Aquaculture, Integrated Multi-trophic (IMTA)

Glossary Biomitigative services provided by extractive aquaculture The environmental, economic, and societal services and benefits received by ecosystems - in their broad definition which includes humans who depend on them - from the conditions and processes of cultivated species, such as seaweeds extracting inorganic nutrients and suspension- and deposit-feeders extracting organic particles recaptured from the activities of fed aquaculture (e.g., fish or shrimp aquaculture), to maintain their health. Biomitigative services can also be provided by natural populations of similar organisms. - Integrated multi-trophic aquaculture (IMTA) The farming, in proximity, of aquaculture species from different trophic levels, and with complementary ecosystem functions, in a way that allows one species' uneaten feed and wastes, nutrients, and by-products to be recaptured and converted into fertilizer, feed, and energy for the other crops, and to take advantage of synergistic interactions between species. Farmers combine fed aquaculture (e.g., finfish or shrimps) with extractive aquaculture, which utilizes the inorganic (e.g., seaweeds or other aquatic vegetation) and organic (e.g., suspension- and deposit-feeders) excess nutrients from fed aquaculture for their growth. The aim is to ecologically engineer balanced systems for environmental sustainability (biomitigative services for improved ecosystem health), economic stability (improved output, lower costs, product diversification, risk reduction, and job creation in disadvantaged communities) and societal acceptability (better management practices, improved regulatory governance, and appreciation of differentiated and safe products).

Definition of the Subject

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 or shrimps fed sustainable commercial diets) with extractive species, which utilize the inorganic (e.g., seaweeds or other aquatic vegetation) and organic (e.g., suspension- and deposit-feeders) excess nutrients from fed aquaculture for their growth. Thus, extractive aquaculture produces valuable biomass , while simultaneously rendering biomitigative services for the surrounding ecosystem and humans. Through IMTA, some of the uneaten feed and wastes, 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, 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 (NTC and CTC) 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.

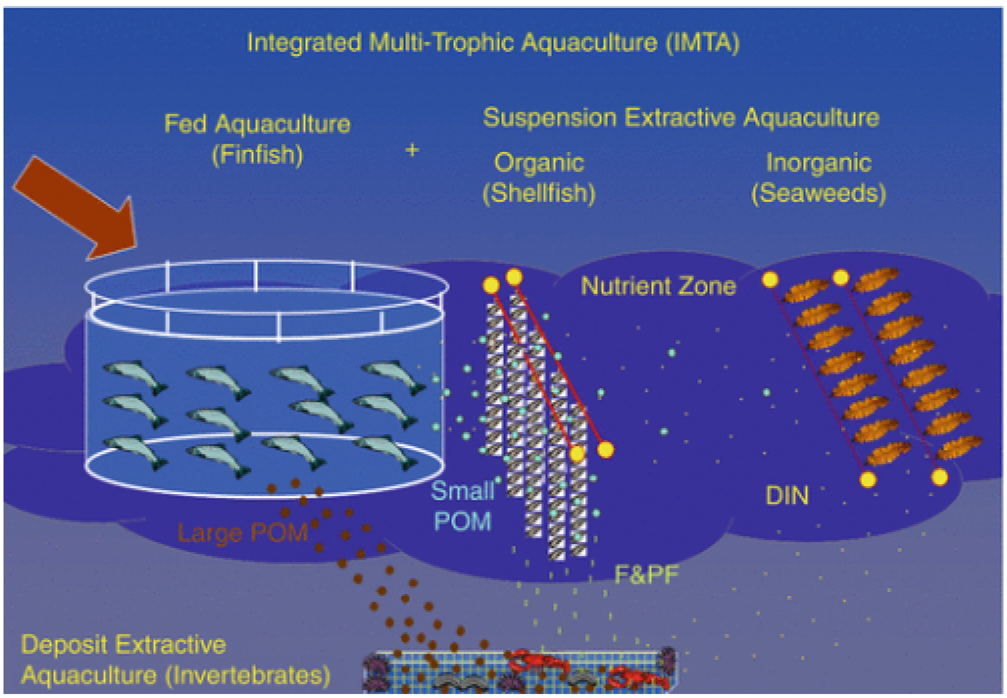
Introduction: Aquaculture Is Needed But Some Practices Need to Evolve

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 ton seafood deficit [1]. This gap will likely not be filled by capture fisheries but by aquaculture operations, which already supply almost 50% of the seafood consumed worldwide [1]. Consequently, it is imperative to design the ecosystem responsible aquaculture practices of tomorrow that maintain the integrity of ecosystems while ensuring 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 [2]; however, the rapid development, throughout the world, of intensive marine fed aquaculture (e.g., carnivorous finfish and shrimp) 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. There are also some concerns with shellfish aquaculture, especially at high density, as shellfish occupy an intermediate trophic level and often play a dual role of organic filtering organisms and waste/nutrient generating organisms [3].

