

Chapter 11

Perspectives on Bivalves Providing Regulating Services in Integrated Multi-Trophic Aquaculture



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Abstract The concept of integrating species into one culture system originates from Asia and the Middle East. Development of integrated aquaculture involving marine bivalves is relatively new, going back to the late 1980s in China and 1990s in the Western world. In this chapter, we present four cases of integrated multi-trophic aquaculture (IMTA) where bivalves are involved in providing regulating services: i) shrimp culture in ponds, ii) cascading pond systems, iii) open-water caged finfish culture and iv) bay-scale culture systems. The bay-scale integrated culture system in Sanggou Bay in China represents commercial IMTA where a range of different regulating services are provided by the bivalves. Bivalves use degraded fragments derived from cultured kelp and organic waste products from fish farming, and play an important role in the ecosystem processes of the bay. The provision of regulating services in shrimp and cascading ponds is evident as the system configurations allow for biogeochemical processing of waste to maximize extraction by the bivalves. The current configurations used in open-water finfish cage culture suggest that adaptation of concepts allowing for control of effluent water, producing longer contact times and increased biogeochemical processing of the waste products, will dominate future IMTA development. If global bivalve culture production is sustained, we will likely see more regulating services from

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bivalves in IMTA systems, as new opportunities may arise for developing novel IMTA configurations and concepts.

Abstract in Chinese 摘要:将不同类型的生物组合到一个养殖系统的理念起源于亚洲和中东。包含滤食性贝类的海水综合养殖方式最早可追溯到20世纪80年代的中国和90年代的西方国家。本章列举了包含滤食性贝类的四种典型多营养层次综合养殖模式(Integrated Multi-trophic Aquaculture, IMTA),包括:i)池塘虾类养殖;ii)级联式池塘养殖系统,iii)开放海域鱼类网箱养殖,iv)海湾养殖。中国的桑沟湾是成功实现IMTA产业化的典型海湾,滤食性贝类通过同化养殖海带产生的碎屑和鱼类养殖过程中产生的有机废物,担负着调节海湾生态系统状态的重要功能。在虾类和串联式池塘养殖系统中,滤食性贝类提供的调节服务功能也非常明显,这主要得益于养殖系统的合理化设计,充分利用了生物地球化学过程来实现滤食性贝类对废物利用效率的最大化。目前基于开放海域鱼类网箱养殖IMTA的经验表明,未来IMTA的发展将趋向于养殖水体富营养化的控制,延长营养物质在各营养层级生物间的接触时间和养殖废物的生物地球化学过程等。如果全球双壳贝类的养殖产量保持持续增长态势,更多新型的IMTA模式将会陆续出现,这也为我们发掘贝类在IMTA系统中更多的调节服务功能提供了新机遇。

Keywords IMTA · Waste recirculation · Extraction efficiency · Biogeochemical processing · Sequential culture

关键词 多营养层次综合养殖 · 养殖废物循环利用 · 利用效率 · 生物地球化学过程 · 可持续养殖

11.1 Introduction

The concept of integrating different species in aquaculture has its roots in ancient traditions in China and other parts of Asia and the Middle East, going as far back as the origin of aquaculture. In 2200–2100 B.C., the document *You Hou Bin* detailed the integration of fish with aquatic plants and vegetable production in China and images on tombs in Egypt showed evidence of historical culture, growing tilapia in conjunction with agricultural activities in 1550 to 1070 B.C. (Bardach et al. 1972; Chopin 2013). In the “Complete Book on Agriculture” by Guangqi Xu, published in 1639, it was said that “the optimized ratio for stocking silver carp and grass carp was 600:200, and only the grass carp was fed with grass” (Zhu and Dong 2013). Experiential and practical knowledge of the farmers have been the basis for the polyculture inventions and traditions, conceived to provide regulating services like mitigating waste materials entering the farming environment, controlling phytoplankton blooms and recirculating nutrient resources. Today a wide variety of polyculture is practiced in many Asian countries (Troell et al. 2009; Soto 2009), mostly dominated China. The classic polyculture model, which essentially includes the co-culturing of species at the same trophic level and/or belonging to different

trophic levels, has widely been applied in freshwater aquaculture all over China, at a production level of about 30 million tonnes in 2015 (Wartenberg et al. 2017). Development of integrated culture involving marine bivalves is relatively new in China, going back to late 1980s (Fang et al. 2016). It is, however, based on the philosophy, principles and strong knowledge base from the ancient traditions and can best be exemplified by the bivalve – macroalgae – fish cage combination used in Sanggou Bay in the Shandong province and in Zhelin Bay in the Guangdong province (Zhou et al. 2006; Fang et al. 2016).

