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Review

Application of open water integrated multi-trophic aquaculture to intensive monoculture: A review of the current status and challenges in Korea

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ABSTRACT

Intensive fish aquaculture has raised serious environmental concerns, including eutrophication, harmful algal blooms, fish kills, etc. Integrated multi-trophic aquaculture (IMTA) may be the most suitable aquaculture technology to achieve environmental and economic sustainability. The objectives of present study are to review the status of aquaculture and IMTA in Korea; and to determine the challenges to apply the principles of IMTA to intensive monoculture in Korean coastal waters. Korea has been one of the leading countries in aquaculture. Like other advanced countries in aquaculture, such as China and Japan, most aquaculture practices in Korea are intensive monoculture and farms are highly concentrated in bays or estuaries with restricted circulation. In intensive open water aquaculture in these waters, nutrient producers (finfish) are cultured mostly in southeastern Korea whereas extractive organisms (seaweeds) are farmed in the southwestern Korea. There are relatively small areas of overlap between these monocultures, causing environmental issues and reduction in the quality of aquacultured products. Recent attempts of IMTA in Korean coastal waters suggest that IMTA can be a good management tool for improving Korean aquaculture although there are still challenges to overcome. These challenges include development of temperature tolerant species/strains of extractive organisms such as seaweeds and sea cucumbers. Most aquacultured seaweed and sea cucumber species in Korea do not grow well during the summer months, when the release of finfish effluent is at its peak. It is essential to the future success of aquaculture in Korea that a coastal zone management (CZM) be developed that reflects coordinating fed and extractive organisms in coastal bays and estuaries rather them keeping them isolated from one another. The importance of a new regulatory framework advocating IMTA solutions will be essential for environmental protection and continued success of aquaculture in Korea. Although this review is a case study in Korea for IMTA, it will also provide critical information for coastal managers, aquaculturists and regulators in other countries where there are intensive monocultures of fed and extractive organisms.

1. Introduction

The world population will increase by over 50% by 2050, reaching 11 billion (Melorose et al., 2015). Considering this rapid growth of population, as well as climate change, economic and financial uncertainty, and reduction of natural resources, it will be challenging to provide sufficient high quality food for humans. In 2013, approximately 17% of animal protein and nearly 7% of all protein consumed by humans, were provided by fish. Worldwide per capita fish consumption was over 20 kg per year (FAO, 2016). Since the 1980s, growth of the capture fishery production has declined while aquaculture production has increased to meet consumer demands. In 2014, aquatic animal production from aquaculture was over 76 million tons, with nearly US $160 billion of economic value (FAO, 2018). Global fish production is expected to be 181 million tons by 2030, and aquaculture is expected to provide over 60% of the fish by that time (World Bank, 2013). However, intensive fish aquaculture has raised serious environmental concerns. For example, eutrophication due to excess nutrients by fish effluents can cause harmful algal blooms (HABs) (Buschmann et al., 2008; Chopin et al., 2012; Ridler et al., 2007). The sediments underneath or nearby intensive fish aquaculture have accumulations of organic matter providing a good breeding ground for parasites (Alonso-Pérez et al., 2010; Richard et al., 2007; McKindsey et al., 2011; Molloy et al., 2013; Lunstrum et al., 2018). With environmental degradation caused by intensive finfish aquaculture, these wastes can kill or diminish the fish production systems. Therefore, it is critical to develop

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Fig. 1. Intensive seaweed (*Pyropia*) farm in Wando, Jeonnam, Korea.

sustainable aquaculture systems for the long-term aquaculture expansion. Integrated multi-trophic aquaculture (IMTA) is a practice that will achieve environmental and economical sustainability.

Integrated multi-trophic aquaculture is a farming technology growing aquaculture species from different trophic levels in one system with fed-aquaculture and extractive aquaculture components. More specifically, in IMTA systems, deposit feeders and suspension feeders (shellfish) can consume the organic particulate waste from the fed-aquaculture (finfish or shrimp). Seaweeds can take up the inorganic wastes. Many studies have shown that IMTA technology increases the biomass yield of aquacultured animals and seaweed while reducing the waste stream (Barrington et al., 2009; Chopin et al., 2008; Hughes and Kelly, 2011; Ren et al., 2012; Wang, 2001; and references therein).