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. 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.

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 or shrimps fed sustainable commercial diets) with extractive species, which utilize the inorganic (e.g., seaweeds or other aquatic vegetation) and organic (e.g., suspension- and deposit-feeders) excess nutrients from aquaculture for their growth (Fig. 1).



Aquaculture, Integrated Multi-trophic (IMTA). Figure 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 polychaetes), taking advantage of the enrichment in large particulate organic matter (POM) and feces and pseudo-feces (F&PF) from suspension-feeding organisms. The bioturbation on the bottom also regenerates some DIN, which becomes available to the seaweeds

IMTA: A Flexible and Functional Concept

The IMTA concept is extremely flexible [4]. 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, marine or freshwater systems (sometimes called "aquaponics "), and temperate or tropical systems. 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 surrounding 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 mussel s (Mytilus edulis) within a few hundred meters: this is only one of the variations (Fig. 2) and the IMTA concept can be extended to very large ecosystems like the Yellow Sea (see below). This also means that IMTA variations include integrated agriculture aquaculture systems (IAAS), integrated sylviculture (mangrove) aquaculture systems (ISiAS), integrated green water aquaculture systems (IGWAS), integrated peri-urban aquaculture systems (IPUAS), integrated fisheries aquaculture systems (IFAS), sustainable ecological aquaculture systems (SEAS), integrated temporal aquaculture systems (ITAS), and integrated sequential aquaculture systems (ISAS, also called partitioned aquaculture system s, PAS, or fractionated aquaculture system s, FAS) [5-7]. There is no ultimate IMTA system to "feed the world." There is not one world but climatic, environmental, biological, physical, chemical, economic, societal, and political conditions, each of which can lead to different choices of systems for feeding these microworlds.

Aquaculture, Integrated Multi-trophic (IMTA). Figure 2 One of the Integrated Multi-Trophic Aquaculture (IMTA) sites in the Bay of Fundy, New Brunswick, Canada, operated by Cooke Aquaculture Inc.: two rows of salmon cages in the background, then a row of mussel rafts and two seaweed rafts in the foreground

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? The reasons for this generally center around social customs and practices, and market-driven economic models not considering externalities that one is already familiar with, even if common sense tells one that one should modify them. Human society does not change quickly unless there are compelling reasons to do so. What to do when early large profit margins create short-term economic booms, followed within a few decades by dwindling meager profit margins? Often, the temptation is to throw more large volume cultivation operations and destructive methods into the mix, without proper regulations and business plans. Pollution, disease and economic busts generally ensue, major restructuring of the industry becomes necessary, and a few clairvoyant visionaries remain afloat and adapt to jump to the next curve to survive. This evolution is not exclusive to the aquaculture industry. Why do humans have such short and selective memories resulting in them repeating mistakes, regularly?

The fact that humans are currently at a crossroad should motivate them to improve current aquaculture practices, without further delay. Fishery management plans in most countries have been single-species approaches, completely neglecting the interactions between species, not understanding the synergies, or antagonisms, between them and how an ecosystem works based on the complementarities of the different functions of the different organisms inhabiting it. It seems that, despite the knowledge of the limitations of mono-agriculture and mono-fisheries, people are ready to develop similar plans for the management of mono-aquaculture. It should be recognized that there is still a chance for incorporating all the learning about the problems of terrestrial monocultures into the relatively new frontier of aquaculture. To better manage marine, brackish, or freshwater environments to the benefits of mankind and the ecosystem, one needs to develop a new science, marine agronomy , learning from the mistakes made in land agriculture over the centuries to do a better job with aquaculture. It is interesting to note that traditional agricultural practices, such as crop alternation and fallow, are now being transposed to aquaculture practices.

Why, then, is IMTA not more widely adopted, especially in the western world? Paul Greenberg, in his fascinating book "Four Fish" [8], mentioned a very interesting point. In Leviticus, the third book of the Hebrew bible in which, according to the Jewish tradition, God dictated commandments to Moses, one can read (19:19): "You must not sow your field with two different kinds of seed" (also translated as "two kinds of seed" or as "mixed seed"). One can wonder if this represents, in fact, one of the most ancient treatises recommending mono-agricultural practices and if it is not the reason why integrated culture techniques have been ignored for centuries in the Judeo-Christian civilization, while they have flourished in other civilizations, especially in Asia. 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.

