same region and similar backgrounds using the same methodology. As already described, in order to compare the environmental impacts of intensive, semi-intensive, and extensive farming models more precisely, Wang et al. (2015b) selected three different intensive levels of sea cucumber farming systems within Qingdao region, so that the results of the LCA could eliminate ‘background noise’ and obtain comparable data.

After retrieving 179 cases of LCA on aquaculture systems, Bohnes et al. (2019) revealed that feed production is a key driver of cumulative energy demand (58% of the studies), net primary production use (86% of the studies), acidification (63% of the studies), and climate change (56% of the studies). As a result, fed aquaculture activities have a higher ecological footprint than non-fed aquaculture activities.

15.3 Carbon Footprint of Aquaculture

Wiedmann and Minx (2008) defined carbon footprint as a certain amount of gaseous emission that is relevant to climate change and associated with human production or consumption activity. Thus, aquaculture carbon footprint is the emission of all greenhouse gases (GHGs), mainly CO_2, CH_4, and N_2O, from manufacturing to disposal.

Ecological footprint assesses all the environmental impact, whereas carbon footprint is a component of ecological footprint that measures GHGs. Product carbon

Table 15.8 Environmental impacts of 1 t of live-weight fish produced (from Cao et al. 2013a)

Species	Systems	Locations	AP (kg SO_2)	EP (kg PO_4)	GWP (kgCO_2)	CEU (GJ)	BRU (kgC)	ADP (kgSb)	HTP (kg 1,4 DB)
Salmon	Bag	Canada	18	31.9	2250	37.3	–	12.1	639
	Flow-through tank		33.3	31	5410	132	–	–	–
	Net pen		17.9	35.3	2070	26.9	–	–	–
Catfish	Flow-through pond	Vietnam	48.1	65	8930	13.2			4280
Tilapia	Net pen	Indonesia	20.2	47.8	1520	18.2	2760	38.1	2580
	Flow-through pond	Indonesia	23.8	45.7	2100	26.5	2700	–	–
Trout	Flow-through tank	France	13.4	28.5	2020	34.9	28,000	13.9	840
	Flow-through raceway	France	19.2	65.9	2750	78.2	62,200	–	–
	Recirculating tank	France	13.1	21.1	2040	63.2	28,100	–	–
Sea bass	Sea cage	Greece	25.3	109	3600	54.7	71,400	–	–
Arctic char	Recirculating tank	Canada	63.4	11.6	10,300	233	–	72.5	54,400
Turbot	Recirculating tank	France	48.3	77	6020	291	60,900	–	–

Note: *BRU* biotic resource use

Table 15.9 Carbon emission factors of inputs to the three farming systems (from Wang 2014)

Items	Unit	CO_2 factor (kg)	CH_4 factor (kg)	N_2O factor (kg)
Concrete	Kg	0.572	0.00	0.00
Steel	Kg	2.10	0.00	1.00×10^{-3}
Polychloride	Kg	8.87	1.30×10^{-2}	1.70×10^{-4}
Polyethylene	Kg	6.41	1.30×10^{-2}	1.70×10^{-4}
Brick	Kg	6.15×10^{-2}	1.04×10^{-4}	3.51×10^{-4}
Feed	Kg	0.26	0.00	0.00
Electricity	kWh	1.07	2.60×10^{-3}	6.46×10^{-3}
Coal	Kg	1.83	8.36×10^{-7}	4.41×10^{-4}
Diesel	L	3.23	1.54×10^{-4}	2.31×10^{-2}

footprint is often assessed based on LCA, which evaluate the carbon footprint of a product's entire life cycle, including not only all the direct on-site emission, but also all the indirect emissions related to manufacturing and transport.

Pandey and Agrawal (2014) have given the formula to calculate carbon footprint:

$$\text{GWP of tier } (\text{kg CO}_2 - \text{e/hm}^2) = \text{emission/removal of CH}_4 \times 25 + \text{emission/removal of N}_2\text{O} \times 298 + \text{emission/removal of CO}_2$$

$$\text{Carbon footprint} = \sum (\text{GWP of all tiers})$$

Of course, the carbon footprint per unit area can also be expressed as the carbon footprint per unit mass.

The carbon footprints of three sea Effects of salinity on survivalEffects of salinity on survivalcucumber farming systems with different levels of intensification have been assessed in order to propose corresponding measures to reduce their carbon emissions (Wang 2014). The scope definition of his study is basically the same as the previous ecological footprint analysis. The carbon emission factors of input materials from domestic and international research results (Wang et al. 2006b; Brentrup et al. 2004) are listed in Table 15.9. Although the emissions of greenhouse gases such as CH_4 and N_2O are relatively small, they have a significant impact on climate change. Therefore, the GHGs selected for this study include CO_2, CH_4, and N_2O, and are expressed in kgCO_2 equivalent. According to the IPCC's Fourth Assessment Report in 2007, the CO_2-e factors for CH_4 and N_2O are 25 and 298, respectively.

The carbon footprints of the three culture systems are shown in Table 15.10. The carbon footprints of the intensive, semi-intensive, and extensive culture systems for producing 1 t of fresh sea cucumber are 38,887, 9024, and 270 kgCO_2 equivalent, respectively, with a ratio of about 144:33:1.

In the intensive system, the carbon emission caused by the consumption of electricity for the production of 1 t fresh sea cucumbers is up to 30,600 kgCO_2, accounting for 78.7% of the total emissions, and electricity is the dominant factor in the carbon footprint of the system; polyethylene accounts for 9.7% of the total

Table 15.10 Carbon footprints for producing 1 t of fresh sea cucumber from the three systems ($kgCO_2$-eq) (from Wang 2014)

Items	Intensive system indoor	Semi-intensive system in pond	Extensive system in pond
Concrete	1052	32.68	38.03
Steel	138.6	4.56	5.32
Polychloride	184.9	0.00	0.00
Polyethylene	3773	193.8	187.9
Brick	18.74	0.64	0.75
Feed	298.0	13.92	0.00
Electricity	30,600	8743	0.00
Coal	1840	0.00	0.00
Diesel	981.5	35.72	37.94
Total CO_2 emission	38,888	9024	270.0

emissions; coal and concrete account for a proportion of 4.7% and 2.7% of the total, respectively; feed carbon emission accounts for only 0.8% of the total.

For most fed species, feeds have high carbon emission, but the benthic omnivorous sea cucumbers only need low protein and low lipid diet (Liu et al. 2009b); therefore, their feeds are not the key point contributed to the carbon emissions of the farming system.

Similar to the intensive system, electricity accounts for 96.9% of total carbon emission in the semi-intensive system. However, the total carbon emission from semi-intensive system is less than one-quarter of that from the intensive system.

The total carbon emission of the extensive system without electrical energy consumption is as low as 270 $kgCO_2$, only 1/144 and 1/33 of the total carbon emissions of the intensive system and the semi-intensive system. The major carbon footprint of the extensive system is the polyethylene substrate, which accounts for 69.6% of the total.

The carbon emissions of both semi-intensive and extensive culture systems in terms of infrastructure materials, feed, and energy are much lower than those of intensive system, i.e., from the perspective of carbon footprint, the pond culture models of the sea cucumber are significantly better than the indoor intensive model, and pond culture models are more in line with the requirements of sustainable development.