IMTA is not a new concept. IMTA-like practices have been conducted in China for centuries possibly as earlier as 470 BCE by Fan Li (Yang et al., 2000), but the modern IMTA concept was originally described by Ryther and his colleagues at Woods Hole Oceanographic Institution in 1970's (Ryther, 1977; Ryther et al., 1979). Since then, many IMTA practices have been described worldwide, principally in western countries (McVey et al., 2002; Abreu et al., 2009, 2011; Buschmann et al., 2008; Chopin et al., 1999; Corey et al., 2014; Neori et al., 2004; Ridler et al., 2007). Although Shangou Bay in China is known to be the world largest IMTA practice (Fang et al., 2016; Mahmood et al., 2016; and references therein), IMTA has not been well developed in other Asian countries. Consequently, these aquaculture practices in most Asian countries are still focused mostly on intensive monocultures, leading to a plethora of environmental problems (e.g. eutrophication, HABs, disease, etc.).

Most Korean IMTA practices have conducted in small land based systems (Chung et al., 2002; Kang et al., 2008, 2013, 2014). The first open water IMTA practice began in 2012 (Park et al., 2016). In Korea, intensive fish aquaculture has been practiced for many decades in highly congested bays and estuaries, causing severe environmental problems. Recently, the open water IMTA has received a lot of attention by aquaculturists and coastal managers to reduce the environmental impact of intensively farmed areas. However, there is scant information available about the status of IMTA in Korea. This review will provide critical information about the status of aquaculture and IMTA in Korea and to determine the impediments to apply the principles of IMTA in Korean coastal waters. To achieve these goals, we reviewed several different perspectives, including: 1) current status of aquaculture in Korea; 2) challenges of intensive open water monoculture; 3) IMTA as a potential solution for the issues of intensive aquaculture; 4) summary of open water IMTA practices in Korea to date; and 4) the challenges to the acceptance of IMTA. Although this review focuses mostly on the cases in Korea, this study will provide critical information for global perspective of sustainable and IMTA development.

2. Aquaculture in Korea

Korea has been one of the leading countries in aquaculture (FAO, 2018). The growth of aquaculture in production is over 110% (nearly 4% annual growth) during the past 30 years. The aquaculture production in 2015 was nearly 1.7 million metric tons (MT) while the production in 1985 was only 790,000 MT. The commercial value of aquaculture in 2015 was over $2.1 billion (FAO, 2018). The Korean aquaculture production is dominated by seaweed, 1.2 billion MT, followed by shellfish, 330,000 MT and finfish, 85,000 MT in 2015 (FAO, 2018). Although aquaculture practices have been conducted in Korea for several centuries, modern intensive aquaculture has only begun in 1980's. Marine aquaculture farms are mostly located in the southern coast of the country (Jeonnam and Gyeongnam Provinces). These provinces have many bays and island archipelagos that offer protection for aquaculture from severe weather events. Together with moderate tidal ranges in these regions, the southern coast of Korea is an ideal location for aquaculture.

Over 90% of seaweed aquaculture occurs in Jeonnam Province, which is in the southwest of Korea (Fig. 1). On the other hand, over 80% of shellfish production is in Gyeongnam Province, which is in southeast of the country (Table 1). Oysters are the most important shellfish species in Korean shellfish aquaculture, occupying over 75% of total shellfish production of the nation (Ministry of Oceans and Fisheries, 2018). Approximately, 90% of oysters are produced in Gyeongnam. Most open water finfish aquaculture is also being conducted in Gyeongnam Province and only small amounts in the southeast of Jeonnam Province, where seaweed aquaculture rarely occurs (Ministry of Oceans and Fisheries, 2018). Aquaculture practices have led to the isolation between extractive and fed aquaculture systems. Monocultures of fish in Gyeongnam Province have lead to excessive nutrient release thereby negatively affecting these coastal waters. Even though shellfish are suspension feeders dependent on organically bound nutrients derived from phytoplankton and detrital particles in the water column they are not able to process the wastes derived from finfish aquaculture. Shellfish also excrete organic material, thereby adding more nutrients to the water column (Bouwman et al., 2011; Shumway, 2011; Ward and Shumway, 2004). Intensive open water aquaculture in Korea is causing environmental degradation and reduction of production quality (Chung et al., 2002; Lee et al., 2016; Wu, 1995; Zhou et al., 2006 see below for more details).

