Chapter 9

Integrated Multi-Trophic Aquaculture

Thierry Chopin, University of New Brunswick, Canada and Canadian Integrated Multi-Trophic Aquaculture[*]

Abstract

Fulfilling aquaculture's growth potential requires responsible technologies and practices. Sustainable aquaculture should be ecologically efficient, environmentally benign, product-diversified, profitable and societally beneficial. Integrated multi-trophic aquaculture (IMTA) has the potential to achieve these objectives by cultivating fed species (e.g. finfish fed sustainable commercial diets) with extractive species, which utilize the inorganic (e.g. seaweeds) and organic (e.g. suspension- and deposit-feeders) excess nutrients from aquaculture for their growth. Thus, extractive aquaculture produces valuable biomass, while simultaneously rendering biomitigating services. Through IMTA, some of the food, nutrients and by-products considered "lost" from the fed component are recaptured and converted into harvestable and healthy seafood of commercial value, while biomitigation takes place (partial removal of nutrients and CO2, and supplying of oxygen). In this way, some of the externalities of fed monoculture are internalized, hence increasing the overall sustainability, profitability and resilience of aquaculture farms. A major rethinking is needed regarding the definition of an "aquaculture farm" (reinterpreting the notion of site-lease areas) and regarding how it works within an ecosystem, in the context of a broader framework of Integrated Coastal Zone Management (ICZM). The economic values of the environmental/societal services of extractive species should be recognized and accounted for in the evaluation of the true value of these IMTA components. This would create economic incentives to encourage aquaculturists to further develop and implement IMTA. Seaweeds and invertebrates produced in IMTA systems should be considered as candidates for nutrient/carbon trading credits within the broader context of ecosystem goods and services. Long-term planning/zoning promoting biomitigative solutions, such as IMTA, should become an integral part of coastal regulatory and management frameworks.

---

[*] Co-authors are: *Max Troell*, The Royal Academy of Sciences and Stockholm Resilience Centre, Sweden; *Gregor K. Reid*, Univeristy of New Brunswick, Canadian Integrated Multi-Trophic Aquaculture Network and Department of Fisheries and Oceans; *Duncan Knowler*, Simon Fraser University, Canada and Canadian Integrated Multi-Trophic Aquaculture Network; *Shawn M.C. Robinson*, Department of Fisheries and Oceans, Canada and Canadian Integrated Multi-Trophic Aquaculture Network; *Amir Neori*, Israel Oceanographic and Limnological Research Ltd.; *Alejandro H. Buschmann*, i-mar, Universidad de Los Lagos, Chile; *Shao J. Pang*, Institute of Oceanology, People's Republic of China; *Jianguang Fang*, Yellow Sea Fisheries Research Institute, People's Republic of China.

Introduction

The global seafood industry is at a crossroads: as capture fisheries stagnate in volume, they are falling increasingly short of a growing world demand for seafood. It is anticipated that by 2030, there will be a 50-80 million tonne seafood deficit (FAO, 2009). This gap will likely not be filled by capture fisheries but by aquaculture operations, which already supply almost 50% of the seafood consumed worldwide (FAO, 2009). Consequently, it is imperative to design the ecosystem responsible aquaculture practices of tomorrow that maintain the integrity of ecosystems and yet ensure the viability of this sector and its key role in food provision, safety and security.

Without a clear recognition of the industry's large-scale dependency and impact on natural ecosystems and traditional societies, the aquaculture industry is unlikely to either develop to its full potential, continue to supplement ocean fisheries, or obtain societal acceptance. The majority of aquaculture production still originates from relatively sustainable extensive and semi-intensive systems (Tacon *et al.*, 2010); however, the rapid development, throughout the world, of intensive marine fed aquaculture (*e.g.* carnivorous finfish and shrimp), and to a lesser extent some shellfish aquaculture, is associated with concerns about the environmental, economic and social impacts that these, often monospecific, practices can have, especially where activities are highly geographically concentrated or located in suboptimal sites whose assimilative capacity is poorly understood and, consequently, prone to being exceeded.

For many marine aquaculture operations, monoculture is, spatially and managerially, often the norm. Species are cultivated independently in different bays or regions. Consequently, the two different types of aquaculture (fed *versus* extractive) are often geographically separate, rarely balancing each other out at the local or regional scale, and, thus, any potential synergy between the two is lost. In an aquaculture environment with fixed spatial limits (*e.g.* lease boundaries), increased production generally comes at the expense of the natural environment, as the farmer tends to squeeze more and more production into a fixed area. Once the natural system is destabilized, the risk that the entire operation will collapse increases. To avoid pronounced shifts in coastal processes, the solution to nutrification by fed aquaculture is not dilution, but extraction and conversion of the excess nutrients and energy into other commercial crops produced by extractive aquaculture (*e.g.* seaweeds and suspension- and deposit-feeding invertebrates).

To continue to grow, while developing better management practices, the aquaculture sector needs to develop more innovative, responsible, sustainable and profitable technologies and practices, which should be ecologically efficient, environmentally benign, product-diversified and societally beneficial. Maintaining sustainability, not only from an environmental, but also from economic, social and technical perspectives, has become a key issue, increased by the enhanced awareness of more and more demanding consumers regarding quality, traceability and production conditions. Integrated multi-trophic aquaculture (IMTA) has the potential to play a role in reaching these objectives by cultivating fed species (*e.g.* finfish fed sustainable commercial diets) with extractive species, which utilize the inorganic (*e.g.* seaweeds) and organic (*e.g.* suspension- and deposit-feeders) excess nutrients from aquaculture for their growth.

The need for diversification and combining fed and extractive aquaculture into IMTA systems

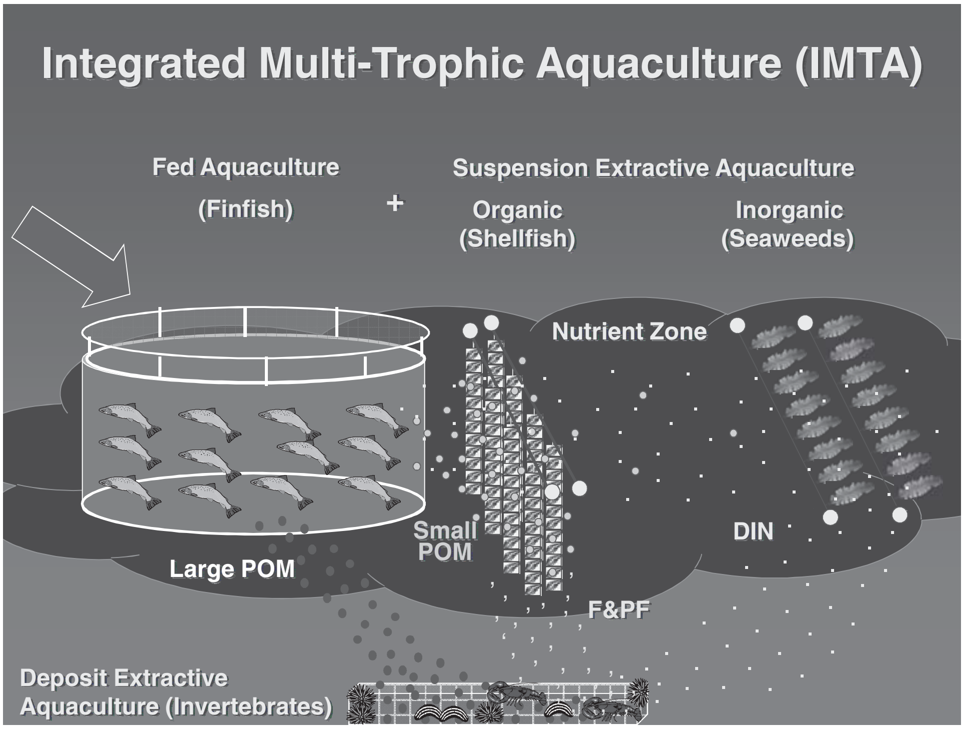
The common old saying "Do not put all your eggs in one basket", which applies to agriculture and many other businesses, should also apply to aquaculture. Having too much production of a single species leaves a business vulnerable to issues of sustainability because of fluctuating prices in what has become commodity markets and potential oversupply, and the possibility of catastrophic destruction of one's only crop (diseases, damaging weather conditions). Consequently, diversification of the aquaculture industry is advisable for reducing the economic risk and maintaining its sustainability and competitiveness.