The development of modern aquaculture in the Western world differs from the Asian model as commercial systems have typically been characterized by increasing intensification of monoculture production. Co-culture and ecosystem-integrative concepts have been researched on an experimental level and promoted as an alternative mitigation strategy to improve sustainability and potentially increase profitability (Ridler et al. 2007), but have rarely developed to the commercial level. Early work in North America on land-based polyculture was done by the team of John Ryther who pioneered the concept of treating nutrients from sewage from urban areas (Boston, Massachusetts) using biological filters, including six species of bivalves (Ryther et al. 1972; Goldman et al. 1974; Ryther et al. 1975; Mann and Ryther 1977; Ryther 1981). This work continued in Israel where researchers began to look at intensive multi-species aquaculture in desert climates with an emphasis on water conservation and nutrient control (Krom et al. 1985; Krom and Neori 1989; Neori et al. 1989; Israel et al. 1995; Shpigel and Neori 1996; Shpigel et al. 1996). From this previous work, the term “integrated multi-trophic aquaculture” (IMTA) eventually emerged (Chopin et al. 2001) and is now a widely accepted label for the practice. Currently, it is slowly being implemented in commercial farming operations in the western world, while in Asia, it has become common to use the IMTA term on systems originally called polyculture. The IMTA concept involved the arrangement of species belonging to different trophic levels where the integrated culture was facilitating conversion of various wastes produced into animal and seaweed biomass (different trophic positions), creating additional aquaculture revenue for the farmer and removing some of the excess nutrients from the environment (Chopin et al. 2001; Troell et al. 2003; Soto 2009). As most bivalves are efficient at filtering particles suspended in the water column and some species are possible to culture in high densities, mussels were initially proposed as an early candidate for IMTA to regulate the fine organic particulate waste (faeces or excess feed) from finfish culture thereby mitigating the farming impact on the environment. Several pilot-scale farms were set up in various parts of the world to test this concept (Fig. 11.1). This approach was also supported by studies demonstrating that bivalves may exert substantial influence on primary production processes and concentrations of particulate matter (Dame 1996; Prins et al. 1998). Waste products that elevate natural concentrations of particles or nutrients stimulating plankton production will theoretically also contribute to higher food availability for bivalve production. Consequently, bivalves have been proposed as a candidate for mitigating and recycling waste in aquaculture, thereby providing a regulating service.



Fig. 11.1 Farming mussels in association with salmon farms in the Bay of Fundy, (a) aerial shot of a salmon farm in the Bay of Fundy with 4 rafts of mussels on the down-stream end, (b) a mussel raft showing the arrangement of mussel lines hanging within an empty fish cage collar and the suspension system using floats, (c) close-up of the mussel lines showing the mussel socks hanging down from the top line that is supported by the buoys, (d) close-up of one of the mussel socks hanging from the top line on one of the rafts. (Photo credit: S.M.C Robinson, DFO)

With experience gained from testing the IMTA concept in varying environments, the approaches and understanding of IMTA principles are continually evolving and have broadened (Chopin 2013; Jansen et al. 2015; Fang et al. 2016). The use of bivalves in IMTA development might be characterized as being in its infancy, as bivalves are being studied for their ability to directly capture of organic particulates from farm sites and also in the larger scale of relative nutrient extraction at the bay level without specific requirements on proximity to a farm and nutritional connectivity (Chopin 2013). Other potential benefits provided by bivalves in IMTA are improved perception of sustainable production by the public (Yip et al. 2017), extraction of pathogens and salmon lice from finfish aquaculture (Molloy et al. 2011, 2014; Bartsch et al. 2013; Webb et al. 2013), their role in the carbon cycle with consequences for CO₂ sequestering and climate change (Jiang et al. 2015; see also Filgueira et al. 2019) and new socio-economic approaches to motivate industry to adopt IMTA (Shi et al. 2013; Hughes and Black 2016).

In this chapter, we present four cases of IMTA where bivalves are involved in providing regulating services. The cases represent a range of culture configurations varying in scale, ecosystems and control of water transport. The cases are pond culture, cascading pond systems promoting micro-algae production, open-water caged finfish culture and finally a bay-scale culture system. Investigating the perspectives of these cases and their characteristics, we assess the scales in which bivalves in IMTA may provide regulating services.

11.1.1 Pond-Scale Systems: Shrimp–Bivalve IMTA

Soto (2009) reviewed the research, implementation and prospects of integrated marine and brackish-water aquaculture in tropical regions, including the co-culture of shrimp and fish with filter feeders (mussel, oyster) and seaweed. A review of integrated shrimp-oyster farming (Table 11.1) suggests that there is a significant potential for oysters to remove particulate material from shrimp culture effluents,

Table 11.1 Bio-w-mitigation potential of bivalves in combination with shrimp

		Bacteria	Suspended solids	Chl <i>a</i>	Total N	Total P	References
Oysters <i>Saccostrea commercialis</i>	Lab scale Flow through After sedimentation	65	81	61	33	44	Jones et al. (2002)
Oysters <i>Saccostrea commercialis</i>	Lab test recirculation After sedimentation	88	84	96			Jones et al. (2002)
Oysters <i>Crassostrea gigas</i>	Lab scale After sedimentation		71	100			Ramos et al. (2009)
Oysters <i>Crassostrea rhizophorae</i>	Lab scale After sedimentation		41	51			Ramos et al. (2009)
Oysters <i>Crassostrea virginica</i>	Shrimp pond coupled to raceways		41		−9	41	Kinne (2001)
Oysters <i>Saccostrea commercialis</i>	Lab scale After sedimentation	70	88	92	33	37	Jones et al. (2001)
Oysters <i>Crassostrea rhizophorae</i>	Experimental in sedimentation tank		~75	~75			de Azevedo et al. (2015)