3. Challenges in the intensive open water monoculture

3.1. Harmful algal blooms

Harmful algal blooms (HABs) have occurred in Korea during the past several decades and have affected human health as well as natural and cultured marine resources (Lee et al., 2007; Lee et al., 2013; Lim et al., 2006). The duration of red tide events have increased from < one week in 1980s to > one month in 1990s and thereafter (Lee et al., 2013). Intensive fish aquaculture is the major source of nutrients that fuel HAB species (Bouwman et al., 2013; Buschmann et al., 2008; Mente et al., 2006). Intensive cultures of fish have lead to organic matter loadings and in increased Biological Oxygen Demand(BOD) in the sediments (Soto and Norambuena, 2004). The occurrence of HABs in Korea was due to, at least in part, the nutrient input from the fish farms (Lee et al., 2013). The accumulation of organic matter beneath the fish cages in southeast Korea is more severe than those in exposed or offshore environments because of reduced circulation and mild currents. Direct economic losses in Korean aquaculture due to the HABs (shell- and fin-fish kills) are estimated to be over US$159 million over the past three decades (NFRDI, 2017). Similar problems have occurred in other countries where there are intense fish farms. Salmon farming in Chile severely increased nutrient loadings, which have resulted in HAB events (Buschmann et al., 2006). The coastal waters of Philippines have also experienced environmental challenges, e.g. ammonia increasing by 56%, nitrite by 35%, nitrate by 90%, and phosphate by 67%, over a 10-year period (1995–2005) due to fed aquaculture activities (San Diego-McGlone et al., 2008).

Park et al. (2013) suggested a few precautionary management tools to be applied before and after HABs occur, including automatic HABs alarm systems, HABs monitoring network, integrated multi-trophic aquaculture (IMTA) and integrated coastal zone management (ICZM). ICZM is a management tool to create policies for coastal management between coastal managers and stakeholders (Langan et al., 2006; Rensel et al., 2006). It develops a structure of decision making for coastal managements (McKenna et al., 2009). The automatic HABs alarm system and HABs monitoring network are rather to prevent/reduce the damages from the HABs than to prevent/reduce the HAB events. IMTA is the only practice that can mitigate HAB events among the four aforementioned management tools (Buschmann et al., 2008).

3.2. Reduction of benthic biodiversity in intensive fin- and shell-fish farms

Intensive open water finfish farms can also cause a significant loss of benthic biodiversity (Buschmann et al., 2006; Soto and Norambuena, 2004). Chile has regulation on biodiversity decrease related to farming activities. If any farm activity causes the formation of anoxic sediments, the farm must reduce its production by 33%. If the oxygen level does not come back within one year, production must be reduced by another 33%. If the sediment does not recover in the following year, the farm must close (Buschmann et al., 2006). However, this regulation may not be practical in areas like Korea, where there are multiple sources of nutrient pollution (e.g. multiple fish farms located in an area, anthropogenic release of nutrients into watersheds, etc.; Lee et al., 2009; Shin et al., 2010).

Shellfish are not only nutrient producers but also nutrient sinks. Many studies have reported that shellfish have a great capacity for nutrient bioextraction (Galimany et al., 2013; Kellogg et al., 2013; Kite-

Table 1
Aquaculture production and economic value in different provinces in Korea (KOSIS, 2018).

	Finfish		Shellfish		Seaweeds	
Province	Production	Economic	Production	Economic	Production	Economic
Busan	(MT)	value ($M)	(MT)	value ($M)	(MT)	value ($M)
Chungnam	183	2452	2914	3580	30,721	32,200
Gyeongnam	2291	25,560	6079	6570	43,400	4908
Jeju	24,553	254,957	292,287	218,907	8719	10,444
Jeonbuk	27,241	39,654	32	1741	-	-
Jeonnam	133	1358	1066	30,137	23,552	29,442
Others	22,879	304,504	48,627	434,733	12,220,055	592,844
Total	2857	41,172	986	8670	23,035	21,470
	80,137	669,657	351,991	714,338	12,349,482	691,308

Powell et al., 2006; Lindahl, 2011; Higgins et al., 2011; Rose et al., 2015). For example, mussels (*Ischadium recurvum*) and oysters (*Crassostrea virginica*) can remove up to 217 kg N ha^{-1} yr^{-1} and 278 kg N ha^{-1} yr^{-1} in Chesapeake Bay (Higgins et al., 2011; Kellogg et al., 2013). However, these filter feeders also eject pseudo-feces or fecal pellets. Therefore, intensive shellfish aquaculture may enhance the organic material deposition to the sediments, increasing BOD that may lead to anoxic sulfur rich sediments and a decline in species richness (Richard et al., 2007; Alonso-Pérez et al., 2010; Lunstrum et al., 2018). Benthic nutrient fluxes are in general greater within shellfish farm areas than at control sites (McKindsey et al., 2011; and references therein). In the mussel, *Perna canaliculus,* farm area in Kenepuru Sound, New Zealand, for example, the organic nitrogen and ammonium concentrations in sediments were greater than those at a control site. The sediment-denitrification rates are also much higher beneath mussel farms than at control sites (Giles et al., 2006; Kaspar et al., 1985).