From an ecological point of view, diversification also means cultivating more than one trophic level, *i.e.* not just cultivating several species of finfish (that would be "polyculture"), but adding into the mix organisms of different and lower trophic levels (*e.g.* seaweeds, shellfish, crustaceans, echinoderms, worms, bacteria, etc.), chosen according to their roles in the ecosystem and their established or potential commercial value, to mimic the functioning of natural ecosystems. Staying at the same ecological trophic level will not address some of the environmental issues because the system will remain unbalanced due to non-diversified resource needs.

It is also important to consider that while some ecosystem goods (*e.g.* fish) generally have a higher market price than other ecosystem goods (potentially making them a more attractive investment), ecosystems are not based on the same principles, but on a balance of biomass between organisms having different complementary functions and a balance of energy flows. Evolving aquaculture practices will require a conceptual shift towards understanding the working of food production systems rather than focusing on technological solutions. In other words, we have to think about how to make the "Blue Revolution" greener and should more appropriately talk of the "Turquoise Revolution"!

One of the innovative solutions promoted for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and societal acceptability (improved support for the industry and its differentiated safe products), is IMTA. This practice combines, in appropriate proportions, the cultivation of fed aquaculture species (*e.g.* finfish) with inorganic extractive aquaculture species (*e.g.* seaweeds) and organic extractive aquaculture species (*e.g.* suspension- and deposit-feeding invertebrates) for a balanced ecosystem management approach that takes into consideration site specificity, operational limits, and food safety guidelines and regulations (Figutr 9.1). The aim is to increase long-term sustainability and profitability per cultivation unit (not per species in isolation as is done in monoculture), as the wastes of one crop (fed animals) are converted into fertilizer, food and energy for the other crops (extractive plants and animals), which can, in turn, be marketed. Feed is one of the core operational costs of finfish aquaculture operations, but with IMTA this cost is reduced because some of the food, nutrients and energy considered lost in finfish monoculture are recaptured and converted into crops of commercial value, while biomitigation takes place. In this way all the cultivation components have a commercial value, as well as a key role in recycling processes and rendering services. The harvesting of the different types of crops participates in the capture and export of nutrients outside of the coastal ecosystem. The biomass and functions of the fed and extractive species naturally present in the ecosystem in which aquaculture farms are operating must also be accounted for or this will lead to the development of erroneous carrying capacity models. For example, the 158 811 tonnes (fresh weight) of the intertidal seaweed, *Ascophyllum nodosum* (rockweed), in proximity to salmon aquaculture operations in southwest New Brunswick, Canada, are not neutral in the ecosystem and represent a significant coastal nutrient scrubber which should be taken into consideration to understand the functioning of that part of the Bay of Fundy.

Figure 9.1: Conceptual diagram of an integrated multi-trophic aquaculture (IMTA) operation*



*Including the combination of fed aquaculture (e.g. finfish) with suspension organic extractive aquaculture (e.g. shellfish), taking advantage of the enrichment in small particulate organic matter (POM), inorganic extractive aquaculture (e.g. seaweeds), taking advantage of the enrichment in dissolved inorganic nutrients (DIN), and deposit organic extractive aquaculture (e.g. echinoids, holothuroids and polychaetees), taking advantage of the enrichment in large particulate organic matter (POM) and faeces and pseudo-faeces 9F&PF) from suspension-feeding organisms. The biotrubation on the bottom also regenerates som DIN, which becomes available to the seaweeds.

The IMTA concept is extremely flexible (Chopin, 2006). To use a musicology analogy, IMTA is the central/overarching theme on which many variations can be developed according to the environmental, biological, physical, chemical, societal and economic conditions prevailing in parts of the world where the IMTA systems are operating. It can be applied to open-water or land-based systems, and marine or freshwater systems (sometimes called “aquaponics” or “partitioned aquaculture”).

What is important is that the appropriate organisms are chosen at multiple trophic levels based on the complementary functions they have in the ecosystem, as well as for their economic value or potential. In fact, IMTA is doing nothing other than recreating a simplified, cultivated ecosystem in balance with its surroundings instead of introducing a biomass of a single type one thinks can be cultivated in isolation from everything else. Integration should be understood as cultivation in proximity, not considering absolute distances but connectivity in terms of ecosystemic functionalities. It should be made clear that in the minds of those who created the acronym "IMTA", it was never conceived to be viewed with the minimalist perspective of only the cultivation of salmon (*Salmo salar*), kelps (*Saccharina latissima* and *Alaria esculenta*) and blue mussels (*Mytilus edulis*) within a few hundred meters: this is only one of the variations and the IMTA concept can be extended within very large systems like the Yellow Sea (see below).

The paradox is that IMTA is not a new concept. Asian countries, which provide more than two thirds of the world's aquaculture production, have been practicing IMTA (often described as a type of "polyculture") for centuries, through trial and error and experimentation. Why, then, is this common-sense solution not more widely implemented, especially in the western world? The reasons for this generally center around social customs and practices, and market driven economic models not considering externalities, that we are already familiar with, even if common sense tells us that we should modify them. Human society does not change quickly unless there are compelling reasons to do so. The fact that we are currently at a crossroad should motivate us to improve current aquaculture practices, without further delay. Moreover, if Asian cultures are accustomed to the concept of considering wastes from farming practices as resources for other crops rather than pollutants, this attitude still has a long way to progress in the western world where aquaculture is a more recent development.

Western countries are regularly reinventing the wheel. Research on integrated methods for treating wastes from modern mariculture systems was initiated in the 1970s (Ryther *et al.*, 1975, 1978). After that period, the scientific interest in integrated aquaculture/ecological aquaculture stagnated, and it was not until the 1980s and 1990s that a renewed interest emerged, based on the common-sense approach that the solution to nutrification is not dilution but extraction and conversion through diversification within an ecosystem-based management perspective (Indergaard and Jensen, 1983; Costa-Pierce *et al.*, 1988; Neori *et al.*, 1991; Edwards, 1993; Chopin, 1995; Buschmann *et al.*, 1996; Troell *et al.*, 1997; Costa-Pierce, 2002). The term "IMTA" was first coined at a workshop in Saint John, New Brunswick, Canada, in March 2004, when Jack Taylor and Thierry Chopin combined "multi-trophic aquaculture" and "integrated aquaculture" into "integrated multi-trophic aquaculture".

This interest has likely been an indirect result of the increased demand for aquaculture products. This increase has in turn, resulted in intensified cultures, a decrease in available habitat (space available for cage sites/aquaculture leases), and increased environmental impacts on the immediate ecosystem. IMTA is potentially a method whereby production can be intensified, diversified and yet be environmentally responsible, thereby ensuring a sustainable aquaculture industry. Multi-trophic integration appears to be one logical next step in the evolution of aquaculture.

The trend in the global recognition of the need for more advanced ecosystem-based aquaculture systems began to show up in the scientific world through the aquaculture conference circuit. For example, in recognition of this growing interest, the Aquaculture Europe 2003 Conference in Trondheim, Norway, whose theme was "Beyond Monoculture. New Multitrophic Systems – Potential and Constraints", was the first large international meeting (389 participants from 41 countries) with what would become known as IMTA as the main topic. In 2006, at the joint European Aquaculture Society and World Aquaculture Society Conference in Florence, Italy, IMTA was recognized as a serious research priority and option to consider for the future development of aquaculture practices. In 2010, IMTA was the topic of a full day session (17 presenters from 12 countries) during the first day of the World Aquaculture Society meeting in San Diego, California USA. To date, the term "IMTA" has been used in more than 100 scientific publications. The determination to develop IMTA systems will, however, only come about if there are some visionary changes in political, social, and economic reasoning. This will be accomplished by seeking sustainability, long-term profitability and responsible management of coastal waters. It will also necessitate a change in consumers' attitudes towards eating products cultured in the marine environment in the same way that they accept eating products from recycling and organic production systems on land, for which they are willing to pay a higher price for the perceived quality or ethical premiums. The differentiation of IMTA products through eco-labelling will be key for their recognition and command of premium market prices.