Numbers are given in percentage reduction by the bivalve unit.

demonstrating the regulating services of bivalves in these integrated cultivation systems. It should be noted though that most of the studies defined removal rates after sedimentation of particulate matter and these rates can therefore not be directly related to total waste production. Growth and physiological state of oysters were generally good, but under conditions with high particle loading, growth was inhibited (Jones et al. 2001, 2002). Similarly, nutritional stress was observed for mussels solely being fed with solid fish wastes (Both et al. 2011). It therefore seems beneficial to allow the shrimp effluent to settle before bivalve biofiltration in order to improve growth and reduce stress (Jones et al. 2002). In Mexico, the black clam (*Chione fluctifraga*) was found to be feasible in co-culture IMTA pond systems with the white shrimp (*Litopenaeus vannamei*) through improving the water quality and increasing the production rate of the shrimp, although this was still at an experimental scale (Martinez-Cordova and Martinez-Porchas 2006; Martinez-Cordova et al. 2011, 2013).

Despite the fact that the potential for using filter feeders in re-circulated shrimp systems has been shown in several small and experimental settings (e.g. in Thailand, China, Vietnam, Malaysia, Mexico, Australia; see Soto 2009), Soto (2009) concluded that virtually no commercial practices can be found.

11.1.2 Cascading-Pond Systems: Linking Fish and Bivalves Through Phytoplankton Production

Stimulation of phytoplankton production in culture operations provides yet another food resource in integrated bivalve systems (Delia et al. 1977; Goldman and Ryther 1976; Ryther et al. 1972, 1975; Milhazes-Cunha and Otero 2017), and is commonly applied in semi-closed cultivation systems such as ponds. Phytoplankton assimilates the inorganic waste streams originating from fish and shrimp culture, while in turn, serves as a valuable food source for bivalves. The combination of phytoplankton and animal (i.e. shrimp, carp, tilapia and other planktivorous fish) production in ponds has been practiced for millennia in China (Neori et al. 2004) and recent trials in the Haiyang city of Shandong province where the effluent water from tanks holding fish flows into cascading-pond ponds with scallop culture show promising results. Phytoplankton blooms in these systems are often uncontrolled and are generally characterized by the lack of nutritionally-desirable microalgae species (Goldman and Ryther 1976; Benemann 1992). When bivalves are integrated with fish cultivation, often a settling basin or a foam fractionator is situated between the fish and the bivalve cultivation units to allow settlement of particulate wastes (Shpigel and Blaylock 1991; Hussenet et al. 1998; Lefebvre et al. 2000; Jones et al. 2001). Although bivalves can feed on both fin fish organic wastes and phytoplankton, a diet solely based on the former is not desirable. Both et al. (2011) indicated that mussels may become nutritionally stressed when only fed with organic wastes from cod farming and Handå et al. (2012a) showed that growth was lower for

mussels fed with salmon faeces compared to those given microalgae or salmon feed. This is not particularly surprising since several studies have shown that bivalves need nutrients such as essential fatty acids (Caers et al. 1998, 2003; Milke et al. 2004; Nevejan et al. 2003) that are often retained by organisms and not readily available in faecal pellets (Reid et al. 2013). Apart from removing particulate wastes, the settling ponds also promote a more stable and diverse phytoplankton production compared to the production in the fish ponds (Shpigel and Blaylock 1991; Lefebvre et al. 2000). Recent developments in pond aquaculture include the increase in culture robustness of phytoplankton by controlling and monitoring a known mixture of phytoplankton species, thus avoiding culture crashes (Milhazes-Cunha and Otero 2017). These types of systems typically consist of a series of cascading ponds, where the effluent water from the fish pond (or tank) flows into a pond where phytoplankton production takes place and finally this water is directed towards the bivalve ponds. Separate ponds for phytoplankton production allow better control and, by introducing phytoplankton reactors and (small) inoculation ponds, a population dominated by microalgae species with high nutritional value can be realized (Hussenot et al. 1998). This could also imply that specific nutrients need to be supplemented to the fish waste water to realize the optimal nutrient balance for the desired phytoplankton species (e.g. silicate for diatom growth) (Lefebvre et al. 1996; Hussenot et al. 1998). Separation of phytoplankton and bivalve ponds is necessary to give phytoplankton the opportunity to grow and multiply before filtration by the bivalves.