The biodeposition from the shellfish aquaculture may affect infaunal communities in the sediment. As the input of organic matter increases, the sediment community changes from large filter feeders to smaller and more deposit feeders and small polychaetes, to nematodes and finally shifting to sulfur bacteria (*Beggiatoa* species; McKindsey et al., 2011). The changes in infaunal community in shellfish aquaculture is farm specific (e.g. farm size, stocking density and age of farm) and site specific (e.g. bathymetry and hydrodynamic regime) (Black, 2001; Hartstein and Rowden, 2004; Hartstein and Stevens, 2005). The many shellfish farms in Korea are in general large and have been leased for many decades sited in enclosed or semi-enclosed areas (Fig. 2). However, we are not aware of any studies in Korea that have analyzed biodeposition and the infaunal community changes. It is very difficult now to determine the effects of shellfish farming in sediment communities in Korea because no metrics are available before the establishment of these farms.

3.3. *Nutrient limitation in intensive seaweed farms*

The issues in intensive seaweed farms are quite different from those at fin- and shellfish farms. Seaweeds require nutrients for their growth. When seaweeds are cultivated intensively, nutrients are often limited for the growth of seaweed (Hurd et al., 2014; Kim et al., 2017a; Troell et al., 2009). Over the past two decades, nutrient limitation in seaweed farms has become severe in Korea and Japan (Matsuoka et al., 2005; Shim et al., 2014; Zhang et al., 2004) due to, at least in part, increases in the number and size of the seaweed farms. The nutrient limitation issues are most critical in the *Pyropia* farms among the major aquacultured seaweed species. It is because *Pyropia* grows rapidly ($>$ 25% d^{-1}; Kraemer et al., 2004; Carmona et al., 2006), accumulates nutrients in tissue at a high rate ($>$ 6%; Kim et al., 2007). When nitrogen is limited, discoloration and low growth of *Pyropia* is observed especially in Korean coastal waters (Kang et al., 2014; NFRDI, 2014). During the October 2010 to March 2011 growing season, discoloration occurred in 15,000 ha of Korean *Pyropia* farms. Over US$25 million of economic losses were reported (NFRDI, 2014). In Korea, most seaweed farms are located in areas away from anthropogenic sources and major watersheds. Therefore, these farms rely mostly on local sources of nutrients, from sediment release and agriculture inputs. However, in recent years, nutrient inputs have declined due to the wastewater treatment upgrades and improvement of fertilizer applications in agricultural areas (Jang et al., 2016; Park et al., 2014).

4. Can IMTA resolve the issues of intensive aquaculture?

Among the extractive organisms, seaweeds are essential species in IMTA. They have a great capacity to efficiently remove nutrients near open water finfish farms (Buschmann et al., 2008). According to Hadley et al., 3D estuary model, the giant kelp *Macrocystis pyrifera* cultivated near a finfish farm could reduce water column chlorophyll concentration significantly, which could result in water quality improvements (Hadley et al., 2016). However, extensive areas would be required for seaweed farms to completely remove nutrients from fed aquaculture (Corey et al., 2014). To completely remove the nitrogen and phosphorus from the effluent generated by each ton of salmon farmed per year, about 22 and 27 *Pyropia* nets (1.8 m wide x 18 m long), respectively, are required (McVey et al., 2002). Salmon production from 1 ha requires up to a 23 ha seaweed farms to sequester only 10% of the nitrogen output (Bostock et al., 2010). This may not be feasible

Fig. 2. Intensive shellfish farms in an enclosed area, Tongyoug, Gyeongnam, Korea.

considering the scale of finfish farms. In IMTA systems, sea urchins, which are deposit feeders have been utilized to remove large particulates (Cook and Kelly, 2007; Ren et al., 2012) whereas shellfish remove small particulates (Galimany et al., 2013; Kerrigan and Suckling, 2016). IMTA systems should combine the cultivation of fed aquaculture species (finfish and shrimp) with extractive ones that remove inorganic nutrients (seaweeds) and organically bound ones too (suspension and deposit feeders including shellfish and sea cucumbers, respectively) to create a more balanced ecosystem approach.