The electricity input of the intensive culture system is mainly used to pump water, while the electricity of the pond semi-intensive system is mainly used for aeration. In order to ensure the growth and health condition of the sea cucumber, it is not advisable to cut down on the electricity input of both systems. However, if non-fossil energy can be used to replace traditional energy sources, the carbon emission of electricity input will be greatly reduced.

The polyethylene input in the semi-intensive and the extensive culture systems is an attachment substrate for sea cucumber, and if other low carbon materials could be used, the carbon footprint of the systems would be further reduced and its sustainability would be further improved.

15.4 Water Footprint of Aquaculture

Agriculture consumes about 70% of the world's water resources each year. In 2011, the freshwater consumption for the production and processing of agricultural products in China already accounted for 73.8% of China's total freshwater consumption (Zhao and Chen 2014). China's water resources per capita are only one-quarter of the world, so China is one of the 13 most water-scarce countries in the world. According to the national water security strategy, China's agricultural (including aquaculture) water use can only maintain zero or negative growth in the next 30 years. Therefore, the mission of water-saving development of agriculture including aquaculture is arduous.

It is generally accepted that mariculture product does not basically consume freshwater resources and is a high-quality food alternative to terrestrial sources of animal protein (Gepgart et al. 2014). However, most seawater fish cultures require feed, and the cultivation of some crop ingredients consumes freshwater. China is the largest fish farming and consuming country in the world, with 69.5% of global aquaculture production. Therefore, understanding the relationship between freshwater consumed and aquaculture structure can help us to optimize the aquaculture structure and develop the trade strategies of aquaculture products. This section will briefly introduce the concept of water footprint and its application in aquaculture.

15.4.1 Water Footprint and Assessment

The water footprint of a product is the volume of freshwater used to produce the product, measured over the full supply chain (Hoekstra et al. 2011). For example, the water footprint of a 100 g apple is 70 L, 1 kg of wheat is 1300 L, 1 kg of rice is 3400 L, and 1 kg of beef is 15,500 L.

The water footprint includes the following three categories: The first one is blue water footprint, which refers to the consumption volumes of surface and groundwater along the supply chain of a product. The second one is green water footprint, which refers to the consumption volumes of direct precipitation. The third one is grey water footprint, which refers to the consumption volumes to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards (Hoekstra et al. 2011).

The goal to assess water footprints in aquaculture is to understand the sustainability of aquaculture production systems from a water perspective. A full water footprint assessment consists of four distinct phases: setting goals and scope, water footprint accounting, water footprint sustainability assessment, and water footprint response formulation (Hoekstra et al. 2011).

15.4.2 Water Footprint of Aquaculture Systems

Mariculture may look like no consumption of freshwater resources, but in fact some feed ingredients require freshwater for cultivation. The water footprint of aquafeeds was 31–35 km^3 in 2008 and was expected to reach 71 km^3 in 2020 (Tacon et al. 2011). Table 15.11 lists the amount of embodied energy and freshwater in several aquafeeds (Boyd et al. 2007). As can be seen, salmon and trout feeds embody great amount of energy due to their great amount of fish oil, but their embodied freshwater is less. Whereas, tilapia feed consumes the greatest amount of freshwater due to its great content of crop ingredient.

Water footprints of different aquaculture species or systems are quite different. In terms of culture species, extractive bivalve consumes almost no freshwater (blue water), while they also purify the culture waters (negative values for grey water); species with more crop in their feed, such as common carp and channel catfish, have more blue water; tilapia, which are omnivorous and can consume zooplankton, consume less blue water and less grey water (Waite et al. 2014). In terms of culture systems, extensive systems have more blue water and less grey water, while intensive systems have less blue water but greater grey water compared to extensive systems (Waite et al. 2014).

In 2014, the water footprint of farmed fish in China was about 139 × 10^9 m^3/year, protein output was about 4.60 × 10^9 kg/year, and economic return was about 163 × 10^9 CNY/year. If the aquaculture structure in China is further optimized, the water footprint can be reduced to 128 × 10^9 m^3/year, the total protein output will increase to 5.34 × 10^9 kg/year, and the economic return will increase to 181 × 10^9 CNY/year. Based on the optimized results, the development of silver carp, bighead carp, and grass carp culture should be encouraged (Yuan 2016).

China is seriously short of water resources, and distribution of water resources between the north and south is grossly uneven. Therefore, the consideration of water footprint should be gradually strengthened in the regional planning, trade, and development of aquaculture in China.

After retrieving 179 cases of LCA on aquaculture systems, Bohnes et al. (2019) revealed that intensive systems seem to have higher impacts than low-intensity systems in global impact categories (e.g., climate change) whereas they seem to perform equally or even better with respect to more local and regional impacts (e.g., aquatic eutrophication and water use).

Table 15.11 Average embodied energy, land use, and water in feed for aquaculture species (from Boyd et al. 2007)

Variables	Species				
	Channel catfish	Tilapia	Atlantic salmon	Rainbow trout	Whiteleg shrimp
Energy (GJ/t)	4.90	5.83	12.48	12.26	9.07
Water (m^3/t)	1227	1685	849	502	1116

15.5 Emergy Analysis of Aquaculture

Most aquaculture systems are semi-natural ecosystems with a high degree of artificial intervention. Important functions of the natural ecosystem such as production, consumption, decomposition, material cycling, and energy flow are still at work in the systems, and even play a dominant role in some production systems. However, the large biomass of stocked animals has caused serious distortions in the trophic pyramid of intensive aquaculture ecosystem, so artificial interventions are necessary to maintain the stability of the structure and function of the ecosystem, such as aquafeed delivery to compensate for the lack of primary production and artificial aeration to meet the demand for dissolved oxygen from the large biomass of stocked animals and strong decomposition. Compared to natural ecosystems, aquaculture ecosystems have much greater material and energy inputs and outputs. To fully understand aquaculture systems, we need to quantify and evaluate both the contribution of environmental resources and the contribution of economic activities in aquaculture ecosystems.

For more than a century, energy has been used as a common measure to study various energy systems, but traditional analysis has been based on comparative analysis of the same type of energy. When two or more different energy sources drive a system, such as sunlight, wind, electricity, feed, and so on, they cannot be added without first converting them to a common measure that accounts for their differences in energy quality.

The term ‘embodied energy‘is used in the early 1980s to refer to energy quality differences in terms of their costs of generation, and a ratio called a ‘quality factor’ for the calories (or joules) of one kind of energy required to make those of another (Odum and Odum 1980). H. T. Odum, a famous American ecologist and pioneer of emergy analysis (Odum 1983), converts different types of energy and substances flowing and stored in ecological and economic systems into a uniform standard emergy for quantitative study. The theory and method of emergy analysis can quantify the contribution of natural resources to economic development, measure the real value of natural resources and human activities, and adjust and coordinate the relationship between economic development and the environment (Lan et al. 2002).

15.5.1 Emergy Analysis Theory

Emergy analysis theory is a quantitative analysis that evaluates resources, goods, or services in common units of solar energy and is measured as solar emergy (sej). Emergy analysis theory also uses a life cycle approach. Emergy analysis theory is a new tool for human to understand nature, society, and economy, and is a bridge linking ecology and economics.