Milhazes-Cunha and Otero (2017) reviewed the biomitigation potential of integrated fish-phytoplankton-bivalve systems indicating that nutrient removal efficiencies are generally high (>90%) for recirculating aquaculture systems. This is higher compared to cascading-pond systems which have lower removal efficiencies (67% ammonia, 47% phosphate) (Hussenot et al. 1998). Shpigel et al. (1993) demonstrated that for a pond system gilthead seabream (*Sparus aurata*) and the Japanese



Fig. 11.2 Left: Four cascading-pond systems each consisting of three interlinked ponds in The Netherlands. The system is designed for cultivation of the common sole (*Solea solea*), the king ragworm (*Alitta virens*) (pond 1) and the Manila clam (*Venerupis philippinarum*) (pond 3) by reusing fish waste streams to stimulate phytoplankton production (pond 2). Right: Manila clams cultured in the cascading-pond system

oyster (*Crassostrea gigas*), including a sedimentation tank, 11% of the total waste nitrogen (TN) was removed, but it was unknown how much of the inorganic waste stream this constituted.

Growth of bivalves is generally good in fish-phytoplankton-bivalve integrated systems (Shpigel and Blaylock 1991; Jara-Jara et al. 1997; Shpigel et al. 1993) and no microbiological contamination of rearing waters or bivalves has been observed (Courtois et al. 2003). The combination of phytoplankton and bivalves can thus remove substantial fractions of the (inorganic) waste streams from fish aquaculture while at the same time resulting in a valuable crop (Fig. 11.2). However, bivalves also produce metabolic waste products in the form of inorganic (NH_4) and organic (faeces) nutrients. Like fish faeces, part of the faecal material will be broken down by bacteria and other microorganisms and contribute to the total pool of inorganic nutrients. In estuaries, approximately half of the particulate nitrogen bivalves feed on is regenerated in inorganic forms (Jansen 2012). It is unknown how much of the particulate nutrients are being regenerated in pond systems. To remove the remaining inorganic nutrients, several studies have therefore integrated a seaweed or periphyton compartment following the bivalve ponds (Shpigel et al. 1993; Levy et al. 2017).

11.1.3 Open–Water Caged Finfish Aquaculture: Salmon–Bivalve IMTA

Open-water cage culture represents the dominant global production method of fed marine finfish where the environment inside the cage is largely dependent on the exchange rate of various water quality variables (Oppedal et al. 2011). This exchange is essential to avoid depletion of oxygen, vital for respiratory needs of the fish, and to ensure waste product discharge from the net pens. Faeces and uneaten feed constitutes the majority of the particulate load while excreted ammonia dominates the dissolved waste fraction. The composition of these nutrients is dependent on the feed and species in culture (Wang et al. 2013). About 60% of the nitrogen in the feed supplied to the farmed salmonids in Norwegian aquaculture is released as waste, 15% particulate and 40–45% dissolved (Wang et al. 2012). This discharge of effluent waste has prompted concerns on environmental impacts which has led to the development of monitoring and regulating systems to manage the industry (Folke et al. 1994; Holmer 2010) and initiatives to develop mitigation approaches like IMTA. In this case, bivalves were proposed to act as a regulating service by extracting these particulates from the waste streams emanating from the cages.

Studies of bivalve performance in suspended culture downstream from open-water finfish net pens, to extract waste particles of feed and fish faeces, have been carried out in a range of environments and cage arrangements (Fig. 11.1) ranging up to 50 m in diameter and 25-m deep, comprising a volume of 36,000 m³ (Handå et al. 2012b) and smaller volumes of about 50 m³ (Jiang et al. 2012). Some studies fed the

cultured fish with trash fish (Gao et al. 2006; Jiang et al. 2012) while the larger sized companies used modern commercial feeds with total amounts of 5216 tonnes for farms with eight cages (50 m in diameter) over a study period of 13 months (Handå et al. 2012b).

The studies of bivalves cultivated in open water IMTA systems have shown varying results with respect to benefits in bivalve growth, ranging from positive (Gao et al. 2006; Sara et al. 2009; Handå et al. 2012b; Lander et al. 2012; Jiang et al. 2012) to no effect (Taylor et al. 1992; Parsons et al. 2002; Navarette-Mier et al. 2010; Cheshuk et al. 2003). Enhanced growth of bivalves seems to only occur at distances very close to the cages and decreases quickly at distances much less than the spatial dimension of the fish-cage arrangements (Sara et al. 2009; Handå et al. 2012b; Lander et al. 2012; Jiang et al. 2012). The recent use of tracer techniques (stable isotopes, fatty acid profiling and DNA), in attempts to assess the assimilation of waste products by extracting bivalves, has generally indicated that contribution of aquaculture-derived nutrients to bivalve nutrition is relatively small (Handå et al. 2012b; Woodcock et al. 2017).