The Need for Diversifying Responsible Aquaculture Systems and for an Ecosystem Approach

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 excess production of a single species leaves a business vulnerable to sustainability issues 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 economic risk and maintaining sustainability and competitiveness.

From an ecological point of view, diversification also means cultivating more than one trophic level, i.e., not just raising 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.) 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 nondiversified input and output needs. Evolving aquaculture practices will require a conceptual shift toward understanding the working of food production systems rather than focusing on technological solutions.

One of the innovative solutions promoted for environmental sustainability (biomitigative services for improved ecosystem health), economic stability (improved output, lower costs, product diversification, risk reduction, and job creation in disadvantaged communities), and societal acceptability (better management practices, improved regulatory governance, and appreciation of differentiated and safe products) is IMTA. The aim is to increase long-term sustainability and profitability per cultivation unit (not per species in isolation as is done in monoculture), as some of the uneaten feed and wastes, nutrients, and by-products of one crop (fed animals) are not lost but recaptured and converted into fertilizer, feed, and energy for the other crops (extractive plants and animals). These, in turn, can be harvested and marketed as healthy seafood, while feed costs are reduced because of their reuse in multiple niches and biomitigation is taking place (partial removal of nutrients and CO_2, and supply of oxygen). In this way, all the cultivation components have a commercial value, as well as key roles in recycling processes and rendering biomitigative services. Some of the externalities of fed monoculture are internalized, hence increasing the overall sustainability, long-term profitability, and resilience of aquaculture farms. 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/assimilative capacity models. For example, the 158,811 t (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.

IMTA, While Not the Panacea to and for Everything, Is, Nevertheless, 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 farm s. 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 2,000 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 carp s (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 UK. 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 (http://www.telegraph.co.uk/earth/earthnews/3318094/Photographer-captures-trouts-great-escape.html). Ideally, land-based recirculation systems would reduce the potential for escapes. However, most recirculation system s have at least partial water exchange [9] 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" offsite. All of these processes leave a "carbon footprint ," and only partly solve the issue of excess nutrients. IMTA, or its variation called "aquaponics ," 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 [10], in their life cycle assessment of alternative aquaculture technologies, warned that one 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 , nonrenewable 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 microorganisms 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 whether there are any positive interactions associated with more diversified systems. In fact, two studies [11; Robinson, pers. comm.] have demonstrated in laboratory experiments that the blue mussel , Mytilus edulis, is capable of inactivating the infectious salmon anemia 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. [12, 13] also reported reduced total bacteria and Vibrio counts in a seaweed-abalone IMTA system.

In regard to parasites , two studies [14; Robinson, pers. comm.] indicate that blue mussels can consume copepodids, the planktonic and infectious stage of sea lice, and several studies, in both Europe and New Zealand, have highlighted the fact that mussels can consume small zooplankton. Having a biofilter such as mussel s at IMTA sites may decrease the frequency of exposure to pathogens and planktonic parasites. The hope is that having multiple species on a farm will result in some positive interactions between species allowing some biological control of the outbreaks of pathogens and parasites, hence reducing the number of costly chemical treatments required. If this is validated, filter feeders may have additional contributions to sustainability beyond reduction of the particle load. One of the 14 projects of the recently created Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) is investigating the role of bivalves in potentially reducing sea lice populations. Most of the work has been conducted in the lab so far, but results are very positive and it has been demonstrated that mussels eat the larval forms. Ongoing work is developing a trap system that exploits various behaviors of sea lice to attract and filter them out of the system. 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 fishmeal 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 fishmeal (about 15-25%) and fish oil (about 15-20%) than they did less than 10 years ago (40-60%). By-products (trimmings, offal) of wild catch fisheries are now used to supply a major portion of the fishmeal ingredients. Finding replacements for marine ingredients is a priority and there are several large research projects worldwide addressing this issue. The feed company Skretting has now produced a salmon feed which includes no marine ingredients. Turning toward land plant proteins is not without its impacts. Extra farmland area (more deforestation) would be needed, which, moreover, would need to be irrigated and fertilized on a planet already suffering from water availability problems and with fertilizer prices soaring. The price of some staple food crops used in traditional agriculture (corn, soya bean, sugar cane, 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 first-generation biofuel s [15-17]. Reallocation of acreage for subsidized potential biofuel crops such as corn, sugar cane, oil palm, canola, switch grass, etc., has already had significant ecological and societal costs due to its impacts on ecosystem health, biodiversity, and food security [18-21]. Partial substitution with organisms already living in water and not needing extra fertilization in an IMTA setting, such as seaweed s, could, in fact, be a very interesting option, fitting well within the sustainability and management concept of IMTA, and representing a logical loop for companies developing an IMTA and diversification strategy. If cultivated in the water column in IMTA systems, there would, moreover, be no issue of raking natural beds of seaweeds attached to the bottom of the ocean (destruction of seafloor and impact on ecosystem functions such as nursery ground for animals).