Many studies during the past decades have determined ecological, environmental, economic and social benefits of IMTA. For example, Shi et al. (2013) compared ecological and economic assessment between monoculture of kelp or scallop and IMTA (kelp + scallop) in Shanggou Bay, China. IMTA showed significantly higher economic benefits than monocultures, 67% higher than the kelp monoculture, and 92% higher than the scallop monoculture. In addition, nutrient removal by extractive organisms in the IMTA system was higher than those of monoculture (202 MT km^{-2} for IMTA vs. 193 MT km^{-2} for kelp monoculture or 49 MT km^{-2} for scallop monoculture; Shi et al., 2013). Other studies also showed biomass production increase in macroalgae and shellfish grown together at IMTA systems in comparison to monocultures (Abreu et al., 2009; Jiang et al., 2013; Kerrigan and Suckling, 2016; Sara et al., 2009; Troell et al., 1997; Wang et al., 2014; and references therein). It may be because shellfish promotes better water clarity by consuming organically bound particles from the water column; therefore, higher photosynthetic rates and growth yields could occur for seaweed (Newell, 2004). Nobre et al. (2010) also reported ecological and economic benefits of IMTA (abalone + kelp) in comparison to monoculture of abalone. These results indicate that IMTA enhanced the growth of extractive species when high concentration of nutrients were available (e.g. adjacent to a finfish farm; Chopin et al., 2008; Ridler et al., 2007; Wang et al., 2014), suggesting a possible solution to resolve the issues in intensive finfish and/or shellfish aquaculture. The effluent from open water fish farm clearly increased the production and quality of *Pyropia.*Chopin et al. (1999) farmed *Pyropia* adjacent to salmon farm and at an oligotrophic site in the Gulf of Maine, USA. A clear difference in production and quality of *Pyropia* was found between the IMTA site and the oligotrophic waters where the *Pyropia* farms were sited.

5. Open water IMTA practices in Korea

IMTA practice requires understanding of multiple types of cultivation systems. Although IMTA is a new concept in Korea (Kang et al., 2013), Korea does not have to reinvent the wheel. The cultivation technologies of individual species for IMTA are well developed for open water farming systems. Korea should readily embrace IMTA applications. The first attempt of a small-scale open water IMTA practice (< 0.25 ha) occurred in 2012 in the east coast of Korea, Susan Pier, Gangwon Province. Seaweeds (*Saccharina japonica* and *Sargassum fulvellum*), pacific oysters (*Crassostrea gigas*) and sea cucumbers (*Stichopus japonica*s) were cultivated adjacent to a finfish *Sebastes schlegeli* cage (Park et al., 2015, 2016). This first pilot scale attempt was successful. The growth of *Saccharina, Sargassum* and oysters in the IMTA system was faster than monoculture of each species. Interestingly, sea cucumbers underneath of the fish cage grew 2.7 times faster than monoculture (Park et al., 2016). This small-scale study demonstrated an IMTA for educational tourism as well. The system was intentionally sited in an area easily accessible to the public. Following that success, a large commercial scale IMTA (> 2 ha) was installed in 2016 in the southeast coast of Korea, Tongyoung, Gyeongnam. Many existing intensive finfish farms were located within 3 km, directly and indirectly affecting this IMTA system (Fig. 3). In the IMTA system, red seabream (*Pagrus major*) cages (12 m × 12 m cage) were installed. Two kelp species, *Saccharina japonica* and *Undaria pinnatifida,* were cultivated as winter crops and a red seaweed *Gracilaria chorda* was cultivated during the summer months. Pacific oysters (*Crassostrea gigas*) were cultivated adjacent to the fish cages. Approximately 100,000 sea cucumbers (*Stichopus japonica*s) were placed underneath the finfish cages (Kim et al., 2017b; Park, 2017). A recent study suggested that the optimal number of sea cucumbers per hectare of finfish farm is about 30,000 individuals (Ren et al., 2012). Since the size of finfish farms directly affecting this IMTA system was > 3 ha (Fig. 3), the density of sea cucumbers was considered to be optimal.

Oysters and the kelps grew well in this IMTA system. In general, the suspension feeders near the finfish cages grow better than those in farther locations (e.g. > 50–60 m) (Kerrigan and Suckling, 2016). However, no location effect was observed in this IMTA system for the growth and tissue nitrogen contents of oysters and the kelps. The growth of *Saccharina, Undaria* and oysters in the IMTA system was similar to monoculture of each species (Hwang et al., 2014, 2017a; Kim et al., 2017b; Ngo et al., 2006). However, the tissue nitrogen contents in these seaweeds (~ 3.5%) and oysters (~0.97%) in the IMTA system were much higher than those in monocultures (e.g. 1.3% for *Saccharina* and 0.7% for oysters; Kang et al., 2011; Kim et al., 2017b; Reitsma et al., 2017). These results indicate higher nutrient availability for extractive species in the IMTA system than in the monocultures. The large-scale Korean IMTA practice concluded that a 0.5 ha finfish farm with about 50 MT of fish, which is a basic unit of open water finfish farm in Korea, discharges about 7.5 tons of nitrogen per year and approximately 25% of this nitrogen can be removed by seaweeds and oysters grown in 1 ha farms. To extract 100% nitrogen from the 0.5 ha finfish farm, therefore, approximately 4 ha of seaweed and oyster farms are required. This estimate did not include the removal by the summer seaweed species *Gracilaria chorda* and sea cucumbers. These two species did not survive during the summer months with unusually high water temperature (nearly 29 °C) in the region during the study period.