IMTA, while not being the panacea to and for everything, is, however, one of the improvement options

IMTA has never been portrayed as the solution to and for everything! For example, IMTA does not address the issues of escapees from open-water fish farms. It is, of course, in the interest of everybody, especially the industry (to not lose money) to reduce the number of escapees. This is, however, a question of engineering of the rearing systems (cages, netting material, etc.) and the suitability of the environment to survival should escapes occur. To solve the escapee issue, it has been suggested that fish farms should be pulled from the open water and placed on land or in closed containment. Moving on land is, however, not a guarantee for zero escapees. There are well-known escapee cases from land-based operations, with serious consequences. For example, the bighead carp (*Hypophthalmichthys nobilis*) and the silver carp (*Hypophthalmichthys molitrix*) were brought from Asia to the southern USA in the 1970s to help control algal proliferation in channel catfish (*Ictalurus punctatus*) farms. There are reports of escapees into the lower Mississippi River system, especially associated with flood episodes in the early 1990s. Self-sustaining populations have been able to move northward to enter the Upper Mississippi River system and the Illinois River system. Presently, there are fears that these fish could enter the Great Lakes system through the Chicago Sanitary and Ship Canal and the Des Plaines River to finally reach Lake Michigan, after an escape of around 2000 km in approximately 20-30 years. Electric fish barriers have been put in place, but their efficiency has been questioned. The use of rotenone, a biodegradable piscicide, was authorized but seemed to have killed more common carps (*Cyprinus carpio*; itself an introduced species from Europe in the 1830s) than bighead and silver carps. On April 26, 2010, the US Supreme Court decided not to get involved in a dispute over how to prevent these carps from making their way into the Great Lakes; it turned down a new request by the State of Michigan to consider ordering permanent closing of the Chicago-area shipping locks. What the impacts on the ecosystems could be, should these fish get into the Great Lakes systems, is unknown, but they are well-known for their ability to consume large amounts of algae and zooplankton, eating as much as 40% of their body weight per day, and they are fierce competitors when it comes to securing their food needs. The silver carp is also a danger to recreational fishers, water-skiers and boaters because of its habit to jump out of the water when startled by boat motors or other noises, creating life-threatening aerial hazards with high speed impacts.

The number of escapees from land-based facilities is not as well documented as with cage-based aquaculture. Perhaps because land-based fish escapes are more likely to occur as a continuous "trickle" instead of a single major event such as a net tear that would lead to "large scale" escapes. However, reports do surface from time to time in the media, particularly if there is some novelty in the story. A recent example is the report of the cultured salmonid brown trout, *Salmo trutta*, escaping from a pond farm in the United Kingdom. A wildlife photographer caught them in action, making large leaps out of the water straight into a metal feed pipe a meter above and connected to a tributary of a river[1]. Ideally, land-based recirculation systems would reduce the potential for escapes. However, most recirculation systems have at least partial water exchange (Timmons *et al.*, 2002) and where there is water exchange and discharge, there is a potential for escapees. These systems are still not widely used and to the authors knowledge there has not been any initiative taken to document escapees, or lack thereof, within these systems. It may, therefore, be premature to classify such systems as "escape proof". It is unlikely that any land-based aquaculture operations could ever be 100% "escapee-proof" and, consequently, they will also need to develop anti-escapee strategies (avoiding flood plains, electric fences, grids of the appropriate mesh, catchment basins, etc.).

Moving to land-based or closed containment operations is one approach that may help address some sustainability issues but is not without its problems. Large amounts of energy, often diesel or electric power, are required to pump and aerate water. Nutrients are either pumped back into the water or settled somewhere and "trucked" off site. All of these processes leave a 'carbon footprint', and only partly solve the issue of excess nutrients. IMTA, or its variations called "aquaponics" or "hydroponics", will have to be added to closed-containment or land-based systems to treat the effluents. One 'impact' may simply be traded for another. Ayer and Tyedmers (2009), in their life cycle assessment of alternative aquaculture technologies, warned that we could be in a case of environmental problem shifting, not solving, where, while reducing local ecological impacts, the increase in material and energy demands may result in significant increased contributions to several environmental impacts of global concern, including global warming, non-renewable resource depletion, and acidification.

Land-based or closed containment operations have also been advocated as a way of controlling diseases and their transmission. However, the proponents very often equate diseases to the sole problem of sea lice, leaving the issues related to viral or bacterial pathogens unaddressed. Some concerns have been expressed that multiple species on the site might increase the risk for disease transmission. It must, however, be realized that sites in the ocean and on land will always have additional unintended species associated with the operation, ranging from micro-organisms to marine mammals, depending on the situation. The question is not whether to have only one species on the site, but at what density do negative interactions occur with the unintended ones and are there any positive interactions associated with more diversified systems? In fact, two studies (Skår and Mortensen, 2007; Robinson, personal communication) have demonstrated in laboratory experiments that the blue mussel, *Mytilus edulis*, is capable of inactivating the infectious salmon anaemia virus (ISAV), as well as the infectious pancreatic necrosis virus (IPNV). Mussels are, consequently, not a likely reservoir host or vector for ISAV and IPNV. Put in an IMTA perspective, this could mean that mussel rafts could be strategically placed to serve as a kind of sanitary/biosecurity cordon around salmon cages to combat certain diseases. Pang *et al.* (2006) also reported reduced total bacteria and *Vibrio* counts in a seaweed-abalone IMTA system.

In regard to parasites, anecdotal information indicates that mussels can consume some of the early larval stages (*nauplius*) in the life cycle of sea lice and several studies, in both Europe and New Zealand, have highlighted the fact that mussels can consume small zooplankton. Since the *nauplius* stage is probably the most dispersive stage due to its size, having a biofilter such as mussels at IMTA sites may decrease the frequency of exposure from outside sources. One of the 14 projects of the recently created Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) will investigate the role of bivalves in potentially reducing sea lice populations. Another CIMTAN project is looking into the possibility that mussels could reduce the horizontal transmission of *Loma salmonae*, responsible for microsporidial gill disease of salmon (MGDS), a serious endemic gill disorder in marine netpen reared, and wild, Chinook (and other Pacific) salmon. Trials will examine the proof of principle that blue mussels remove microsporidial spores from water and to what extent these spores retain short-term infectious potential as determined by branchial xenoma expression in test fish.

IMTA is not entering directly the debate regarding the inclusion of fish meal and fish oil in commercial feeds (nor are land-based or closed containment operations). IMTA could, however, provide a partial solution. Modern commercial salmon diets in Canada contain much less fish meal (about 15-25%) and fish oil (about 15-20%) than they did less than ten years ago (40 to 60%). In Atlantic Canada, by-products (trimmings) of wild catch fisheries are used to supply a major portion of the fishmeal ingredients. The feed company Skretting has now produced a salmon feed which includes no marine ingredients. Some eNGOs arguing for fish meal/fish oil replacement have also voiced concerns that, after all, marine fish should eat marine ingredients… Obviously, one cannot have it both ways! Finding replacements for marine ingredients is a priority and there are several large research projects worldwide addressing this issue. Using land plant proteins is not without its impacts. Extra farmland area (more deforestation) would be needed, which, moreover, would need to be irrigated on a planet already suffering from water availability problems. The price of some staple food crops used in traditional agriculture (corn, soya, etc.) would rise considerably due to announced competition for their uses, as recently seen when they were potentially sought out as energy crops for the production of biofuels. Partial substitution with organisms already living in water, such as seaweeds, could, in fact, be a very interesting option. If cultivated in the water column in IMTA systems, there would, moreover, be no issue of raking seaweeds attached to the bottom of the ocean.