Some environmental nongovernmental organizations arguing for fishmeal/fish oil replacement have also voiced concerns that, after all, marine fish should eat marine ingredients … obviously, one cannot have it both ways! There is also the paradoxical situation of farmed freshwater fish, which are being grown less and less on humans and animal wastes and naturally occurring algal blooms, but more and more on already competing staple foods such as corn and soy: they have lost their off-flavored or muddy taste to become tasteless or "unfishy"! So, what does one want to receive in one's kitchen? A flavor-neutral, versatile product easily adapted with numerous sauces, while one is lamenting that farmed salmon or bass are not what wild salmon or bass used to be? Quite an irony, even more so when people learn that these herbivorous whitefish are more and more being fed pellets containing fishmeal and fish oil because they grow faster! What is really important is a balanced diet using balanced sourcing of raw material.

Some will argue that "fish require nutrients, not ingredients." At the same time, there is also the well-known saying "You are what you eat," and in this case, people have to realize and accept that humans are mostly corn, soya, and fishmeal, if they look at what the four mammals (cow, pig, sheep, and goat) and four poultry (chicken, turkey, duck, and goose) that they have selected as their meat choices are eating. Historically, most of the reduction fishery (small fish such as anchovies, herring, sardines, and menhaden) went into the production of pet feeds and farm animal feeds. Subsequently, this fishery supplied a significant part of the marine ingredients for fish feeds. The landing of the reduction fishery has been fairly stable (fluctuating between 15 and 30 million metric tons since the 1970s) and, in the absence of aquaculture, the fishery would likely return to supplying pet and farm animal feeds, and a current resurgence of interest directly by humans. This is not to justify relaxed vigilance for finding replacements for marine ingredients in fish feed, but simply to suggest that an absence of fish farming will not stop the use of this resource. How can one get out of this vicious circle? Cultivating several organisms, at different trophic levels, in proximity so that the food and wastes are utilized efficiently more than once through a cascade of recapturing and remetabolizing is one approach: that is IMTA. The other is to consider that if terrestrial food production systems are close to their limits, one does not have other options but to turn again to the sea, this time not for fish but to have seaweeds and invertebrates entering one's food habits, either directly or delivered through feed given to intermediates to what reach one's plate. The discrepancy between the marine and agricultural production systems has to be reduced: presently, especially in the western world, humans feed approximately two steps higher in the marine food web than in the agricultural food web.

People should continue to eat seafood (fish but also invertebrates and seaweeds), not according to seafood pocket guides which simplistically paint species with one stroke of green (best choice), orange (good alternative), or red (avoid), but according to the fishing and aquaculture practices used to grow, harvest, and process them: an admittedly more complex mosaic, but also much more realistic and attractive to look at than a traffic light!

Interestingly, what is referred to as the fifth tasting sense by Japanese (after sweet, sour, salty, and bitter) and called umami (= savoriness or good flavor) comes from seaweeds. The product responsible for umami was first identified in 1908 by Professor Kikunae Ikeda, of the Tokyo Imperial University, searching for the chemical reason of the strong flavor in seaweed broth (mostly of the kelp Saccharina japonica, formerly Laminaria japonica). It is due to the detection in our mouth of the carboxylate anion of the amino acid called glutamic acid and its salts, glutamates, in particular monosodium glutamate (MSG). Inosine monophosphate (IMP) and guanosine monophosphate (GMP), degradation products of the energy-storing molecule adenosine triphosphate (ATP) greatly enhance the perceived intensity of umami. This explains, chemistry displacing romantics, why a dead tuna (once full of energy) served with seaweeds is such a savory delicacy, the very essence of the success of the sushi bar fad gaining the western world.