The dispersion patterns of the particulate waste leaving the cages and its availability to bivalves intended for extraction in IMTA have recently been examined in several studies (Reid et al. 2009; Cranford et al. 2013; Brager et al. 2015; Jansen et al. 2016a; Brager et al. 2016; Filgueira et al. 2017). In general, the larger and heavier particles sink faster while the finer material remains suspended for longer periods of time and therefore travels over longer distances from the cages (Bannister et al. 2016). An extensive study of temporal variability in waste concentrations in the water column at open-water fish farms in eastern Canada and Norway indicated that temporal variations in suspended particulate material (SPM) around the farms were largely driven by natural processes and that the addition of fish wastes had a negligible effect on background SPM concentrations (Brager et al. 2016). The authors concluded that there is little rationale for introducing bivalves in IMTA to mitigate the horizontal flux of small particulate fish wastes, confirming earlier modelling studies (Troell and Norberg 1998). The rapid dilution of nutrients away from fish cages has been documented by some of the work looking at therapeutant dispersion with a high dilution rate happening in minutes (Page et al. 2014). Cranford et al. (2013) identified constraints on the capacity of mussels (*Mytilus edulis*) to capture and absorb organic fish waste under open-water IMTA scenarios. They demonstrated how waste particle capture by mussels is severely limited by the time available to intercept solid wastes contained in the horizontal flux of the particles. Increasing the waste extraction efficiency by using higher mussel biomass may ultimately be constrained by current velocity, available IMTA farm space, negative feedback effects on fish culture from flow reduction caused by mussel culture, and depletion of their particulate food supply to a level that will limit production. Cranford et al. (2013) also argued that the proportion of organic fish faeces relative to ambient seston concentration and seston organic content affects the ability of mussels to absorb more IMTA-generated waste than they egest as mussel faeces. Consequently, the biomitigation potential of mussels will be greatest where seston abundance is low and the organic content of IMTA waste is high. This was also

pointed out by Filgueira et al. (2017) who simulated pumping rate (*e.g.* ingestion) of mussels in a finfish-bivalves IMTA configuration with different background seston concentrations. From their modelling study exploring different spatial arrangements of an IMTA case, they concluded that waste mitigation would be best achieved by placing extractive species such as deposit feeders on the seabed directly beneath the cages rather than using suspension filter feeders to extract the horizontal flux of waste, although one study found that scallops (*Placopecten magellanicus*) would grow and survive well directly under fish cages (Robinson et al. 2011). Handå et al. (2012a) found a more pronounced incorporation of nutrients in the tissues and better growth in shell length of mussels from salmon feed compared to salmon faeces, which suggests that mussels will utilize fish feed more efficiently than faecal particles when cultured in IMTA. Assuming that bivalves efficiently encounter waste particles, Reid et al. (2013) suggested that estimating the dietary quality of the waste particles provides useful information for assessing the mitigation potential of filter feeders and inferring a nutrient reduction potential. They assessed that the percentage of fish culture solids in an extractive species' diet that must be exceeded for mussel culture to reduce the net IMTA site organic load is 14.5% for salmon faeces and high-quality seston, 19.6% for salmon faeces and low quality seston, 11.5% for salmon feed fines and high-quality seston, and 15.6% for salmon feed fines and low-quality seston.

11.1.4 Bay-Scale Interactions: Fish-Bivalve-Seaweed Cultivation in Sanggou Bay, China

China's leading case for a truly commercial, engineered IMTA system is Sanggou Bay (Wartenberg et al. 2017), located on the eastern coast of the Shandong peninsula facing towards the Yellow Sea. The bay is famous for its mariculture and development of polyculture and IMTA concepts for over 30 years (Fang et al. 2016). Sanggou Bay is now one of the most important and dense farming areas in China and is a model globally. The bivalve culture in the bay is evidently integrated with the other main group cultured, the macroalgae.

Table 11.2 Summary of aquaculture in Sanggou Bay, China

Cultured species	Stocking period	Harvesting period	Culture period	Production (tonne year ⁻¹)
<i>Crassostrea gigas</i>	May	March	1–2 year	~60,000
<i>Chlamys farreri</i>	May	March	1–2 year	~15,000
<i>Saccharina japonica</i>	November	May	7 month	~84,500 dry weight
<i>Gracilaria lemaneiformis</i>	June	October	5 month	~25,000
<i>Paralichthys olivaceus</i>	May	October	6 month	~24,000

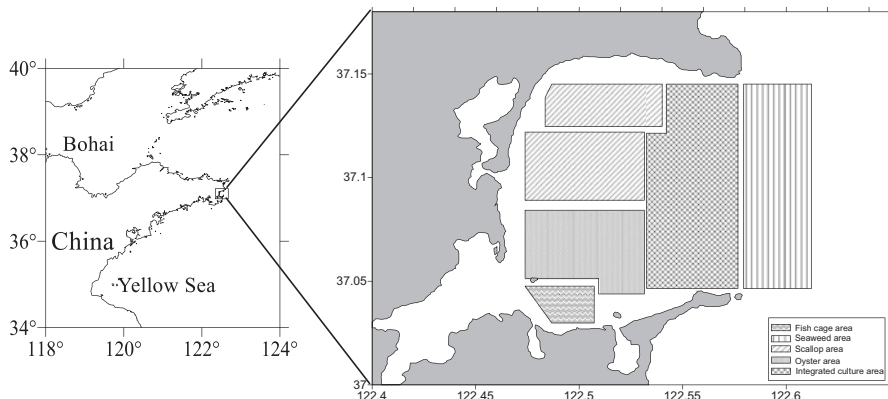


Fig. 11.3 Layout map of aquaculture practices in Sanggou Bay, Shandong Province, China