15.5.1.1 Emergy

Emergy is the amount of energy of one form that is used in transformations directly and indirectly to make a product or service, and its unit is emergy joule or emjoule. In most cases, emergy data are given in solar emjoules (sej). The amount of solar energy embodied in any flowing or stored state of energy is the solar emergy of that energy. For example, the solar emjoules of 1 g of rainwater is about 1.54×10^4 sej, the solar emjoules of 1 g of coal is about 4.00×10^4 sej, and the solar emjoules of 1 g of sea cucumber seedlings is about 2.00×10^6 sej.

15.5.1.2 Emergy Transformity

Before doing emergy analysis, all system's inputs of different types of energy and energy inherent to different materials and services should be converted to emergy units using a conversion factor, i.e., emergy transformity. Transformity is a fundamental concept of emergy analysis theory, which is the emergy input per unit of available energy output. The solar transformity of the sunlight is 1.0 by definition, thus, the wood is 10,000 solar emjoules per joule (sej/J), i.e., 10,000 solar emjoules are required to generate a joule of wood.

Commonly used values of emergy transformity can be found in Odum (1996), Lan et al. (2002), and other works. It should be noted that the value of the emergy transformity for the same substance may vary from country to country due to different national circumstances.

15.5.1.3 Basic and Performance Indicators of Emergy Analysis

15.5.1.3.1 Emergy/Money Ratio

Emergy/money ratio or emergy per unit money is the emergy supporting the generation of one unit of economic product, which is a very important parameter to convert money into emergy units. The ratio is a bridge between economic products and natural resources in emergy analysis. An average emergy/money ratio in solar emjoules/$ can be calculated by dividing the total emergy use of a state or nation by its gross economic product. For example, the emergy/money ratio in 1983 was 3.2×10^{12} sej/$ for the United States and 8.7×10^{12} sej/$ for China (Odum 1996). A high ratio means that more emergy wealth is exchanged per unit of money, indicating a large share of natural resources used in the production process. The emergy/money ratio provides a measure of the real purchasing power of money in circulation and the real capacity of the labor force.

15.5.1.3.2 Emergy Investment Ratio

Emergy investment ratio (EIR) is the emergy investment needed to exploit one unit of local (renewable and nonrenewable) resource, i.e., $\mathrm{EIR} = (\mathrm{Em_F} + \mathrm{Em_{R1}})/(\mathrm{Em_N} + \mathrm{Em_R})$, where $\mathrm{Em_F}$ is the feedback of nonrenewable emergy, $\mathrm{Em_{R1}}$ is the feedback of renewable emergy, $\mathrm{Em_N}$ is the input of nonrenewable emergy, and $\mathrm{Em_R}$ is the input of renewable emergy (Fig. 15.2).

The emergy investment ratio, also known as the 'economic emergy/environmental emergy ratio', is a measure of the degree of economic development and

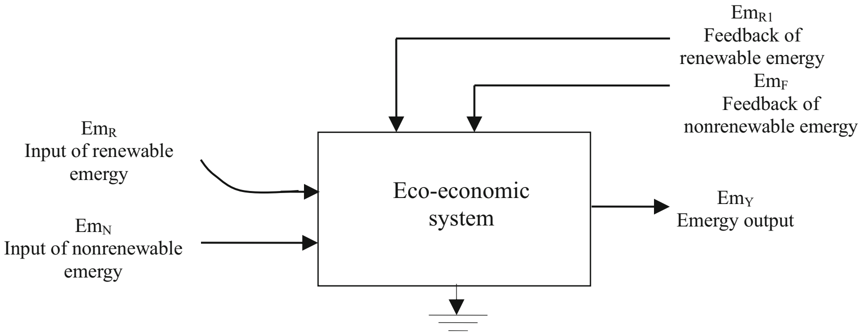

Fig. 15.2 Input and output of emergy in ecological-economic systems (from Lan et al. 2002)

environmental loading, and can also be used to determine the effectiveness of economic activities under certain conditions and to measure the loading rate of environmental resource conditions on economic activities.

15.5.1.3.3 Emergy Yield Ratio

Emergy yield ratio (EYR) is the emergy released (used up) per unit invested. The ratio is a measure of how much an investment enables a process to exploit local resources, i.e., $EYR = Em_F/(Em_F + Em_{R1})$. This indicator evaluates the output efficiency of the system and reflects the system's ability to utilize renewable resources. A higher value indicates a more efficient and quantitative exploitation of renewable resources by the system.

15.5.1.3.4 Emergy Self-Support Ratio

Emergy self-support ratio (ESR) is the ratio of a country's or region's local resource emergy inputs (both renewable and non-renewable resource emergy inputs) to foreign or external emergy inputs, i.e., $ESR = (Em_N + Em_R)/(Em_N + Em_R + Em_F + Em_{R1}) = 1–1/EYR$.

15.5.1.3.5 Environmental Loading Ratio

Environmental loading ratio (ELR) is the ratio of nonrenewable and imported emergy use to renewable emergy use, i.e., $ELR = (Em_F + Em_N)/(Em_R + Em_{R1})$. This indicator can be used to measure the stress and coercive effects on the environment due to the input and use of nonrenewable resources, and is an indicator that examines the stress on the environment from emergy transfer and transmissions processes, and can also be seen as a measure of the ecological stress from production.

15.5.1.3.6 Renewable Emergy Input Ratio

Renewable emergy input ratio (RIR) is the ratio of the total system renewable emergy input energy value to the total system energy input value, i.e., $RIR = (Em_R + Em_{R1})/Em_Y$, where Em_Y is the emergy output of the system.

15.5.1.3.7 Emergy Exchange Ratio

Emergy exchange ratio (EER) is the ratio of emergy exchanged in a trade or purchase (what is received to what is given). The ratio is always expressed relative to a trading partner and is a measure of the relative trade advantage of one partner over the other.

15.5.1.3.8 Emergy Sustainability Index

Emergy sustainability index (ESI) is the ratio of EYR to ELR, i.e., ESI = EYR/ELR. It measures the contribution of a resource or process to the economy per unit of environmental loading. Generally, ESI < 1 in developed countries, 1–10 in developing countries.

15.5.1.3.9 Emergy Index for Sustainable Development

Emergy index for sustainable development (EISD) = EYR × EER/ELR.

15.5.1.4 Basic Steps of Emergy Analysis

In terms of research objects, emergy analysis includes emergy analysis of national and regional ecological and economic systems, emergy analysis of resources and economy, emergy analysis of urban or agricultural ecological and economic systems, and emergy analysis of specific production systems, etc. In terms of research methods and steps, emergy analysis includes data collection, energy system mapping, emergy analysis table preparation, integrated emergy structure chart construction, emergy indicator system establishment, system simulation, development evaluation, and strategy analysis.

15.5.2 Emergy Analysis of Different Aquaculture Systems

Beginning in the 1980s, H. T. Odum began to apply the emergy analysis theory to different systems in the United States and other countries. For example, he used it to study shrimp aquaculture systems in Ecuador (Odum and Arding 1991). In recent years, many aquaculture species have been studied using this theory, such as tilapia (*Tilapia mariae*), whiteleg shrimp, salmon (*Salmo salar*), gilthead seabream (*Sparus aurata*), sea cucumber, eel (*Anguilla japonicas*), snakehead (*Channa argus*), mullet (*Mugil cephalus*), largemouth black bass (*Micropterus salmoides*), silver carp, bighead carp, grass carp, and so on. In addition, some Chinese scholars have used this theory to comparatively study the status of aquaculture in different regions and analyze the sustainability of some farming systems.