We have never pretended that IMTA is the solution, the silver bullet, to and for everything. It is now up to us to develop the better aquaculture practices of tomorrow. IMTA is based on several common sense principles:

- The solution to nutrification is not dilution, but extraction and conversion through diversification.
- This is, in fact, a rewording of the first law of thermodynamics "Rien ne se perd, rien ne se crée, tout se

transforme" ("Nothing is lost, nothing is created, everything is transformed") as summarized by Antoine Laurent de Lavoisier, the well-known French chemist and physicist (but also tax collector, which explains his premature death at age 51 in 1794 under the Terror period of the French Revolution).

- What is waste for some is gold for others.
- Do not put all your salmon eggs in the same basket.

A lot of common sense, but, unfortunately, common sense is not that common! IMTA is one of the promising options, but, certainly, it needs to be tailored to the location in the world where it is implemented. It should also be developed in association with other practices. Like for energy, not one solution will satisfy all the needs and it is a variety of solutions that will help one secure one's seafood procurement in a responsible manner. The solutions will be at the interfaces of these techniques and will be interdisciplinary. They will embrace both scientific and technological advancements and traditional knowledge. IMTA is exactly at this interface, modernizing traditional practices: combining ecosystem complementary crops, bay management area, and fallowing are nothing new, but revisited and updated, based on what humans have learned from past experience (which includes a lot of mistakes over the centuries, but not assimilated by the characteristically short-term memory of humans!).

Recognizing and Valuing the Biomitigative Services Rendered by the Extractive Components of IMTA: Should a System of Nutrient and Carbon Trading Credits Be Developed?

A few economic analyses have indicated that the outlook for increased profitability through IMTA is promising [22, 23]. However, these analyses were based solely on the commercial values from the sale of biomass - being of fish, shellfish, or seaweeds - and used conservative price estimates for the cocultivated organisms based on known applications. One aspect not factored into these analyses is the fact that the extractive component of an IMTA system not only produces a valuable multipurpose biomass, but also simultaneously renders waste reduction services to society. 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 is one of the few realistic and cost-effective options. 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. Further development of economic models is needed to help shed light on the economic (society) and commercial (industry) attractiveness of IMTA.

Ecosystem services have been ignored until recently [24]. 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: localized benthic anoxia and, consequently, hydrogen sulfide release may occur when solid waste deposition rate exceeds aerobic decomposition rate. Ocean acidification due to increased dissolved CO_2 levels has also prompted serious new concerns [25] and a Carbon Trading Credit (CTC) system should also be contemplated. With an appropriate composition of cocultured species, IMTA has the potential to reduce the amounts of 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 and CTC, or other suitable approaches, to deal with the pressing issues of coastal nutrient loading.

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 [26], 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. [27] and Chopin et al. [28] 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 of 100, than that of carbon. The cost of removing nitrogen is not clearly defined, but there are several interesting studies that may help define a range of possible prices for economic evaluation of the NTC concept. The cost of removing 1 kg of nitrogen varies between US$3 and US$38 at sewage treatment facilities, depending on the technology used and the labor costs in different countries [28]. The municipality of Lysekil, in Sweden, is paying approximately US$10/kg removed by the filter-feeding mussel , Mytilus edulis, to the farm Nordic Shell Produktion AB [29, 30]. Ferreira et al. [31, 32], with the development of the Farm Aquaculture Resource Management (FARM) model, determined a net value of €18-26 billion/year of nutrient eutrophication reduction services provided by shellfish aquaculture in the coastal waters of the European Union. Gren et al. [33] 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 €0.1 and €1.1 billion/year in the Baltic Sea.

Using this information, and without presuming what the final design of IMTA sites will be in the future, preliminary calculations for the relatively small-scale IMTA project on the East coast of Canada indicate that the annual harvesting of kelps (Fig. 3) would equate to the removal of 35.75 t of nitrogen from the ecosystem, representing an NTC of between US$357,504 and US$1,072, 512. The same could be applied to another key nutrient, phosphorus. With an annual removal of 4.09 t and a value of US$4/kg removed [28], this would represent another contribution to the NTC of US$16,343, 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).