It has taken decades to reach current salmon production levels and learn new species husbandry. We are now realizing that we have to rethink the definition of what an "aquaculture site" is, within the broader framework of Integrated Coastal Zone Management (ICZM). Amending regulations to allow such culture will not occur overnight. This should, however, not discourage the finfish industry from practicing IMTA, as even small amounts of co-cultured species production are useful. When the project started on the east coast of Canada, in 2001, there were obviously no IMTA sites in the Bay of Fundy. Nine years later, five out of 96 sites in SW New Brunswick have the combination salmon (or cod)/mussels/kelps and 11 other sites have been amended to develop IMTA. This is a respectable conversion of almost 16% in nine years. Moreover, it would not be reasonable to anticipate an instant conversion, as the industry needs to develop markets to absorb the co-cultured biomass: this also takes time and can only be progressive.

IMTA is slowly gaining recognition and developing in more regions of the globe

Presently, the most advanced IMTA systems in open marine waters and in land-based operations have three components (fish, suspension feeders or grazers such as shellfish, and seaweeds in cages, rafts or floating lines), but they are admittedly simplified systems. More advanced systems will have several other components (*e.g.* crustaceans in mid-water reefs; deposit feeders such as sea cucumbers, sea urchins and polychaetes in bottom cages or suspended trays; and bottom-dwelling fish in bottom cages) to perform either different or similar functions, but for various size ranges of particles, or selected for their presence at different times of the year (different species of seaweeds, for example).

The most advanced IMTA systems, near commercial scale or at commercial scale, can be found in Canada, Chile, South Africa, Israel and China (Chopin *et al.*, 2008; Barrington *et al.*, 2009). On-going research projects related to the development of IMTA are taking place in the United Kingdom (mostly Scotland), Ireland, Spain, Portugal, France, Turkey, Norway, Japan, Korea, Thailand, the USA and Mexico.

What will it take to increase the acceptance and adoption of IMTA as a responsible aquaculture practice of the future?

In order to ensure further development of IMTA systems worldwide, from the experimental concept to the full commercial scale, defining and implementing the appropriate regulatory and policy frameworks and creating the proper financial incentive tools will be required.

Proving the concept at the economic level: establishing the economic value of IMTA systems and their co-products

It is important to ensure that additional co-cultured species increase profit potential. Several IMTA projects throughout the world have now accumulated enough data to support the proof of concept at the biological level. The next step is the scaling up of these experimental systems to reproduce the biological outcomes at a commercial scale, in conjunction with appropriate measures of economic and social potential otherwise required to promote the benefits of IMTA over mono-specific aquaculture.

Initially, open-water IMTA farms require planning and design as a complete system, considering the "integrated" in IMTA rather than clusters of different crops. Optimal design will not only facilitate nutrient recovery, but should also promote augmented growth beyond what would be expected were these species cultured in isolation. In addition to the obvious economic return from increased growth rates from additional species, some less tangible benefits should also be factored in, such as the biomitigating services rendered by the extractive species. Economic analyses need to be inserted in the overall modelling of IMTA systems, especially as they move to commercial scale in coastal communities. It will, then, be possible to compare profitability and economics between IMTA and monocultures. Such models could also explore the savings due to multi-trophic conversion of feed and energy which would otherwise be lost, the pricing and marketing potential of organic and other eco-labels, the reduction of risks through crop diversification and the increase in social acceptability of aquaculture (including food safety, food security and consumer attitudes towards buying sustainable seafood products).

Economic diversification should also mean looking at seafood from a different angle. Research and development on alternative species should no longer be considered R&D on alternative finfish species for food consumption, but rather on alternative marine products. Aquaculture products on the market today are very similar to those from traditional fishery resources, and are thus, often in direct competition. The opportunity exists to diversify from traditional seafood products to a potentially large untapped array of bioactive compounds of marine origin (*e.g.* pharmaceuticals, nutraceuticals, functional foods, cosmeceuticals, botanicals, pigments, agrichemicals and biostimulants, and industry-relevant molecules). The culture of species that might otherwise be inappropriate for food markets fits well within the sustainability and management concept of IMTA. Applications with seaweeds, or seaweed-derived products, remain a field to explore, especially in the western world. It may also be interesting to observe how new seaweed cultivation initiatives in different parts of the world for biofuel production could be an additional driver to adopt IMTA practices.

Putting in place enabling legislation for the commercialization of IMTA products

For IMTA to develop to a commercial scale, appropriate regulatory and policy frameworks need to be put in place. Present aquaculture regulations and policies are often inherited from previous fishery frameworks and reasoning, which have shown their limitations. To develop the aquaculture of tomorrow, the present aquaculture regulations and policies need to be revisited. Adaptive regulations need to be developed by regulators with flexible and innovative minds, who are not afraid to put in place mechanisms that allow the testing of innovative practices at the R&D level, and, if deemed promising, mechanisms that will take these practices all the way to C (commercialization). As the IMTA concept continues to evolve, it is important that all sectors of the industry are aware of the implications of the changes involved, so that they can adapt in a timely and organized manner.

To move research from the "pilot" scale to the "scale up" stage, some current regulations and policies may need to be changed or they will be seen as impediments by industrial partners who will see no incentive in developing IMTA. For example, an earlier version of the Canadian Shellfish Sanitation Program (CSSP) prevented the development of IMTA because of a clause that specified that shellfish could not be grown closer than 125 m of finfish netpens. This paragraph was clearly not written with IMTA in mind, but it seriously impinged its development. After four years (2004-2008), it was amended so that IMTA practices could develop to commercial scale legally, based on recent, reliable and relevant data and information provided by three government departments and the IMTA project on the East coast of Canada. While four years may seem long, it is a relatively short delay considering that regulations and legislations require thorough review with due governmental process involving several federal and provincial departments. This suggests that new aquaculture practices should be accompanied by timely regulatory review to avoid market delays for new products. As governments move to revise current regulatory regimes, it will be necessary to press the importance of accommodating and indeed encouraging new sustainable solutions such as IMTA. IMTA also requires approaching aquaculture development and management with a holistic approach and not one species, or group of species, at a time. We know that this approach has led to many failures in the management of the fisheries; we should be particularly vigilant that the same flaw is not repeated in the management of aquaculture.

Developing commercial and economic models for IMTA systems

It is important to ensure that newly emerging sustainable aquaculture approaches generate net economic benefits for society if they are to be advocated. Assuming that this is true (and preliminary evidence suggests that this is true for IMTA, but research is continuing), the development and promotion of IMTA will be multi-faceted from an economic perspective. Does the IMTA system generate enough additional commercial profits under existing tax and related incentives to be adopted voluntarily by commercial aquaculture operators? What if not? Presumably some adjustments would be needed to bring these tax and related incentives in line with the social desirability of promoting IMTA over conventional aquaculture practices. What sorts of new incentives would be needed and what are the dynamics governing the adoption of new technologies in a concentrated industry such as finfish aquaculture (versus terrestrial small farming agriculture)? These are the sorts of questions that need to be addressed in assessing the economics aspects of IMTA. Research into these questions is just in its infancy. In this section we examine the commercial case for promoting IMTA as distinct from any need for regulatory measures to support its adoption.

A commercial model of integrated salmon-mussel farms was developed by Whitmarsh *et al.* (2006) using baseline data from farms on the west coast of Scotland. The net present value (NPV) of a salmon-mussel IMTA system was greater than the combined NPV of salmon and mussel monocultures, assuming a 20% greater production rate of mussels due to their proximity to fish cages and a discount rate of 8%. Enhanced mussel productivity translated into a measurable financial benefit, recognized as a genuine “economy of integration”. Integration was economically profitable if the price of salmon remained constant or dropped by 1% per year; however, a drop of 2% per year would result in a negative NPV for this IMTA system, making it a financially unattractive investment. It should be noted, however, that the aquaculture operation would be non-viable due to the salmon prices rather than the value of the associated species, in this case mussels.

The IMTA project in the Bay of Fundy, Canada, is presently developing an economic model (Ridler *et al.*, 2007). Economic estimates (with risk scenarios) have been undertaken to compare the profitability of a kelp/mussel/salmon IMTA system with salmon monoculture. Profitability (NPV) was estimated by projections over 10 years (5 salmon harvests) using discount rates of 5% and 10%. To take risk into consideration, three scenarios were run, and each scenario was given a probability of occurrence. The optimistic scenario, Scenario 1, has 5 successful salmon harvests with the usual mortality rate of 11% and a probability of occurrence of 20%. Scenario 2 (intermediate, 40% probability of occurrence) has 4 successful salmon harvests and one harvest with a mortality rate of 70%. Pessimistic Scenario 3 (40% probability of occurrence) has 4 successful harvests and there is no fifth harvest as all fish are assumed destroyed. Scenarios 2 and 3 are plausible because of infectious salmon anaemia, other diseases, or winter chill. The NPVs for these scenarios are shown in Table 9.1.