Since different regions of the world, even different areas within a country have different levels of economic development and may have very different meteorological, hydrological, and other natural conditions, the emergy of the same products and services may vary greatly. Without access to more accurate data on the emergy of products or services, it is difficult or imprecise to compare the results of the studies between different regions or areas.

In 2013, in order to identify the environmental impacts of intensive, semi-intensive, and extensive systems, while overcoming the difficulty of obtaining precise data for certain geographical areas, an emergy analysis of three farming systems of sea cucumber located in Qingdao (with similar levels of economic development and meteorological and hydrological conditions) was conducted (Wang et al. 2015a).

15.5.2.1 Economic Benefits of the Three Farming Systems of Sea Cucumber

Table 15.12 shows the economic benefits of the three culture systems of sea cucumber. The intensive system indoor is a high input (6.53 × 10^6 CNY) and high output (8.00 × 10^6 CNY) culture system, while the extensive system in pond is a low input (1.10 × 10^5 CNY) and low output (1.81 × 10^5 CNY) culture system. However, the output-input ratio of the intensive system (1.23) is lower than that of the extensive culture system (1.65). Semi-intensive system in pond is in between.

15.5.2.2 Emergy Calculation and Analysis

Emergy resources are divided into renewable resources inputted and purchased resources inputted. The former includes solar, wind, rain, tide, and sediment accumulation, while the latter includes seedlings, electricity, coal, direct labor, rent, maintenance costs, pesticide, feed, and capture. Calculated emergy for the three farming systems is presented in Table 15.13.

The total emergy inputs for the intensive, semi-intensive, and extensive systems are 8.31 × 10^{18}, 1.73 × 10^{17}, and 1.59 × 10^{17} sej/(hm^2·year), respectively. The input emergies of labor, rent, and feed are the same order of magnitude, and higher than the inputs of other purchased resource in the intensive culture system. The intensive culture system requires a large amount of labor resource input. Rent input of intensive system is the largest in all three systems.

Several performance indicators of the three systems are presented in Table 15.14. Emergy yield ratio (EYR) is a reflection of the system's ability to utilize renewable resources. The EYR (2.06) for the extensive system is the highest, and the lowest (1.18) for the intensive system. It is evident that as the intensification of culture systems increases, its conversion rate of renewable resources decreases. The EYR of

Table 15.12 Annual economic accounting table for sea cucumber *A. japonicus* farming systems (from Wang et al. 2015a)

Items	Unit/ hm^2	Intensive system indoor	Semi-intensive system in pond	Extensive system in pond
Stocking density	Kg	1.25 × 10^4	4.95 × 10^2	4.60 × 10^2
Total economic input	CNY	6.53 × 10^6	1.31 × 10^5	1.10 × 10^5
Total economic output	CNY	8.00 × 10^6	2.10 × 10^5	1.81 × 10^5
Income per unit area	CNY	1.48 × 10^6	7.93 × 10^4	7.02 × 10^4
Output input ratio		1.23	1.60	1.65

Table 15.13 Emergy accounting table of three culture systems for sea cucumber [sej/(hm^2·year)] (from Wang et al. 2015a)

Items	Intensive system indoor	Semi-intensive system in pond	Extensive system in pond
Local renewable resource input			
1. Solar radiation	\	3.42×10^{13}	3.42×10^{13}
2. Wind	\	1.40×10^{12}	1.40×10^{12}
3. Rain	\	5.70×10^{14}	5.70×10^{14}
4. Tides	\	6.51×10^{15}	6.51×10^{15}
5. Sediment accumulation	\	6.39×10^{16}	6.39×10^{16}
Purchased resource input			
6. Fingerlings	2.05×10^{15}	8.12×10^{13}	7.54×10^{13}
7. Electricity	2.88×10^{17}	2.16×10^{15}	\
8. Coal or oil	3.38×10^{17}		\
9. Direct labor	1.92×10^{18}	1.92×10^{16}	1.44×10^{16}
10. Rent	1.92×10^{18}	5.76×10^{16}	5.76×10^{16}
11. Maintenance	1.09×10^{18}	1.44×10^{16}	4.80×10^{15}
12. Pesticide	9.90×10^{17}	\	
13. Feed	1.76×10^{18}	8.64×10^{15}	\
14. Capture	\	1.33×10^{16}	1.14×10^{16}
Total emergy	8.31×10^{18}	1.73×10^{17}	1.59×10^{17}
Economic returns	1.54×10^{19}	4.03×10^{17}	3.47×10^{17}

Table 15.14 Emergy indices for three culture systems for sea cucumber (from Wang et al. 2015a)

Items	Intensive system indoor	Semi-intensive system in pond	Extensive system in pond
Emergy of economic value from outputs (sej/year)	1.54×10^{19}	4.03×10^{17}	3.47×10^{17}
Renewable emergy flow (sej/year)	1.28×10^{18}	9.04×10^{16}	8.19×10^{16}
Nonrenewable emergy flow (sej/year)	7.04×10^{18}	1.01×10^{17}	7.74×10^{16}
Total emergy flow (sej/year)	8.32×10^{18}	1.91×10^{17}	1.59×10^{17}
Emergy yield ratio (EYR)	1.18	1.90	2.06
Environmental loading ratio (ELR)	5.50	1.12	0.94
Emergy sustainability index (ESI)	0.21	1.70	2.18
Emergy exchange ratio (EER)	1.85	2.11	2.17
Emergy index for sustainable development (EISD)	0.40	3.58	4.74

the intensive system is close to 1.0, indicating that the system can only convert a small amount of renewable resources and relies more on high-energy material inputs.

Emergy exchange rate (EER) is an indicator that expresses the relationship between the system under study and the market. The party that receives more emergy in a transaction tends to receive a greater in-kind gain or a greater economic benefit. The EER values for the intensive, semi-intensive, and extensive systems in the studies are 1.85, 2.11, and 2.17, respectively, meaning that the systems receive 85%, 111%, and 117% of the emergy benefit, respectively. From this perspective, the emergy benefit of the extensive system is significantly higher than that of the intensive system.

Environmental loading rate (ELR) is the pressure of a system on the environment due to production activities and is directly related to the proportion of renewable resources. A high value of ELR usually implies a greater pressure on the environment. The ELR (5.50) of the intensive system is 5.9-fold and 4.9-fold higher than those of extensive culture system (0.94) and semi-intensive system (1.12), which indicates that the pressure on the environment is significantly greater in the intensive system than those in the other two culture systems.

Emergy sustainability index (ESI) is a composite ratio that represents the relationship between emergy benefits and environmental pressures. In other words, ESI indicates whether a process or system provides a sustainable contribution. ESI combines ecological and economic factors, and the higher the ESI, the more sustainable a system or process is. The extensive system has a high sustainability (ESI = 2.18), while the intensive system has a low ESI value of 0.21, which indicates that the intensive system is less sustainable.

Emergy index for sustainable development (EISD) complements the ESI by taking into account the factors of product trading in the market, and measuring the sustainability of the study object with complex characteristics in time and space. The EISD is 4.74 and 3.58 for the extensive and semi-intensive systems, respectively, and both are much higher than the EISD for the intensive systems (0.40).