Polyculture of the kelp (*Undaria pinnatifida* and *Saccharina japonica*) and abalone (*Haliotis discus hannai*) have been conducted in Korea during the past decade (Hwang et al., 2017b; Park and Kim, 2013). The abalone industry has grown dramatically in Korea with an annual value of US$2 billion (Son et al., 2014). Simultaneously, the kelp, *Saccharina japonica* farming increased by 671% (9147 ha) between 2001 and 2014 mostly to provide food for abalone (Hwang et al., 2017b; KOSIS, 2018). The kelp are cultured in close proximity to the abalone farms to feed the animals (Fig. 4). This polyculture began per the needs of the abalone farmers without considering environmental impacts (see below for more details).

6. Challenges to the acceptance of IMTA in Korea

6.1. Regulations

In most cases, the scale and placement of the extractive organisms are determined by the space availability rather than maximizing nutrient uptake (Hughes and Kelly, 2011). To apply IMTA to existing intensive finfish aquaculture, lease sites must be expanded or downsized to add extractive organisms. Either of these options will be difficult in Korea. The latter one requires an agreement from the current farmers and may need financial encouragement from local and national governments. Extending the farm footprint to accommodate extractive organisms is not easy in Korea either because most ‘good’ sites for aquaculture in Korean coasts have long-term leases. Therefore, it is necessary to minimize the required area for extractive organisms in IMTA systems.

Finfish aquaculture in general produces much higher value products than extractive aquaculture (Table 1); therefore, regulatory encouragement may be necessary to expand IMTA. Although the existing regulatory frameworks for aquaculture are generally amenable to experimental IMTA practices, for IMTA to expand to commercial scale in Korea, a new regulatory framework will be required. Environmental fees or taxes may be charged to farmers, who discharge wastes to the

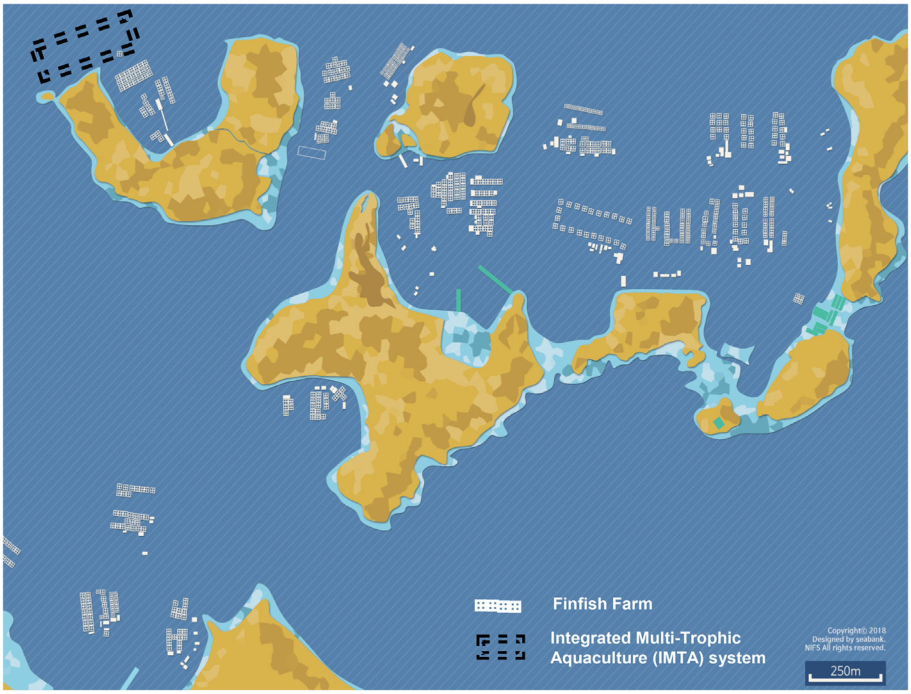

Fig. 3. IMTA research site (dotted box) at Tongyoung, Gyeongnam, Korea in an intensive finfish aquaculture zone.

environments. For IMTA adaptors, some incentives (such as nutrient credits and subsidies) to facilitate the acceptance should be provided (Rose et al., 2015; Kim et al., 2014, 2015).