Table 9.1: Scenarios of salmon monoculture versus kelp/mussel/salmon IMTA in the Bay of Fundy, Canada.

Operation	Discount rate	Scenario 1 (optimistic)	Scenario 2 (intermediate)	Scenario 3 (pessimistic)
Salmon monoculture	NPV at 5%	8 146 477	2 664 112	50 848
IMTA	NPV at 5%	8 906 435	3 296 037	674 850
Salmon monoculture	NPV at 10%	6 885 181	2 391 135	-228 345
IMTA	NPV at 10%	7 508 913	3 014 866	403 579

Note: Ten year run net present value (NPV) discounted at 5% and 10% (in USD).

Source: Ridler *et al.*, 2007.

Additional revenues from mussels and seaweeds more than compensate for additional costs, providing higher NPVs for IMTA than for salmon monoculture in all scenarios. Mussels and seaweeds provide alternative uncorrelated sources of income, thereby softening the damaging effect of salmon losses. Even under the pessimistic scenario (3), IMTA provided a positive NPV at both discount rates. Just one bad harvest can have a negative impact on the entire ten year run of a monoculture salmon farm, whereas IMTA effectively reduces the risk. The natural factors that affect salmon mortality may not necessarily affect mussels and kelps. For instance, salmon experience winter chill at -0.8 ˚C, while mussels and kelps can survive much colder temperatures (*e.g.* mussels live in the intertidal zone that can experience drops to -40 ˚C); similarly, kelps are temperate cold water organisms and, in fact, grow mostly between winter and late spring). Therefore, the addition of these co-products can reduce risk (it is unlikely that all three species will be affected simultaneously) and increase the overall sustainability, profitability and resilience of aquaculture farms.

Nobre and collaborators are presently comparing abalone (*Haliotis midae*) monoculture to abalone/seaweed IMTA at a South African farm with an abalone annual production of about 240 tonnes. In the IMTA setting, seawater is recycled and up to 30% of the wild kelp, *Ecklonia maxima*, consumed by abalone is replaced by *Ulva lactuca* grown on site in the recirculation system. The overall commercial gain from using an IMTA approach was estimated at between USD 1.1 and 3.0 million per year, including a significant increase in farm profits (USD 200 000 to 700 000). The environmental benefits included the reduction of nitrogen discharges into adjacent coastal waters by 3.7 to 5.0 tonnes per year, the reduction in harvesting of wild kelp beds by 2.2 to 6.6 hectares per year, and the reduction of CO_2 emissions (reduced pumping needs) by 290 to 350 tonnes per year. The values of the environmental and societal (jobs) benefits by adopting an IMTA design were larger than the gains in farm profitability.

Further development of these economic models and others is proceeding and will help to shed light on the current economic (society) and commercial (industry) attractiveness of IMTA.

Recognising and valuing the biomitigating services rendered by the extractive components of IMTA

The above economic analyses indicate that the outlook for IMTA is promising. It is, however, important to note that these analyses were based solely on the commercial values from the sale of biomass - being of fish, shellfish or seaweeds - and using conservative price estimates for the co-cultivated organisms based on known applications.

One aspect not considered and not factored into the commercial/economic analyses described above, is the fact that the extractive component of an IMTA system not only produces a valuable multi-purpose biomass, but also simultaneously renders waste reduction services to society. Through IMTA, some of the food, nutrients and by-products considered “lost” from the fed component are recaptured and converted into harvestable and healthy seafood of commercial value, while biomitigation takes place (partial removal of nutrients and CO_2, and supplying of oxygen). In this way, some of the externalities of fed monoculture are internalized by extractive co-cultures, thus increasing the overall sustainability, profitability and resilience of aquaculture farms. The economic values of the environmental/societal services of extractive species should, therefore, be recognized and accounted for in the evaluation of the true value of the IMTA components. It is particularly important to recognize that once nutrients have entered coastal ecosystems, there are not many removal options available: the use of extractive species being one of the few realistic and cost-effective options.

Ecosystem services have been ignored until recently (Costanza *et al.*, 1997). To improve the sustainability of anthropogenic nutrient loading practices such as aquaculture, incentives such as Nutrient Trading Credits (NTC) should be established as a means to promote nutrient load reduction or nutrient recovery. During the last few years, there has been much talk and excitement about carbon credits. However, within coastal settings the concerns have largely been with nitrogen, due to the fact that its typical role as the limiting nutrient is not any longer the case in some regions. Potential effects of carbon loading in the marine environment should also be considered. Organic carbon loading below fish farms may promote localized benthic anoxia and, consequently, hydrogen sulfide release. Hydrogen sulfide concentrations (or its proxy, the redox potential) form the basis of environmental regulations of cage-based aquaculture in several jurisdictions. Ocean acidification due to increased dissolved CO_2 levels has also prompted serious new concerns (Feeley *et al.*, 2004). With an appropriate composition of co-cultured species, IMTA has the potential to remove dissolved (inorganic) and solid (organic) forms of nitrogen, carbon, phosphorus (more an issue in freshwater environments), etc., making extractive aquaculture a good candidate for a NTC or other suitable approaches.

Currently, there are few countries with laws or regulations that require aquaculture operations to responsibly internalize their environmental costs, such as nutrient discharges. There are some precedents, such as where land-based trout farmers in Denmark are allowed to increase their feed quota with documented evidence of reduced effluent discharge (Thomsen, 2006), but such incentives are not widely spread. In most jurisdictions, adjacent ecosystems are left to accommodate the nutrient load, and performance based standards are used to determine if farms have exceeded their assimilative capacity.

The implementation of regulations resulting in internalization of environment costs by fish farms, without a direct economic compensatory response such as the Danish feed quota increase, could result in a significant reduction in profitability. In land-based systems, it is relatively easy to quantify nutrient load and concentration via comparison between farm inflows and outflows, thereby creating a benchmark for “economic compensation”. Such values are practically impossible to empirically measure in an open-water system, “leaky” by definition, and, consequently, so is the practical implementation of such incentives. However, Troell *et al.* (1997) and Chopin *et al.* (2001) demonstrated that by integrating the seaweed, *Gracilaria*, in the dual role of nutrient scrubber and commercial crop (for agar production), with salmon farms in Chile, the environmental costs of waste discharges would be significantly reduced and profitability significantly increased.

Interestingly, the removal of nitrogen could be much more lucrative, by approximately a factor 100, than that of carbon (see example below). The cost of removing nitrogen is not clearly defined, but there are six interesting studies that may help define a range of possible prices for economic evaluation of the NTC concept. Chopin *et al.* (2001) indicated that at some sewage treatment facilities the cost of removing 1 kg of nitrogen varies between USD 3 and USD 38, depending on the technology used and the varying labour costs in different countries. An interesting case to consider is the municipality of Lysekil, in Sweden, which is paying approximately USD 10 per kg removed by the filter-feeding mussel, *Mytilus edulis*, to the farm Nordic Shell Produktion AB (Lindhal *et al.*, 2005, 2009). Ferreira *et al.* (2007, 2009), with the development of the Farm Aquaculture Resource Management (FARM) model, determined a net value of EUR 18-26 billion per year of nutrient eutrophication reduction services provided by shellfish aquaculture in the coastal waters of the European Union. Gren *et al.* (2009) calculated that the cleaning costs of nutrients by mussel farming can be considerably lower than other abatement measures and estimated that mussel farming should be credited between EUR 0.1 and 1.1 billion per year in the Baltic Sea.