A comparative study was conducted on an in-pond raceway aquaculture system (IPRS, Fig. 10.8, right) set up in a seawater pond (4 hm^2 in area) and a conventional polyculture pond (4 hm^2 in area, 1.8–2.0 m in depth) for puffer fish (Li 2020). The results showed that emergy yield rate (EYR) of the IPRS was higher than that of the polyculture system, the environmental loading rate (ELR) was lower than that of the polyculture system, while the emergy sustainability index (ESI) and emergy index for sustainable development (EISD) were all greater than those of the polyculture system (Table 15.15), which indicates that the IPRS utilizes more renewable resources, has a less negative effects, more efficient use of natural resources, and more in line with the requirements of sustainable development in aquaculture.

In terms of farmed species, the EYR of gilthead seabream (Vassallo et al. 2007), salmon (Odum 2001), and tilapia (Brown and Bardi 2001) are reported to be 1.20, 1.23, and 1.02, respectively, which are similar to the EYR value of the intensive culture system of sea cucumber (1.18). In terms of environmental carrying capacity and sustainability, the more intensive the system, the greater the pressure on the environment and the less sustainable it is.

Table 15.15 Emergy indicators in in-pond raceway (IPRS) and earthen pond systems for seawater puffer fish (from Li 2020)

Parameters	IPRS	Pond
Total yield /MJ	201843.20 ± 1274.23[a]	39515.25 ± 534.27[b]
Emergy yield ratio(EYR)	1.24	1.10
Environmental loading ratio(ELR)	4.16	10.33
Emergy sustainability index(ESI)	0.30	0.11
Emergy exchange ratio(EER)	1.07	1.10
Emergy index for sustainable development (EISD)	0.32	0.12

Note: The values with different letters in the same line are significantly different from each other ($P<0.05$)

15.6 Sustainability of Aquaculture Production Systems in China

Due to environmental challenges and resource constraints, there is a great deal of uncertainty about further development of aquaculture in China, and this uncertainty can have a significant impact on world aquatic food product supply, consumption, and prices (FAO 2018). Therefore, a holistic evaluation on aquaculture production systems is critical for the further development of the aquaculture industry in China and globally.

15.6.1 Uncertainties of Aquaculture Development

With the global population projected to increase to 9.7 billion in 2050 from 7.6 billion in 2017 (United Nations 2017), how to feed the growing global population is a grand challenge for human society. To meet the expected demand for aquatic food product, global aquaculture production will need to reach 140 million tons in 2050 (Table 15.16). Five or seven million hm^2 (0.6%) of global arable land and aquaculture ponds are currently being encroached annually by industrialization and urbanization, while the negative impacts of aquaculture on the environment have reached a level that cannot be ignored.

In 2018, aquaculture production in the world was 82.1 million tons, excluding 32.4 million tons (fresh weight) of aquatic plants, with a value of US$ 263.6 billion. Due to a dramatic slowdown in the growth of aquaculture production in China, the growth of aquaculture production in the world has also slowed (FAO 2020). According to the estimation done by FAO (2018), the aquaculture production in China would continue to increase by 24.7%, 31.1%, and 36.5% in 2030 compared to 2016 under the scenarios of no-plan (with a loose environmental protection policy), baseline and full-plan (with a stringent environmental protection policy), respectively; while aquaculture production in the world would grow by 38.3%, 36.7%, and 34.8%, accordingly.

Table 15.16 Major environmental challenges and resource constrain for increasing aquaculture production (from Ahmed et al. 2019)

Elements	Environmental challenge and resource constrain
Aquaculture	Global aquaculture production will need to reach 140 million tons in 2050
Capture fisheries	Global capture fisheries will likely be stable at 93 million tons by 2030
Land requirement	Aquaculture will occupy 44 million hectares of land in 2050
Water demand	Aquaculture will use 469 km^3 of freshwater in 2050
Freshwater eutrophication	Aquaculture-related freshwater eutrophication will reach 0.89 million tons P-e in 2050
Marine eutrophication	Aquaculture-related marine eutrophication will reach 3.2 million tons N-e in 2050
Nutrient release	Nutrient release from mariculture will increase up to sixfold by 2050
Biotic depletion	Demand for wild fish to produce fishmeal and fish oil for aquafeeds will need 47 million tons in 2050
Greenhouse gas emissions	Aquaculture-related GHG emissions will reach 776 million tons CO_2-e in 2050

According to our estimation China's aquaculture production will reach 55.2 mmt (including aquatic plants) by 2030, increasing only by 15.4% over 2016, if following last 10 years' trajectory under a stringent environmental protection policy. However, it will reach 61.5 mmt by 2030, increasing by 28.4% over 2016, if following the last 20 years' trajectory under relatively loose environmental protection policy.

Over the last 25 years, China is a trade surplus country of aquatic food product in value, but in volume it is a trade deficit country in general. Owing to a strong domestic demand for aquatic food product, China would become a big aquatic food product trade deficit country if the growth rate of China's aquaculture dropped dramatically in future. Therefore, it is imperative for China's aquaculture to achieve sustainability not only for China but also for the world.

15.6.2 Sustainability Assessment of Aquaculture Production Systems

China has the greatest number of farmed aquatic species, and among the highest diversity of aquaculture production systems (APSs) in the world. Low trophic level carps are the major culture species in inland APSs and bivalves in seawater APSs. The China's APSs can generally be classified into 10 major groups based on their location, feeding strategy, and environment (Table 15.17). In general, non-fed APSs in China, such as non-fed aquaculture in ponds (nFAP) and non-fed nearshore aquaculture (nFEN), have less ecological footprints in terms of pollution, energy consumption, and fishmeal consumption; while some intensively fed APSs, such as fed nearshore aquaculture (FEN) and recirculating aquaculture systems (RAS), have greater ecological footprints.

Table 15.17 Main characteristics and ecological footprints of the 10 major aquaculture systems in China (from Dong et al. 2022)

Systems[a]	nFEN	nFAL	nFAP	PFA	FOA	RAS	SALA	FAL	FAP	FEN
Production value (mCNY)	242.87	31.95	51.76	43.57	11.88	35.20	20.61	8.64	402.98	46.73
Edible food production (mmt)	1.73	2.83	4.52	2.03	0.13	0.41	1.23	0.59	17.04	0.51
Growth rate (%)[b]	5.8	2.8	4.3	7.1	15.7	8	3.8	−7.0	4.4	5.7
Pollution (COD g/kg)	0	0	0	2.18	85.9 (59.9–154)	60.4 (2.28–227)	37.1 (6.35–126)	38.8 (2.54–196)	34.1 (2.18–276)	97.3 (59.9–154
Fishmeal consumption (portion)	0	0	0	0.01	0.03	0.11	0.05	0.01	0.68	0.12
Freshwater footprint (m^3/kg)	0	0	2.83 (1.66–5.04)	0.01	1.6 (1.1–2.2)	1.50 (0.71–8.73)	5.22 (3.89–11.5)	2.49 (1.40–11.8)	4.91 (0.95–47.15)	1.6 (1.10–2.20)
Land use (m^2/kg)	0	0	0.178	0	0	0.116	0	0	0.132	0
Energy consumption (kwh/kg)	0.017	0.017	0.37	0.017	3.16	8.66	0.37	3.16	0.37	3.16