6.2. Development of high temperature tolerant strains of extractive species

It is predicted that global climate change will warm up the water temperatures by nearly 5 °C in the next century (Intergovernmental Panel on Climate Change (IPCC), 2014). This warmer temperature will affect aquaculture production (De Silva and Soto, 2009; Peterson et al., 2017; Troell et al., 2014). The above result in Korean IMTA practices indicates the importance of developing high temperature tolerant strains of seaweeds and sea cucumbers considering the global climate change. Having suitable summer strains should increase the bioextraction capacity and reduce the required area for extractive organisms in the IMTA system. Recent studies showed that some *Gracilaria* species native to Korea (*G. vermiculophylla*) is tolerant to high temperature (Gorman et al., 2017; Kim et al., 2016). A kelp strain of *Saccharina japonica* tolerant to high temperature has also been developed using selective breeding technologies in Korea (Hwang et al., 2017a). These strains with further cultivation technology development can be potential summer species for the Korean IMTA practices.

Sea cucumbers are known to be very efficient deposit feeders (Ju et al., 2017; Nelson et al., 2012; Ren et al., 2012; and references therein). Sea cucumbers can assimilate fish farm waste and can achieve high growth and survival rates when co-cultivated with finfish (Cook and Kelly, 2007; Hannah et al., 2013; Lamprianidou et al., 2015; Ren et al., 2012; Yu et al., 2014). If cultivated with optimal density underneath of the finfish cages, sea cucumbers can remove up to 70% of large particulates from the cages (Ren et al., 2012). This too can be another positive benefit to IMTA. *Apostichopus japonicas* has been the major aquaculture species in Korea and China (Yang et al., 2015; and references therein). This species however, stops growing when the water temperature reaches 23 °C, becoming inactive and undergoing aestivation. High water temperature (29 °C or higher) can kill this species (Yu et al., 2014). This is a big challenge for sea cucumber aquaculturists in Korea and China. A recent study suggested a tropical sea cucumber species, *Holothuria leucospilota*, as new aquaculture

Fig. 4. Open water cage culture of abalones (orange cages) adjacent to seaweed farms in Jindo, Jeonnam, Korea (left) and abalones feeding on the kelp (*Undaria pinnatifida*).

species (Yu et al., 2013; Huang et al., 2018), but more studies are needed to understand the physiology of this species and to develop the cultivation technologies. Development of summer species/strains of seaweed and deposit feeders is an urgent task for the IMTA technology system to be efficiently used in commercial scale intensive fish farms in Korea.

Another critical challenge is the seasonal growth mismatch of different trophic organisms. Nutrient emissions from fish (e.g. red seabream) in general increase throughout the growth period, peaking at the later summer when body metabolism increases. When the water temperature is below 10 °C, red seabream consumes less feed, therefore lower nutrient emissions (Hwang et al., 2012; Kerrigan and Suckling, 2016). The growth period of kelp is, however, from fall to spring, when nutrient emissions from the fish are minimal. Although the pacific oysters grow well year round as long as sufficient food is available (Kim et al., 2017b; Park, 2017), the nutrient bioextraction of this suspension feeders is limited in creating a balanced ecosystem in IMTA systems. This phenomenon emphasizes again the importance of developing summer seaweed and sea cucumber species/strains.

6.3. Application of IMTA to intensive seaweed and invertebrate farms

The IMTA concept can be applied to intensive seaweed farms where nutrients are limited. If fish aquaculture is added to the existing intensive seaweed farm areas, nutrients will be supplied by the fish, benefiting seaweed. The scale of fish aquaculture component to provide sufficient nutrients to seaweeds can be calculated based on the previous IMTA studies. Two kelp species, *Saccharina latissima* and *Alaria esculenta*, cultivated at an IMTA system in the Bay of Fundy, Canada were certified organic to the Canadian Organic Aquaculture Standards (Chopin et al., 2014), suggesting a high quality of seaweed grown in IMTA systems. However, consumers may feel that the seaweeds grown in fish effluent (feces) are not so clean no matter if this was true or not. In this case, the seaweed can be used for other purposes, such as animal feed or fertilizers, rather than direct human consumption (Johnson et al., 2014).

There may be positive benefits of growing seaweeds near shellfish aquaculture (Barton et al., 2012; Green et al., 2013). Ocean acidification may negatively impact aquaculture animals, but fleshy seaweeds will thrive in lower pH and could improve the shellfish production as well (Clements and Chopin, 2017). Ocean acidification causes calcium carbonate shell to be dissolved in seawater. Recent studies indicate that ocean acidification increases the production of some seaweed species (Hepburn et al., 2011; Martin et al., 2008; Fabricius et al., 2011; Vizzini et al., 2010). If co-cultured, seaweeds may benefit shellfish by reducing the ocean acidification.