Using the information above, and only for illustration purposes, without presuming what the final design of IMTA sites will be in the future, we can make some preliminary calculations for the IMTA project on the East coast of Canada to get an idea of the monetary magnitude of these services. There are presently 96 finfish sites in South West New Brunswick. Because of the Bay Management Area Plan, put in place to create a fallowing period and contain diseases, only 2/3 of the sites (*i.e.* 64 sites) are active in any given year. If each site was designed to have eight seaweed rafts (38 ropes of kelps, 35 m long and supporting a biomass of 15 kg/m), there would be 512 rafts producing 10 214.40 tonnes fresh weight (FW) of seaweeds. With an average of 0.35% nitrogen content in FW kelp tissues, the harvesting of kelps would equate to the removal of 35.75 tonnes of nitrogen from the ecosystem per year. If the nitrogen removal was fixed at USD 10 per kg, this would represent a NTC of USD 357 504; if it was fixed at USD 30 per kg, this would represent a NTC of USD 1 072 512. The same could be applied to another key nutrient, phosphorus. With an average of 0.04% phosphorus content in FW kelp tissues, 4.09 tonnes of phopshorus would be removed per year. With a value of USD 4 per kg removed (Chopin *et al.*, 2001), this would represent another contribution to the NTC of USD 16 343.04, a much smaller amount but it could also be an important way of extracting phosphorus, at a time when some are predicting it to be the next element human society will be short of (in its natural or mined forms).

Carbon Trading Credits (CTC) could also be calculated. There may be some arguments about what is meant by trapping and sequestering carbon. Some may argue that it should be reserved to long/geological term storage (sink) and not to transient storage (Lackner, 2003). This is, in fact, a question of how long one allows the recycling clock to run. There is no permanent storage of carbon; it happened to have been sequestered over geological time to suddenly be reused at an accelerated rate over the last few centuries. But the first law of thermodynamics, as enunciated by Antoine Laurent de Lavoisier more than two centuries ago, still applies: “Rien ne se perd, rien ne se crée, tout se transforme”, *i.e.* “Nothing is lost, nothing is created, everything is transformed”. If even temporary removal of carbon from the ocean until further transformation can be credited for potentially increasing seawater pH and absorbing CO_2 from the atmosphere and/or the cultivated animals, then we can do the following calculations. With an average of 3% carbon content in FW kelp tissues, 306.43 tonnes of carbon would be removed per year. With the value for carbon removal often cited to be around USD 30 per tonne (Lackner, 2003), this would represent a CTC of USD 9 192.96: a large amount of carbon, but for a much smaller financial amount, underlining the difficulty in removing dissolved nutrients from aquatic systems and the acute issue of their presence in coastal systems.

Similar calculations could be applied to the organic extractive component of IMTA. In the case of shellfish, accumulation of nitrogen, phosphorus and carbon should be considered both in meat and shells, especially rich in calcium carbonates.

Moving to a much larger scale, the occurrence of large and recurrent “green tides” should also be brought into focus. Large proliferations of opportunistic green algae, especially of the genus *Ulva*, as a response to large anthropogenic nutrient loading, have been in the news over the last few years in places around the world such as Northern Brittany in France, the southern regions of the United Kingdom, and Venice in Italy. The green tide event that got a lot of attention was the one in

Qingdao, China: as it occurred just before the sailing competitions of the 2008 Olympic Games held there, it was reported on by a lot of foreign journalists. We need to ask ourselves: are these green tides a negative media photo opportunity, or are they reminders of the significant role seaweeds play in coastal processes and the services they render? Within three weeks, 1 million tonnes of *Ulva prolifera* were removed from the vicinity of Qingdao to allow the sailing boats and windsurfs to compete (but it is estimated that approximately 2 million tonnes of *U. prolifera* sank to the bottom of the Bay, another environmental problem shifting, but not a solution). With an average nitrogen content between 0.3% and 0.5% in the tissues and a nitrogen removal cost between USD 10 and USD 30, the harvesting of 1 million tonnes equated to between 3 000 and 5 000 tonnes of nitrogen removal for a NTC value between USD 30 and 150 million! Additional NTCs of USD 1.6 million for the removal of 400 tonnes of phosphorus, and CTC of USD 900 000 for the removal of 30 000 tonnes of carbon should also be factored in. In 2009, there was another green tide event covering at least 17 400 km^2 of the Yellow Sea. We are now beginning to understand this phenomenon (Liu *et al.*, 2009; Pang *et al.*, 2010). As a massive cultivation of the juvenile river crab, *Eriocheir sinensis*, is taking place in Animal Aquaculture Ponds (AAPs) in the province of Jiangsu, south of the province of Shandong where Qingdao is located, large organic fertilizer applications are made periodically in ponds of the green alga *Chlorella*, which is used to feed rotifers, which are then used to feed the river crabs. The AAPs, with very high levels of ammonium and phosphates, are the reservoirs of germlings of *U. prolifera*, which are then discharged along the coast, where they find favorable conditions to bloom and be transported north by the prevailing currents and winds. A smaller green tide occurred in 2007, in 2008 it hit the coast around Qingdao and in 2009 it stayed offshore, but out of sight should not mean out of mind. If urgent measures are not taken, this will be a recurrent event for years to come.

Is there a solution? Green tides are not the cause, but the unintentional consequence of coastal eutrophication. With the presence of sufficient nutrients and solar energy, these opportunistic species, with a well-adapted anatomy, morphology and physiology, will proliferate. Obviously, it would be beneficial to reduce nutrient loading at the source; but this may not be possible in the present context of economic development along the coastal zone of China. The problem is that *U. prolifera* is presently an unwanted and uncontrolled growing nuisance species of limited commercial value. The solution may be to create a competition for nutrients by intentionally cultivating species, which not only carry on the biomitigation, but also have a commercial value, where *U. prolifera* starts to enter the coastal environment in order to control its proliferation. This time, the IMTA concept has to be interpreted as an integrated land pond/coastal aquaculture system in a supra Integrated Coastal Zone Management (ICZM) effort, beyond provincial borders, to address issues at the Yellow Sea scale. We understand that this “out of the box” approach to ICZM will, initially, raise eyebrows as the idea of growing more seaweeds (but of commercial value) to contain the proliferation of other seaweeds, presently considered nuisances, is not the most intuitive approach for a lot of people or decision makers! The question is simple: what are the best nutrient scrubbers once nutrients are in a dissolved state and have reached coastal waters? The answer is seaweeds, but can we, preferably, grow the ones we have applications for?

The development and adoption of technology often depends in part on the level of legislative pressure from a nation's government, itself reacting to pressures from consumers, ENGOs and the public at large. If environmental legislation remains a low priority with government, then little progress toward the use of biofilters (as a means of effluent mitigation) will occur. The only motivator will be profits obtained from additional product growth and regulatory incentives. Therefore, if governments put legislative pressure on the proper management of wastewater effluent, openly support the use of biomitigation for effluent management, and put in place the appropriate corresponding financial tools (funding for IMTA R&D, outreach and technology transfer, and NTC and CTC incentives), then the development of IMTA will be encouraged.

It is also important to note that present aquaculture business models do not consider or recognize the economic value of the biomitigating services provided by biofilters, as there is no cost associated with aquaculture discharges/effluents in land-based or open-water systems. Regulatory and financial incentives may therefore be required to clearly recognize the benefits of the extractive components of IMTA systems (seaweeds and invertebrates). A better estimate of the overall cost/benefits to nature and society of aquaculture waste and its mitigation would create powerful financial and regulatory incentives to governments and the industry to jointly invest in the IMTA approach, as the economic demonstration of its validity would be even more obvious. Moreover, by implementing better management practices, the aquaculture industry should increase its societal acceptability, a variable to which it is very difficult to give a monetary value, but an imperative condition for the development of its full potential. Reducing environmental and economic risk in the long term should also make financing easier to obtain from banking institutions (Brezeski and Newkirk, 1997).

Conclusions

Several IMTA projects, in different parts of the world, have now accumulated enough data to support the proof of concept at the biological level. The next step is the scaling up of more experimental systems to make the demonstration at a commercial scale, and to document the economic and social advantages of the concept, which will be key to offering IMTA to practitioners of monospecific aquaculture as a viable option to their current practices. Underlying this demonstration will be the development of a better understanding of the major ecological interactions involved with IMTA systems. Working on appropriate food safety regulatory and policy frameworks in the respective countries will be essential for enabling the development of commercial scale IMTA operations in a more universal fashion.