[a] *FAL* fed aquaculture in large inland waters, *FAP* fed aquaculture in ponds, *FEN* fed nearshore aquaculture, *FOA* fed offshore aquaculture, *nFAL* non-fed aquaculture in large inland waters, *nFAP* non-fed aquaculture in ponds, *nFEN* non-fed nearshore aquaculture, *PFA* paddy field aquaculture, *RAS* recirculating aquaculture systems, *SALA* waterlogged salt-alkali land aquaculture

[b] Average annual growth rates of production from 2009 to 2018

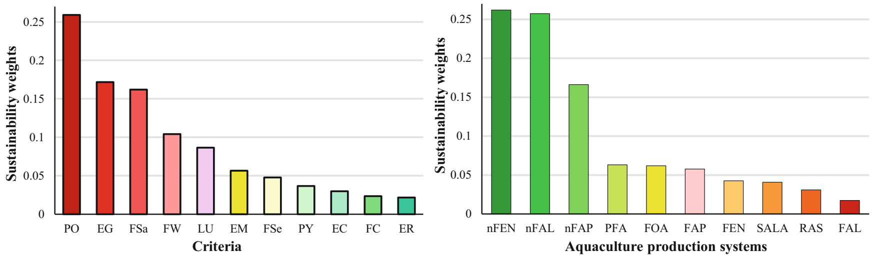

Fig. 15.3 Sustainability weights of the criteria (left) and aquaculture production systems (right) (from Dong et al. 2022). *EC* fossil energy consumption, *EG* economic growth, *FAL* fed aquaculture in large inland waters, *FAP* fed aquaculture in ponds, *FC* fishmeal consumption, *FEN* fed nearshore aquaculture, *FOA* fed offshore aquaculture, *FSe* food security, *FW* freshwater consumption, *LU* arable land use, *nFAL* non-fed aquaculture in large inland waters, *nFAP* non-fed aquaculture in ponds, *nFEN* non-fed nearshore aquaculture, *PFA* paddy field aquaculture, *PO* aquaculture pollution, *RAS* recirculating aquaculture systems, *SALA* waterlogged salt-alkali land aquaculture

FAP and nFEN are the most important APSs in terms of production volume and value. The former is also the largest user of arable land, freshwater, and fishmeal. FAP and FEN employ the most employee.

The sustainability of APSs refers to long-term development integrating society, economy, environment, and resources, mainly involving 11 criteria (Fig. 15.3 left). According to expert's evaluation (Dong et al. 2022), the first three of important criteria with regard to aquaculture sustainability among these criteria are pollution, economic growth, and food safety in China. The sustainability assessment of APS is a multi-criteria decision-making problem relating to above-mentioned criteria; so it can be done by an analytical hierarchy process (AHP) (Saaty and Vargas 2012). The sustainability weight calculated based on available data of the criteria of each APS (see Table 15.17) shows that the sustainability of non-fed APSs is higher than that of fed APSs.

The growth of China's aquaculture industry in past decades is realized mainly by area expansion and intensification. However, the negative effects of increasing external inputs of energy and materials as in the case of fed APSs have occurred widely and aroused public concern. Meanwhile, non-fed APSs have also encountered the challenge of overstocking in some areas. Therefore, the development strategy of aquaculture in China should be changed to some extent.

15.6.3 Ecological Intensification of Aquaculture Production Systems

In the context of increasing land and water constraints, there has been a trend toward intensification of APSs in the world over the past decades. However, the practice of agricultural development has shown that simplistic intensification often has non-negligible negative effects while increasing productivity (Tilman et al. 2011).

As population still continues to grow and living standards continue to improve, the development of aquaculture in China cannot go back to the extensive models with high ecological efficiency but low productivity, and at the same time, there are obvious shortcomings in simple intensification; therefore, ecological intensification of aquaculture systems (ELIAS) has become the reasonable way for aquaculture development.

ELIAS is a concept and approach to integrate anthropogenic inputs with aquaculture ecosystem services in order to improve the production and comprehensive benefits of aquaculture production systems (Dong 2015a; Dong et al. 2022). Ecosystem services are processes or conditions that lead to benefits for humans directly and indirectly, which are classified into provision services, regulation services, support services, and culture services (Daily 1997). The boundary of an aquaculture ecosystem is the extent of a fish farm or farming area, including aquaculture waters, ancillary land, and the available space above them. Since APSs are highly diverse, various ecosystem services can be integrated into aquaculture ecosystems (Fig. 15.4) to improve their productivity, comprehensive benefit, and sustainability. In agroecosystems, the production and benefits of the system are often maintained and enhanced by enhancing and maintaining the biodiversity of the agroecosystem

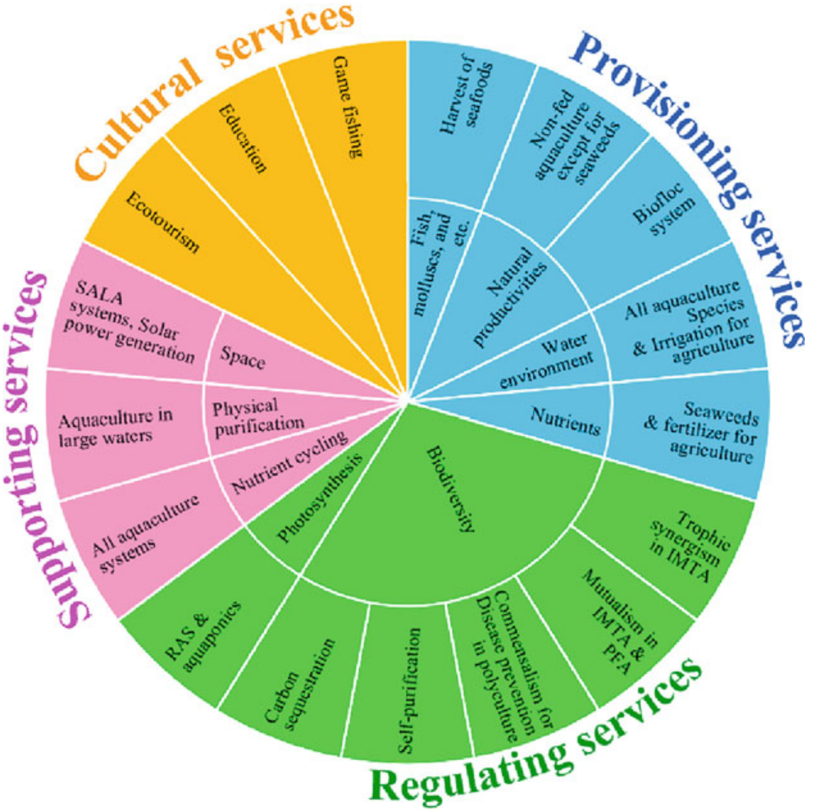

Fig. 15.4 Major ecosystem services of aquaculture ecosystem (from Dong et al. 2022)

(Bommarco et al. 2013). For aquaculture ecosystems, integrated aquaculture is also used to improve production and benefits with the help of trophic synergism, mutualism, commensalism, and so on (Bosma and Verdegem 2011; see also Chap. 9 for detail).