The bay is 140 km², with an average depth of 7 m and a maximum depth of 20 m at the entrance of the bay. It receives freshwater from one large and a few smaller rivers with the main input occurring during summer. The sediment is dominated by mud and sand. The main farmed species are kelp (*Saccharina japonica*), red algae (*Gracilaria lemaneiformis*), Ferreri's scallop (*Chlamys farreri*), and Pacific oyster (*Crassostrea gigas*) (Table 11.2), which are all cultured from longline systems. Fish culture in cages is now dominated by Japanese flounder (*Paralichthys olivaceus*), although the Japanese pufferfish (*Fugu rubripes*) has previously been farmed. Kelp monoculture occurs mainly near the mouth and outside of the bay (Fig. 11.3), bivalves are mainly raised near the head of the bay and the middle part is characterized by a co-culture of kelp and bivalves. Fish cages are situated south west in the bay, and bivalves and seaweed are cultivated on long lines around the fish cages. The bivalves are mainly cultured in nets hung from longlines and kelp is tied to ropes and grows vertically in the water column.

Mahmood et al. (2016) used a stable isotopic technique to study pathways of organic matter (OM) in Sanggou Bay in order to better understand the role of fish-bivalve-seaweed IMTA practices related to assimilation and accumulation of OM in the cultured species during the summer and winter seasons. They indicated that 90% of carbon and 60% of nitrogen in the diet of bivalves originated from fish faeces and uneaten particles from trash fish during the summer. Alternative sources of OM in the winter season, during low temperatures, may be from detritus lost in large-scale cultivation of kelp. The bivalves cultured in Sanggou Bay are important in reducing OM, but it is suggested that they may also be able to increase production and survival rate of other species in the IMTA system by maintaining high water quality, thereby improving the economic benefit of the entire system (Mahmood et al. 2016). A study in the adjacent Ailian Bay showed that the assimilation efficiency of the Pacific oyster for fish-aquaculture-derived organic matter was 54% (10% waste feed and 44% fish faeces) (Jiang et al. 2012). Given that 50% of the total solid nutrient loads from fish cages are assumed to be within the suitable size

range that can be efficiently retained by the gills, the oysters will theoretically be able to recover 27% of the total particulate organic matter released from fish cages if the waste source is directed towards the location where bivalves are cultured. Bivalves functioning as recyclers of organic matter could contribute to environmentally-sustainable aquaculture and could increase the profitability of fish cultivation.

The detritus lost during the kelp growth cycle is regarded as an important food resource for the filter-feeding bivalves (Xu et al. 2016). Using the stable isotope technique, it has been demonstrated that the diet of filter feeders inhabiting natural kelp forest habitats and adjacent environments was largely based on kelp detritus (Fredriksen 2003; Schaal et al. 2009; Miller and Page 2012). Xu et al. (2016) evaluated the trophic importance of kelp (*S. japonica*) fragments to the co-cultured scallop *C. farreri* in Sanggou Bay and showed with stable isotope techniques that the diet of scallops consisted of 14–43% of kelp-derived organic carbon. Additionally, substantial amounts of dissolved organic carbon (DOC) are released to the surrounding water by kelp (Mahmood et al. 2017). DOC can directly be taken up by bivalves, in addition to particulate organic matter (Roditi et al. 2000), and Mahmood et al. (2017) indicated that the bivalves farmed in Sanggou Bay act both as a source and a sink of DOC, with the highest removal rate of 60% occurring in the bivalve culture area. There are a number of additional positive interactions between bivalves and seaweeds. Bivalve respiration (see Filgueira et al. 2019) generates CO₂ and also releases other metabolic waste products such as ammonia, all of which can serve as an input for growth of seaweeds. Jiang et al. (2014) reported that a scallop (*C. farreri*) population in Sanggou Bay sequestered $78.1 \pm 5.8 \text{ g C}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$ deposited in the shell, while the CO₂ fluxes due to calcification and respiration resulted in $54.0 \pm 4.0 \text{ g C}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$ and $71.7 \pm 6.5 \text{ g C}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$, respectively. In this context, the CO₂ released from the bivalves can provide part of the dissolved inorganic carbon (DIC) requirement of the seaweed. The macroalgae harvest from the bay is an important component providing powerful support for revealing the role of Sanggou Bay in the carbon cycle (Jiang et al. 2015). In terms of the bay scale, Sanggou Bay acted as a net DIC sink with an annual mean uptake estimated at 139,000 tonnes (Jiang et al. 2015).