We need to rethink how an aquaculture farm works within the broader framework of Integrated Coastal Zone Management (ICZM), where integration can range from the small scale (a leased site with its spatial limits) to the larger scale of a region connected by the functionalities of the ecosystem. Selecting the right combination of species with complementary ecological functions will be critical. They will have to be appropriate for the habitat, the available culture technologies, and the environmental and oceanographic conditions. They will have to be complementary in their ecosystem functions, growing to a significant biomass for efficient biomitigation, commanding an interesting price as raw material or presenting an interesting added-value for their derived products, and their commercialization should not generate insurmountable regulatory hurdles.

Economic analyses need to be undertaken as part of the overall modelling of IMTA systems as they get closer to commercial scale and their economic benefits and costs, as well as impacts on coastal communities, are better understood. It will then be possible to add profitability, resilience, social/economic desirability and economic impacts to the comparison between IMTA and monoculture settings. These models will need to be sufficiently flexible with respect to the most volatile parameters and explicit assumptions so as to allow modelling of IMTA systems that is tailored to the environmental, economic and social conditions of the different regions where they will be installed. They could be modified to estimate the impact of organic and other eco-labellings, the value of biomitigating services for enhanced ecosystem resilience, the savings due to multi-trophic conversion of feed and energy which would otherwise be lost, and the reduction of risks through crop diversification and increased societal acceptability.

Nutrient extractive aquaculture is a viable ecological engineering option for managing the externalities generated by aquaculture operations. Effective government legislation/regulations and incentives to facilitate the development of IMTA practices and the commercialization of IMTA products will be necessary. True recognition of the environmental/economic/societal services of extractive crops would create strong incentives to develop sustainable marine agronomy practices, such as IMTA, in which seaweeds and invertebrates should also be considered as candidates for a variety of regulatory measures that internalize these benefits. For example, nutrient and carbon trading credits could be used to promote nutrient removal, CO_2 sequestration, oxygen provision and coastal eutrophication reduction. Including NTC and CTC in the financial spreadsheets of aquaculture operations would create economic incentives to encourage aquaculturists to further develop and implement IMTA systems and increase the societal acceptability of aquaculture by the general public. Only when these services are properly recognised and valued, will we be able to establish the true value of the extractive components of IMTA so that biomitigative solutions become an integral part of coastal regulatory and management frameworks.

At the present time, we seem to be at the stage of recognition, awareness and communication of the concepts of ecosystem services and biomitigating services rendered by extractive aquaculture (the differences between the two not always being clearly identified and explained in some publications). Next will come the time to transform the concepts into biomitigative solutions and then their inclusion in regulatory and management frameworks. Establishing and implementing a structure for the payment schemes (credits or incentives) of these services will be a delicate matter. Will it be one agency, but with funds coming from where? Should it be a regional, national or international agency(ies), trading at which scale(s)? Will an extractive aquaculture operation in existence for many years receive credits, or will only the new ones? Would a fed aquaculture operation also practicing extractive aquaculture be eligible for credits, or will it be the case for the extractive only aquaculture operations? What about the situation in which people run both types of farms. Moreover, due to complex hydrographic and current patterns, it is obvious that extractive species at a site are not limited to absorbing/sequestering the nutrients generated exclusively at that site. Consequently, is it possible to establish a clear spatial nutrient removal budget which would be associated with the corresponding credits/incentives? Will the sequestration have to be “permanent”, or will a temporary removal/storage be acceptable and more realistic? A lot of regulatory details will have to be worked out before this complex scheme becomes reality.

There is still a large amount of education required to bring society into the mindset of incorporating IMTA into their suite of social values. Some of the attitudinal surveys conducted in Canada (Ridler *et al.*., 2007; Barrington *et al.*., 2010) and the USA (Shuve *et al.*, 2009) indicate that the general public is in favour of practices based on the "recycling concept". Perceptions will have to change. Why is recycling and the concept of “what is waste for some is gold for others” well accepted in agricultural practices, but is not yet acquired when transposed to aquaculture practices? Will a greater appreciation of the sustainable ecological value of the concept, a willingness to support it tangibly with shopping money, and an increased pressure on elected representatives emerge? This will be the ultimate test. The degree to which researchers and extension people become creatively involved with this educational component will be vital to the success of IMTA practices.

For some, the ecological, engineering, economic and social challenges remaining to be solved may be daunting. However, the goal is to develop modern IMTA systems, which are bound to play a major role worldwide in sustainable expansions of the aquaculture operations of tomorrow, within their balanced ecosystem, to respond to a worldwide increasing seafood demand with a new paradigm in the design of the most efficient food production systems. As was the case on land where the acquisition of food by hunter/gatherer societies had to evolve towards agricultural practices, we will have to accept an evolution in our seafood procurement. The agricultural revolution has been associated with significant changes in landscape and land use; we can expect that the “turquoise” (a greener blue!) revolution will also trigger significant “seascape” and “sea use” modifications, all the way to our deepest human social structures and governance. Let us also not forget that we are still in the infancy of modern, intensive aquaculture and that some agricultural practices have taken centuries to develop into better, not necessarily yet best, management practices.

Beyond the biological, environmental, economic, technological, engineering and regulatory issues of aquaculture developments, it will all come down to the basic question of societal acceptance. Are we ready to evolve in our use of the “last frontier” of this planet and consider not only the challenges of the physical forces at sea (wave exposure, winds, currents, depth, etc.) but also those of shipping routes, fishing zones, offshore gas and mineral extraction areas, migration routes for marine mammals, recreational uses, and then finally deal with the concept of zoning some portions of the oceans for large aquaculture parks, as sustainable food production systems for an ever seafood hungrier human population? The same question of readiness for marine spatial planning could also be applied to emerging projects of wind farms and biofuel farms at sea. In fact, combining IMTA open-ocean farms with wind, underwater turbine and/or biofuel farms could be a means for reducing their cumulative footprint. However, if the “Not In My Back Yard” (NIMBY) and the “Build Absolutely Nothing Anywhere Near Anything” (BANANA) attitudes continue to prevail, especially in the western world, then we will not be able to secure our seafood or our energy in an ecosystem responsible manner despite all the rhetoric we can hear today regarding alternative technologies and solutions.

Basically, are we ready to "walk the talk"? Thankfully, as Jules Verne wrote more than 130 years ago, "tout ce qui est impossible reste à accomplir" (*i.e.* "all that is impossible remains to be accomplished")...!

Additional information

- Web site of Thierry Chopin: www.unbsj.ca/sase/biology/chopinlab/
- Web site on IMTA on Wikipedia: www.en.wikipedia.org/wiki/Integrated_Multi-trophic_Aquaculture

Notes

[1] www.telegraph.co.uk/earth/earthnews/3318094/Photographer-captures-trouts-great-escape.html

References

Ayer, N.W. and Tyedmers, P.H. (2009), “Assessing alternative aquaculture technologies: life cycle assessment of salmon culture systems in Canada”, *Journal of Cleaner Production* 17: 362-373.

Barrington, K., Chopin, T. and Robinson, S. (2009), “Integrated multi-trophic aquaculture IMTA) in marine temperate waters”, in Integrated mariculture: a global review, pp 7-46.

D. Soto (Ed.), *Integrated Mariculture. A global review*, FAO Fisheries and Aquaculture Technical Paper No. 529, FAO, Rome, 183 p.

Barrington, K., Ridler, N., Chopin, T., Robinson, S. and Robinson, B. (2010), “Social aspects of the sustainability of integrated multi-trophic aquaculture’, *Aquaculture International* 18: 201-211.

Brzeski, V. and Newkirk, G. (1997), “Integrated coastal food production systems – a review of current literature”, *Ocean and Coastal Management* 34: 55-71.

Buschmann, A.H., Troell, M., Kautsky, N. and Kautsky, L. (1996), “Integrated tank cultivation of salmonids and Gracilaria chilensis (Gracilariales, Rhodophyta)”, *Hydrobiologia* 326/327: 75-82.