Different APSs have different concerns, so different APSs have to take different approaches to improve their production and sustainability under the ELIAS framework (Table 15.18). APSs in reservoirs, lakes, or other large and public waters are generally sensitive to water quality; therefore, pollutant discharge from these systems is strictly prohibited. The systems in small private or collectively owned waters, such as FAP and RAS, are generally profit sensitive and prioritize high economic benefits; however, the systems must also meet the standards of wastewater discharge through ELIAS modification. PFA, SALA, and FOA are currently promoted by the government in China; for these systems, however, supplementary effects between aquaculture and agriculture, self-purification function of the ocean, and so on must be fully exploited.

The ecosystem services such as cultural service of aquaculture ecosystems can also be used to magnify the economic benefits of APSs. Integrating aquaculture with tourism, education activity, game fishing, solar power generation, or wind turbines can improve the economic efficiency and employment level of aquaculture systems.

15.7 Outlook

Aquaculture is the fastest-growing sector among food production industries and has become a significant contributor of essential macro- and micro-nutrients to the diets of the global population (Hicks et al. 2019). Compared with land-raised animal meat increasing consumption of aquaculture products can reduce a significant amount of land required for growing feed crops by 2050 with expected 9.7 billion people (United Nations, Department of Economic and Social Affairs, Population Division 2019). However, due to the high and increasing pressure of environmental challenges and resource constraints there is a great deal of uncertainty in the further development of aquaculture (Froehlich et al. 2018b).

Aquaculture production systems or models have gone through or are going through development stages of extensive monoculture, extensive polyculture, semi-intensive polyculture, intensive monoculture (industrial monoculture), and intensive integrated culture, which is called by Costa-Pierce (2010) the ecological aquaculture (Table 1.3). The history of aquaculture development is an evolutionary process of ELIAS, in which intensification and ecological modification take place alternately with the increasing demand for aquatic food product, technology advances, and increasing environmental concerns. If the extensive fish culture 8000 years ago is counted as the first step of mankind from fishing to fish farming, then the emergence of polyculture afterward is an important step of ecological modification in which mankind makes full use of the productivity of natural diet organisms in ponds. In the 1950s and 1960s, with the invention of pelleted feeds, floating polyethylene net cages and the widespread use of aerators, aquaculture

Table 15.18 Approaches to ecological intensification for major APSs in China (from Dong et al. 2022)

APSs	Challenges or constraints	Major ecosystem services that need to be integrated	Explanation
RAS	Fishmeal consumption, energy consumption, economic feasibility	Regulating services (RS) of photosynthesis, supporting services (SS) of alternative energy	Integrating with the photosynthesis of aquatic plants in situ or ex situ; leveraging alternative sources of energy, such as thermal drainage from power plants or geothermal water or underground cool water; adopting wind and/or solar power generation, and integrating with tourism and education activity.
Fed aquaculture in ponds	Pollution, fishmeal consumption, freshwater consumption, land use, food safety	RS of trophic synergism, SS for power generation, cultural services (CS) of tourism	Integrating *ca* 20% of filter-feeders in freshwater ponds, and integrated multi-trophic aquaculture (IMTA) in seawater ponds, such as 1:1 of shrimp: clams in the standing crop; adopting the models of raceways in ponds and partitioned aquaculture systems; codesigning the integration with other sectors of wind and/or solar power generation, tourism, and education activity.
Fed nearshore aquaculture	Pollution, fishmeal consumption, energy consumption, food safety, ecological risks, conflicts with other users	RS of trophic synergism and self-purification, SS for power generation, CS of tourism	IMTA; moving to offshore areas to take advantage of the physical self-purification function of the ocean; informed planning based on ecological and social carrying capacities; codesigning the integration with other sectors of wind power generation, tourism, and education activity.
Fed offshore aquaculture	Pollution, energy consumption, ecological risks, economic feasibility	Regulating services (RS) of trophic synergism and self-purification, SS for power generation	IMTA; informed planning based on ecological carrying capacity of the ocean; codesigning the integration with wind and/or solar power generation; stocking triploid varieties.
Non-fed nearshore aquaculture	Over stocking, conflicts with other users	PS of natural productivity, SS for power generation, CS of tourism	Stocking suitable species and optimal quantities of seed according to the compositions and productivity of natural diet organisms; codesigning the integration with other sectors of wind and/or solar power generation, tourism, and education activity; informed planning based on ecological and social carrying capacities.

(continued)

Table 15.18 (continued)

APSs	Challenges or constraints	Major ecosystem services that need to be integrated	Explanation
Non-fed aquaculture in large inland waters	Disproportionality of fish stocking	PS of natural productivity, CS of tourism	Stocking suitable multi-species and optimal quantities of seed according to the compositions and productivity of natural diet organisms, such as stocking *ca* 70% silver carp and *ca* 30% bighead carp in smaller lakes, but stocking *ca* 70% bighead carp and *ca* 30% silver carp in larger reservoirs; codesigning the integration with other sectors of wind and/or solar power generation, tourism, and education activity.
Non-fed aquaculture in ponds	Freshwater consumption, land use	PS of natural productivity, SS for power generation, CS of tourism	Stocking suitable species and optimal quantities of seed according to the compositions and productivity of natural feed organisms; integrated aquaculture with agriculture and animal husbandry; codesigning the integration with other sectors of wind and/or solar power generation, tourism, and education activity.
Paddy field aquaculture	Food safety, disproportionality of fish and paddy	RS of trophic synergism, PS of natural productivity	Farming fish and planting rice in proportion, commercialized production, banned pesticides. The area for animal culture is less than *ca* 10% of the total paddy field area normally.
Waterlogged salt-alkali land aquaculture	Freshwater consumption, re-salinization	RS of trophic synergism, SS for power generation, PS of irrigation water	Area ratio of terraces + roads to pond is about 6:4, and polyculture in ponds; farming salt-tolerant aquatic species, such as whiteleg shrimp and tilapia; application of freshwater conservation techniques, such as fishnet cages in ponds; codesigning the integration with wind and/or solar power generation.
Fed aquaculture in large inland waters	Pollution, conflicts with other users	Regulating services (RS) of photosynthesis, supporting services (SS) of alternative energy	Gradually banning conventional aquaculture models and developing the water-based recirculating aquaculture systems with zero discharge.

production and area coverage increased rapidly, leading to a new stage of intensive monoculture, which is called the industrial monoculture by Costa-Pierce (2010). However, as the negative environmental impacts of the intensive monoculture have become apparent on a large scale, the development of intensive integrated aquaculture (ecological aquaculture) is on the new agenda of aquaculture development.

Nowadays, human beings are facing the triple serious challenges of population growth, environmental pollution, and global climate change, and only the development of the GREEN AQUACULTURE models or production systems based on non-fossil energy and/or photosynthesis can enable aquaculture to achieve simultaneously the ultimate goals of high yield, zero discharge, and low carbon. The main forms of the green aquaculture will include land-based and sea-based RASs driven by non-fossil energy, offshore mariculture based on non-fossil energy and self-purification capacity of the ocean, and seedling stocking-based aquaculture in large waters (lakes, reservoirs, coastal sea areas) based on photosynthesis (natural productivity) and so on. The European Union has pledged to become carbon neutral by 2050, when carbon dioxide emissions are balanced with the use of carbon dioxide removal technologies. China has also pledged to reach a carbon peak by 2030 and become carbon neutral before 2060. It can be expected that in the near future we will usher in a phase of green aquaculture based mainly on non-fossil energy and photosynthesis, which will be a new era of aquaculture development using high technology with the help of biosphere provision services. From this perspective, the development of aquaculture systems or models is a process by which humans gradually integrate broader ecosystem services with anthropogenic inputs (Fig. 9.4).