11.2 Discussion

The four cases presented in this chapter show a variety of IMTA configurations, environments and socio-economic settings where bivalves are positioned to exploit aquaculture waste products, and thereby potentially provide regulating services. An assessment of how the bivalves provide regulating services will rest on the definitions applied to IMTA, which can range from the direct capture of the particulate waste on the farm, to removal of an equivalent amount of the effluent-related nutrients in the far-field by harvesting the bivalves. The latter scenario can occur regardless of distance and connectivity to the actual waste nutrients, where it can also

support sustained ecosystem functioning, depending on the scales of extraction involved. Also, aspects related to traditions and philosophy of integrating aquaculture (like in Asia) and the state of integrated aquaculture development will influence how regulating services are perceived. The wide ranging and sometimes ambiguous nature of the IMTA definition and questions on how much extraction, in our case by bivalves, is enough to qualify for the definition, have frequently been raised (Chopin 2013; Reid et al. 2013; Jansen et al. 2015). Ultimately, the benchmark for comparison will likely be made to monoculture systems growing comparable amounts of biomass of the same species, such as the pioneering work done in Sanggou Bay (Shi et al. 2013). Considering that IMTA may mitigate undesirable impacts, a reference state of environmental condition may be needed, depending on the socio-economic setting and regulatory requirements. The environmental hazard or impact to be mitigated by the bivalves will therefore, in most cases, need to be identified to justify the development of IMTA principles.

Adapting principles of IMTA to local environments and regulatory frameworks seems to be crucial for the successful development of integrated aquaculture systems. The success of IMTA in Sanggou Bay (Fang et al. 2016) is based on a complex set of factors such as the existing high variety of species cultured, inherent philosophy among farmers of combining species in culture, ability to rapidly adapt to environmental changes, a pliant regulatory framework and a socio-economic system promoting multi-species culture. The Sanggou Bay case represents full-scale commercial IMTA where a range of goods and services from bivalves can be achieved. Although there is a need for understanding the role of bivalves in the ecosystem when assessing regulating services in this coastal bay, other factors (e.g. socio-economic issues) seem to be the main driver for the development. In this case, recirculation and recycling of waste nutrients is as important as any direct extraction of aquaculture waste providing regulating services from IMTA in Sanggou Bay.

One comparison that can be made among the case studies, relates to the efficiency of using bivalves to capture waste particles directly from the farm discharge before they are assimilated or bio geochemically cycled, compared to extraction of products coming from another trophic level that converts the waste (bacteria, phytoplankton, zooplankton). Direct capture has typically been anticipated for the open-water cage finfish aquaculture case, while the fish waste products stimulating phytoplankton production that is then extracted by bivalves is achieved in the cascading-pond system. The efficiencies in removal of waste experienced in these two cases are strikingly different, mainly caused by the ability to direct water flow in the cascading-pond system determining particle dispersion and thereby ability to maintain the availability of the converted particles for extraction by the bivalves. The pattern of particles horizontally dispersed from open-water cage finfish aquaculture explains the marginal estimates of waste removal (Troell and Norberg 1998; Cranford et al. 2013; Brager et al. 2015, 2016; Filgueira et al. 2017). In contrast, the cascading-pond systems with integrated fish-phytoplankton-bivalves show generally high removal efficiencies (Milhazes-Cunha and Otero 2017) supporting the concept of sequential control of the effluent water to maintain the nutrient quantity and quality through the biogeochemical cycle and thereby maximize extraction of

the waste by the bivalves through greater contact times. The provision of regulating service in the cascading-pond system is evident and supports the earlier studies of Ryther (1981).

There is a consensus that extractive species in open-water cage finfish aquaculture should be placed underneath the cages where most of the organic waste flux goes, rather than trying to extract the horizontal flux which is marginal in terms of total particulate waste amounts (Cubillo et al. 2016; Brager et al. 2016; Filgueira et al. 2017). The gradient of increased waste flux towards the vertical plane from the cages is also affected by the size distribution of the waste particles that are smallest in the horizontal plane and largest in the vertical plane from the cages, thereby influencing the ability of bivalves to extract the waste (Bannister et al. 2016). Of course, an option always exists to resize the larger waste particles into smaller ones through the manipulation of the binders in the diets resulting in looser (smaller) or more compact (larger) faecal pellets (Appleford and Anderson 1997; Brinker 2007; Brinker and Friedrich 2012; Brinker et al. 2005; Dias et al. 1998; Rodehutschord et al. 2000). Size of the waste particles also determines how fast assimilation by the bivalves and bacterial degradation occur which, together with the dispersion patterns from the cages, will influence the ability of bivalves to directly capture the waste. The challenges of using bivalves to effectively capture and feed on highly-dispersive waste particles from open-water finfish cages seems overwhelming for current practices (Troell et al. 2009; Cranford et al. 2013; Filgueira et al. 2017). This conclusion assumes, however, that future technology will be based on the status quo open-water net cages with high water exchange. But it is possible that new concepts and designs may arise for open-water cages where particles may exit the cages in a more controlled manner. This would likely increase the potential efficiency of assimilation of farm waste by bivalves. Today, due to various environmental challenges with using open-water cage culture systems (e.g. diseases, parasites, organic loading), efforts are now being encouraged to focus on developing new technology, including closed containment systems at sea mainly to reduce disease and parasite interaction with the environment (Lekang et al. 2016). These enclosed systems will require handling and treatment of the waste nutrients, so knowledge on various IMTA concepts converting waste nutrients into feed for bivalves will have more potential, similar to the cascading-pond system. The technology development on sea-based closed containment is expected to diversify future finfish production systems with possibly a higher proportion of the production including options for controlling the effluent waste water. Such systems allow for the development of IMTA concepts with a much higher potential for sequential control of the effluent water and higher removal efficiency of waste than in current open-cage systems.