Lack of seaweed farming during the summer months can still be a challenge. Insufficient (or lack of) bioextraction of extractive organisms during the summer months can cause serious issues even in intensive seaweed and abalone aquaculture areas. For example, the abalone cultivations in intensive seaweed cultivation areas in Korea have created some environmental problems. Abalone retain about 80% of ingested seaweed and the rest is discharged to the local environment (Park, 2005). The deposition of feces and uneaten seaweed from abalone farms may change sediment composition, increasing organic material and biological oxygen demand, which may result in hypoxia and anoxia. Nutrient release may ensue to the water column leading to eutrophication (Kim et al., 2011). This might be the reason why the abalone production has decreased in Korea although the number of abalone cages have increased (Kang et al., 2015).

6.4. Designing a sustainable IMTA model balancing wastes and extraction

A critical challenge in IMTA systems is a better understanding of complex interactive processes connecting fed and extractive aquaculture nutrient discharges and removal, respectively (Zhang et al., 2015). Mathematical models have been applied to predict production and the environmental impact of IMTA systems (Cubillo et al., 2016; Ferreira et al., 2012; Lamprianidou et al., 2015; Ren et al., 2012; and references therein) but the accuracy of these models are questionable. The scale of farm size affects the growth and nutrient uptake of extractive organisms. Increase of the infrastructure and biomass of extractive species may influence water and nutrient circulation patterns (Troell et al., 2009). Therefore, production, nutrient uptake and removal efficiency of extractive organisms do not linearly increase as the farm size increases. The recent Korean IMTA operations in Tongyoung, Korea, might be one of the largest IMTA systems to date. However, the predictions made in this study (0.5 ha finfish farm vs. ha of seaweed and 4 ha of oyster farms) have limitations and should be further evaluated as IMTA systems increase in scale.

The principles of CZM approach may be useful in the redesign of aquaculture areas in Korea to facilitate IMTA systems (Langan et al., 2006; Rensel et al., 2006; Hughes and Black, 2016; Reid et al., 2013). For this, the physiological and metabolic characteristics of each of the components of IMTA must be thoroughly evaluated in addition to physical, chemical and hydrodynamic characteristics. The optimal environmental conditions for cultivation of IMTA organisms in different trophic levels may be different. High densities of sea cucumbers (e.g. $> 30{,}000$ individuals ha^{-1}) should be placed below the finfish cages. Oyster farms should be located near.

the finfish farms (Hughes and Black, 2016) at a critical distance to maximize the extractive capacity of these organisms. A low density of sea cucumbers (> 500 individuals ha^{-1}; Ren et al., 2012) may also be located underneath the oyster farms to remove particulate matter from the oysters too. The locations for seaweed farms can be flexible as long as the inorganic nutrients from farm activities can reach the seaweeds (Abreu et al., 2009; Kerrigan and Suckling, 2016). Considering the locations of Korean intensive fish monoculture farms (Fig. 3), suitable areas for seaweed farming should be located within 800 m from the sources of nutrients from animal aquaculture.

7. Conclusions

IMTA can be a good tool for Korean intensive aquaculture as a means to increase sustainability and lessen the impact on the environment. However, there are challenges. Strategies will be required to move Korean intensive aquaculture away from monoculture farms to highly efficient IMTA systems with a small environmental footprint. First, a new regulatory framework is required, providing incentives for IMTA adaptors. Charging fees and taxes to waste discharging intensive farmers should reflect the true cost of the environmental impact of these farms. This regulatory framework may be an efficient tool for sustainable aquaculture in coastal waters. Second, with the expansion of IMTA systems, there is a need to develop high temperature tolerant species/strains of extractive organisms in light of global climatic change. The seasonal growth mismatch between fed and extractive organisms adds the importance of having high temperature tolerant extractive species/strains since nutrient emissions from fish aquaculture peak at the later summer when the extractive capacities of seaweeds and sea cucumbers are minimum. Third, integrating fish aquaculture with existing intensive seaweed farms can help minimize the nutrient limitation issues in seaweed farms. On the other hand, applying seaweed aquaculture to intensive shellfish/abalone aquaculture can also be beneficial in reduction of the impacts of ocean acidification. Forth, designing a sustainable IMTA model balancing wastes and extraction is critical. This model must include not only the physiological and metabolic characteristics of each of the IMTA components, but also the physical, chemical and hydrodynamic characteristics of the farm region.

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