The world's population is expected to increase from 7.7 billion in 2019 to 9.7 billion by 2050; therefore, further increase in aquaculture production is necessary to ensure human food security. Before carbon neutrality is achieved, it is a critical and difficult period for aquaculture development. Unless the governments give the food production industries special policies to increase carbon emissions to some extent, the aquaculture industry should also implement the development strategy of carbon reduction. Even if the governments give some loose policies to aquaculture industry, energy conservation and carbon dioxide emission reduction should also be the incumbent responsibility of the aquaculture industry.

At the present stage, the main concerns of aquaculture development in China are aquaculture pollution, economic development, and food safety, while the concerns in developed countries or from a global perspective may be different from Chinese. Even there are concern differences between the developed eastern coastal areas and the less developed inland western areas in China. Since there are huge differences among countries in the world in terms of development stage, geographical location, degree of marketability of aquaculture products, dietary habits, etc., it is unlikely that there is a certain model (system) of aquaculture that can dominate anywhere in the world. Long-term coexistence of multiple types of aquaculture models in the world will become the norm. However, ecological intensification would be a solution to guide the sustainable development of all types of aquaculture production systems.

With the ecological intensification of aquaculture systems, we will encounter some new problems that need to be solved. At present, there are still many basic scientific issues and key technologies of aquaculture that have not been solved. For example, is bivalve mariculture a source or sink of atmospheric CO_2? To answer this question, there is a lack of well-defined boundary, long-term accurate experimental verification. The completion of this experiment will confirm the function of ‘carbon sink fishery’ of bivalve mariculture. For another example, the water-based RASs based on non-fossil energy in large inland waters may be one of the optional aquaculture models with low ecological footprint, land saving, and economic feasibility in the future, but there are still many technical issues to be solved. So, scholars of aquaculture ecology still have a long way to go!

Of course, aquaculture development is not just a matter of science and technology, let alone a matter of aquaculture models or aquaculture ecology. Consumer markets have an irreplaceable role in pulling the development of aquaculture and shaping aquaculture structure, among other things. The realization of ELIAS will require close collaboration among policymakers, scientists, farmers, and the supporting industry. Further advances in breeding, feed innovation (decoupling aquafeeds from wild fish and terrestrial plant ingredients), disease prevention, and so on will ensure a solid underpinning for achieving the sustainable development of the aquaculture industry.

Brief Summary

1. To alleviate the constraints of the factors such as land and freshwater resources on aquaculture development, there is a trend worldwide toward the intensification of aquaculture systems. Income per unit area is substantially higher in intensive aquaculture systems than in extensive aquaculture systems, which is the main intrinsic economic driver for the eagerness to implement aquaculture intensification. However, simplistic intensification of production systems may pay high prices while increasing yield.
2. Aquaculture is closely linked to wild fish resources. The development of aquaculture can relieve fishing pressure on wild fish resources, meanwhile, the extensive use of fishmeal and fish oil in aquafeed can also put pressure on wild fish resources. Reducing the trophic level of farmed animals, improving feed utilization, and developing alternatives to fishmeal are important ways to alleviate this contradiction.
3. In terms of unit weight of production, omnivorous tilapia farming requires more land than carnivorous rainbow trout farming, because tilapia feed contains more plant meal that requires land for cultivation. Farmed omnivorous fish is more dependent on land, while farmed carnivorous fish is more dependent on wild fish resources.
4. The environmental impacts of aquaculture should include all aspects of the process (from ‘cradle to grave’), i.e., from obtaining raw materials and energy from the nature, producing aquatic products, storing, transporting, and marketing the products until its product is consumed. The ecological footprint of aquaculture is a measure of the environmental impact of resource consumption and waste discharge in all the process. Life cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a

product's life cycle, i.e., from raw material acquisition, via production and use stages, to waste management.

5. Comparative studies using LCA showed that the ecological footprints of intensive farming system were much higher than those of semi-intensive and extensive systems, despite the former used significantly less land than the latter two systems. This is mainly due to the fact that the former uses more electricity and feeds, etc., than the latter two systems. Compared with chicken and livestock aquatic food product is not only high-quality animal proteins, but also better eco-friendly products.
6. Carbon footprint is a component of ecological footprint that measures GHGs, and is defined as a certain amount of gaseous emission that is relevant to climate change and associated with human production or consumption activity. In general, intensified aquaculture systems have higher carbon footprint.
7. The water footprint of a product is the volume of freshwater used to produce the product, measured over the full supply chain. The water footprint of aquaculture includes mainly the water footprint of aquafeed, the direct water uses in aquaculture, the water used to dilute the tailwater with exceeding discharge concentration standards, and the water footprint of facility construction. Omnivorous fish requires more crop ingredients and therefore requires indirectly more freshwater resources than carnivorous fish. Mariculture does not directly consume freshwater resources and has less potential freshwater consumption. The culture of filter feeders purifies the water and therefore reduces the water footprint.
8. Emergy is the amount of energy of one form that is used in transformations directly and indirectly to make a product or service. The unit of emergy is the emjoule or emergy joule. Emergy analysis theory is a quantitative analysis that evaluates resources, goods, or services in common units of solar energy and measured as solar emergy (sej). From the perspective of emergy analysis, extensive pond farming system has high sustainability, while intensive indoor farming system has low sustainability.
9. Generally, aquaculture production systems (APSs) in China can be divided into 10 major types based on feeding strategy, location, and environment. APSs in reservoirs, lakes, or other large and public waters are generally sensitive to water quality, therefore, pollutant discharge from these systems is strictly prohibited. The systems in small private or collectively owned waters, such as FAP and RAS, are generally profit sensitive and prioritize high economic benefits; however, the systems must also meet the standards of wastewater discharge through ELIAS modification. PFA, SALA, and FOA are currently promoted by the government; however, supplementary effects between aquaculture and agriculture, self-purification function of the ocean, and so on must be fully exploited.
10. In general, non-fed APSs, such as non-fed nearshore aquaculture and non-fed aquaculture in ponds, and supplement fed systems (such as paddy field aquaculture) have higher sustainability. In contrast, some intensively fed APSs, such as RAS and fed nearshore aquaculture, have lower sustainability. Due to increasing demand for high-quality aquatic food product in China, the development of

aquaculture can't adopt wholly the aquaculture systems with high sustainability but low productivity. On the other hand, simplistic intensification of APSs has obvious flaws. Therefore, the ecological intensification of aquaculture systems should become the main way in the development of aquaculture.

11. Integrating aquaculture with culture services of the ecosystem such as tourism, education activity, game fishing, solar power generation, or wind turbines can improve the economic efficiency and employment level of aquaculture systems.
12. The history of aquaculture development is an evolutionary process of ELIAS. It can be expected that in near future we will usher in a phase of GREEN AQUACULTURE, which will be a new era of aquaculture development based on high-technology and biosphere services. The main models or systems of green aquaculture will include land-based RASs and sea-based RASs relying on non-fossil energy, offshore mariculture based on non-fossil energy and self-purification capacity of the ocean, and seedling stocking-based aquaculture in large waters (lakes, reservoirs, coastal sea areas) relying on photosynthesis (natural productivity), and so on.

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