Chopin, T. (1995), “Mixed, integrated, poly-, or multi-level aquaculture - whatever you call it, it is time to put seaweeds around your cages!”, In: Proc. Conference on Cold Water Aquaculture to the Year 2000, St. Andrews, Canada, 6-8 September 1995, Aquaculture Association of Canada, Special Publication No. 2 (1997): 110; 117 p.

Chopin, T. (2006), “Integrated Multi-Trophic Aquaculture. What it is and why you should care and don’t confuse it with polyculture”, *Northern Aquaculture* 12 (4): 4.

Chopin, T., Buschmann, A.H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G.P., Zertuche-Gonzalez, J.A., Yarish, C. and Neefus, C. (2001), “Integrating seaweeds into marine aquaculture systems: a key towards sustainability”, *Journal of Phycology* 37: 975-986.

Chopin, T., Robinson, S.M.C., Troell, M., Neori, A., Buschmann, A.H. and Fang, J. (2008), “Multitrophic integration for sustainable marine aquaculture: 2463-2475”, In: The Encyclopedia of Ecology, Ecological Engineering (Vol.3), S.E. Jørgensen and B.D. Fath (eds.), Elsevier, Oxford.

Costanza, R., d’Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P. and van den Belt, M. (1997), “The value of the world’s ecosystem services and natural capital”, *Nature* 387: 253-260.

Costa-Pierce, B.A., Zainal, S. and Effendi, P. (1988), "ICLARM and south-south technology transfer: Philippine aquaculture technology and Indonesia. Part 1. Naga", *The ICLARM Quarterly* 11: 10-11.

Costa-Pierce, B.A. (2002), *Ecological Aquaculture: The Evolution of the Blue Revolution* Blackwell Science, Oxford, 382 p.

Edwards, P. (1993), "Environmental issues in integrated agriculture-aquaculture and wastewater-fed fish culture systems", In: Environment and Aquaculture in Developing Countries, pp 139-170, R.S.V.

Pullin, H. Rosenthal and J.L. Maclean (eds.), ICLARM Conference Proceedings 31.

FAO (2009), *The State of World Fisheries and Aquaculture 2008*. FAO of the United Nations, Rome, xvi + 176 p.

Feely, R.A., Sabine, C.L., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J. and Miller, F.J. (2004), "Impact of anthropogenic CO2 on the CaCO3 system in the oceans", *Science* 305 (5682): 362-366.

Ferreira, J.G., Hawkins, A.J.S. and Bricker, S.B. (2007), "Management of productivity, environmental effects and profitability of shellfish aquaculture – the Farm Aquaculture Resource Management (FARM) model", *Aquaculture* 264: 160-174.

Ferreira, J.G., Sequeira, A., Hawkins, A.J.S., Newton, A., Nickell, T.D., Pastres, R., Forte, J., Bodoy, A. and Bricker, S.B. (2009), "Analysis of coastal and offshore aquaculture: application of the FARM model to multiple systems and shellfish species", *Aquaculture* 289: 32-41.

Gren, I.M., Lindhal, O. and Lindqvist, M. (2009), "Values of mussel farming for combating eutrophication: an application to the Baltic Sea", *Ecological Engineering* 35: 935-945.

Indergaard, M. and Jensen, A. (1983), "Seaweed biomass production and fish farming", In: Energy from Biomass. Proc. 2nd EC Conference on Biomass, Berlin, September 1982. A. Strub, P. Chartier, and G. Schleser (eds.). Applied Science Publishers, London.

Lackner, K.S. (2003), "A guide to CO2 sequestration", *Science* 300: 1677-1678.

Lindhal, O. and Kolberg, S. (2009), "Can the EU agri-environmental aid program be extended into the coastal zone to combat eutrophication?", *Hydrobiologia* 629: 59-64.

Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L.-O., Olrog, L., Rehnstam-Holm, A.-S., Svensson, J., Svensson, S. and Syversen, U. (2005), "Improving marine water quality by mussel farming: a profitable solution for Swedish society", *Ambio* 34: 131-138.

Liu, F., Pang, S.J., Chopin, T., Xu, N., Shan, T.F., Gao, S.Q. and Sun, S. (2009), "The dominant Ulva strain of the 2008 green algal bloom in the Yellow Sea was not detected in the coastal waters of Qingdao in the following winter", J. *Appl. Phycol.* DOI 10.1007/s10811-009-9489-7.

Neori, A., Cohen, I. and Gordin, H. (1991), "Ulva lactuca biofilters for marine fishpond effluents. II. Growth rate, yield and C:N ratio", *Botanica Marina* 34: 483-489.

Pang, S.J., Xiao, T. and Bao, Y. (2006), "Dynamic changes of total bacteria and Vibrio in an integrated seaweed-abalone culture system", *Aquaculture* 252: 289-297.

Pang, S.J., Liu, F., Shan, T.F., Xu, N., Zhang, Z.H., Gao, S.Q., Chopin, T. and Sun, S. (2010), "Tracking the algal origin of the Ulva bloom in the Yellow Sea by a combination of molecular, morphological and physiological analyses", *Marine Environmental Research* 69: 207-215.

Ridler, N., Wowchuk, M., Robinson, B., Barrington, K., Chopin, T., Robinson, S., Page, F., Reid, G., Szemerda, M., Sewuster, J. and Boyne-Travis, S. (2007), "Integrated multi-trophic aquaculture (IMTA): a potential strategic choice for farmers', *Aquaculture Economics and Management* 11: 99-110.

Ryther, J.H., Goldman, J.C., Gifford, C.E., Huguenin, J.E., Wing, S.A., Clarner, J.P., Williams, L.D. and Lapointe, B. (1975), "Physical models of integrated waste recycling-marine polyculture systems', *Aquaculture* 5: 163-77.

Ryther, J.H., DeBoer, J.A. and Lapointe, B.E. (1978), "Cultivation of seaweeds for hydrocolloids, waste treatment and biomass for energy conversion', Proceeding of the Ninth International Seaweed Symposium 9: 1-16.

Shuve, H., Caines, E., Ridler, N., Chopin, T., Reid, G.K., Sawhney, M., Lamontagne, J., Szemerda, M., Marvin, R., Powell, F., Robinson, S. and Boyne-Travis, S. (2009), "Survey finds consumers support Integrated Multi-Trophic Aquaculture. Effective marketing concept key", Global Aquaculture Advocate 12 (2): 22-23.

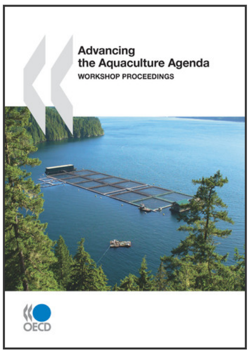
Tacon, A.G.J., Metian, M., Turchini, G.M. and De Silva, S.S. (2010), "Responsible aquaculture and trophic level implications to global fish supply", *Reviews in Fisheries Science* 18 (1): 94-105.

Thomsen, B. (2006), "Freshwater aquaculture in Denmark: a new platform for sustainable growth', Proceeding of the Canadian Freshwater Aquaculture Symposium, Aquaculture Canada 2004, Aquaculture Association of Canada Special Publication 11: 26-30.

Timmons, M.B., Ebeling, J.M., Wheaton, F.W., Summerfelt, S.T. and Vinci, B.J. (2002), *Recirculating aquaculture systems* (2nd edition), NRAC Publication No. 01-002, Cayuga Aqua Ventures, Ithaca, 769 p.

Troell, M., Halling, C., Nilsson, A., Buschmann, A.H., Kautsky, N. and Kautsky, L. (1997), "Integrated marine cultivation of Gracilaria chilensis (Gracilariales, Rhodophyta) and salmon cages for reduced environmental impact and increased economic output', *Aquaculture* 156: 45-61.

Whitmarsh, D.J., Cook, E.J. and Black, K.D. (2006), "Searching for sustainability in aquaculture: an investigation into the economic prospects for an integrated salmon-mussel production system', *Marine Policy* 30: 293-298.



Advancing the Aquaculture Agenda

Workshop Proceedings

Please cite this chapter as:

Chopin, Thierry (2010), "Integrated Multi-Trophic Aquaculture", in OECD, *Advancing the Aquaculture Agenda: Workshop Proceedings*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/9789264088726-15-en