The role of bivalves in the bay-scale integrated aquaculture production system in Sanggou Bay is evident as a provider of regulating services. These services include: (1) bivalves using degraded fragments derived from the cultured kelp, (2) bivalves directly using organic waste products from fish farming, (3) bivalve harvest removes nutrients supporting sustained functioning of the ecosystem. Bivalve farming ultimately also provides regulating services on extracting nutrients derived from the populated surrounding land area of the bay. Mahmood et al. (2016) estimated that

72% of particulate organic matter in the bay during the summer season originated from land and their results indicated that ~80% of the particulate organic matter, including faecal material and riverine material, is extracted by cultured oysters and scallops. The interaction between the bivalves and the microbial food web was elucidated in experimental mesocosm and flow-through system studies indicating how farmed scallops (*C. farreri*), through phosphorous egestion and size selection of particles, affected the different microbial components (Lu et al. 2015; Jiang et al. 2017). This impact on the “protozoan trophic link” may enable a positive feedback by energy transfer from the microbial loop to the scallops. Protists (nanoflagellates and ciliates) were the dominant source of carbon retained by the scallops (49%). Dissolved organic carbon released from phytoplankton and seaweeds can also serve as energy sources for micro-heterotrophic organisms available as food for the scallops. Of recent and increasing interest is also the role of bivalve respiration and calcification processes to the carbon cycle in this bay, and its importance in how low-trophic aquaculture (bivalves and seaweed) at a coastal scale affects carbon sequestering and climate change (Jiang et al. 2014). These studies demonstrate how bivalves in Sanggou Bay may provide regulating services at the same time as providing provisioning services through their role in processes of carbon cycling related to environmental and climate-change issues.

The regulating services provided by bivalves in Sanggou Bay are assessed, based on investigations and IMTA culture practice over more than three decades (Fang et al. 2016). The ancient history of integrated culture and the inherent approach in China to combine species to maximize yield are essential factors in explaining their success in developing IMTA. Considering the long history of national need for increased food production as the main driver for the dramatic expansion of aquaculture in the coastal zone (Liu and Su 2017), IMTA concepts have been a key component to mitigate the often severe challenges related to environmental impacts and related socio-economic issues. In a recent review, Wartenberg et al. (2017) listed the most adverse impacts of suspended mariculture in China and how these could be mitigated through the application of IMTA systems. The main impacts identified were chemical, ecological, physical and socio-economic. Out of eighteen measures recommended for improving suspended mariculture, IMTA was most frequently considered to have capabilities for bioremediation and increased farm production. The challenges facing the expansion of commercial IMTA included lack of new technology, limited skills development, limited production of low trophic-level species, biogeographic and temporal barriers and negative system feedbacks. They concluded that implementing commercial IMTA is a promising measure for reducing the impacts of suspended mariculture because it presents a range of secondary benefits that can improve the overall sustainability of aquaculture in the coastal zone. Fang et al. (2016) and Wartenberg et al. (2017) clearly demonstrate the existing and future potential for provisions of regulating services by bivalves in IMTA.

The position of China as the dominant global aquaculture producer is expected to continue into the foreseeable future (FAO 2016; Wartenberg et al. 2017), based on its need for internal food production. Global aquaculture production is dominated by low-trophic resources, with bivalves among the most important contributors.

If the bivalve culture position is sustained and the development of IMTA in China is realized, as projected by Wartenberg et al. (2017), we will likely see more regulating services from bivalves in IMTA and new opportunities for developing novel IMTA configurations and concepts with bivalves playing a central role providing such services. The current knowledge of open-water finfish cage culture and the low efficiency of direct capture of waste suggest that adaptation of production systems allowing for sequential control of effluent water, thereby maintaining higher contact times of bivalves with the nutrients and biogeochemical processing of the waste products, will dominate future IMTA.

Bivalves are a dominant aquaculture group worldwide and because they efficiently consume food that is relatively low in the food chain, they may play a key role in the anticipated contribution from aquaculture to the increasing global demand for human food in the coming century (Wijsman et al. 2019). There will be a range of challenges to be solved for this development, among them technology, spatial issues, disease control, government policies and regulations, eutrophication and resource recirculation. Innovative approaches to integrate bivalve aquaculture with other marine sectors (Buck et al. 2017; Jansen et al. 2016b) to optimize the ecological efficiency of the increasing production will be essential to ensure sustainable expansion and obtaining the regulating services from future bivalve aquaculture.

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