Aquaculture, Integrated Multi-trophic (IMTA). Figure 3 Harvesting of the kelp, Saccharina latissima, at an Integrated Multi-Trophic Aquaculture (IMTA) site in the Bay of Fundy, New Brunswick, Canada. Kelps remove dissolved nutrients from the ecosystem while providing commercial products

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 [34]. 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 that a particular fossil biofuel , petroleum, has 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 by biomass harvesting until further transformation (and rerelease of carbon) can be credited for potentially increasing seawater pH and absorbing CO_2 from the atmosphere and/or the cultivated animals, then CTC should be calculated. Marine vegetation is getting more and more recognition as a sink for anthropogenic carbon emissions (the so-called blue carbon [35]). Marine primary producers contribute at least 50% of the world's carbon fixation and may account for as much as 71% of all carbon storage in oceanic sediments. Then, micro-alga e, macro-algae , and marine plants, such as mangroves and seagrasses, have a role to play in CO_2 sequestration and removal, and carbon storage [36]. Marine photosynthesis accounts for 50% of the total primary productivity of the planet (54-59 PgC/year from a total of 111-117 PgC/year [37]). Of this, marine macrophytes (seaweeds and seagrasses) account for approximately 1 PgC/year concentrated in coastal regions where they can play a significant role in the sequestration of anthropogenic carbon emissions and the global carbon cycle. Brown marine macro-algae (such as Macrocystis, Saccharina, Laminaria, Ecklonia, Sargassum, Ascophyllum, and Fucus), red algae (such as Porphyra, Palmaria, Eucheuma and Gracilaria) and green algae (such as Ulva), are capable of very high rates of photosynthesis and productivity. These rates of productivity compare very favorably to those of terrestrial crops that have been recommended as possible sources of first-generation biofuels (corn, Zea mays) or second-generation biofuels (switch grass, Panicum virgatus; E-grass, Miscanthus giganteus) and position marine macro-algae very well for being part of the third-generation biofuels [36].

Coming back to the IMTA project on the East coast of Canada, using a value for carbon removal of around US$30/t [34], the annual harvesting of kelps would represent an annual removal of 306.43 t and a CTC of US$9,193: a larger amount of carbon, but for a much smaller value of trading credits, 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, which are especially rich in calcium carbonates.

At 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 , in 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 UK, and Venice in Italy. The green tide in Qingdao, China, just before the sailing competitions of the 2008 Olympic Games, got a lot of attention (Fig. 4). The following question needs to be asked: 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 3 weeks, 1 million tons of Ulva prolifera were removed from the vicinity of Qingdao to allow the sailors and windsurfers to compete (but it is estimated that approximately 2 million tons of U. prolifera sank to the bottom of the Bay; another environmental problem shifting, but not a solution). The harvesting of 1 million tons equated to between 3,000 and 5,000 t of nitrogen removal for a NTC value between US$30 and US$150 millions! Additional NTC of US$1.6 million for the removal of 400 t of phosphorus, and CTC of US$900,000 for the removal of 30,000 t of carbon, should also be factored in.

Aquaculture, Integrated Multi-trophic (IMTA). Figure 4 A green tide of Ulva prolifera in Qingdao, China, just before the 2008 Olympic Games, triggered a massive cleanup

A smaller green tide occurred in 2007. Large ones were also reported in 2009 and 2010 but they stayed offshore in the Yellow Sea [38, 39]. Out of sight should, however, 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 China's coastal zone. The problem is that U. prolifera is presently an unwanted and uncontrolled growing nuisance species of limited commercial value. To control its proliferation, the solution may be to create a competition for nutrients by intentionally cultivating algal species, which not only carry on the biomitigation, but also have a commercial value, where U. prolifera starts to enter the coastal environment (discharges from juvenile river crab land-based aquaculture ponds along Jiangsu province, south of Shandong province where Qingdao is located). 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. It is understood 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 people, preferably, grow the ones they have applications for?

At the present time, there seems to be a stage of recognition, awareness, and communication of the concepts of ecosystem services and biomitigative 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 a reality.

What Will It Take to Increase the Acceptance and Adoption of IMTA as a Responsible Aquaculture Practice of the Future?

Presently, the most advanced IMTA systems in open marine waters and 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 [40]. 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 (e.g., different species of seaweeds). The most advanced IMTA systems, near or at commercial scale, can be found in Canada, Chile, South Africa, Israel, and China [41, 42]. Ongoing research projects related to the development of IMTA are taking place in the UK (mostly Scotland), Ireland, Spain, Portugal, France, Turkey, Norway, Japan, Korea, Thailand, the USA, and Mexico. It will 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.

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. It is, therefore possible that some of the existing regulations and policies could impose unintentional constraints on the future growth of IMTA. To develop the aquaculture of tomorrow, current governance structures pertaining to aquaculture need to be revisited and reviewed with the aim of identifying changes in the regulatory/policy environment that are needed to facilitate the operation of IMTA farms. 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 4 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 4 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. It is known that this approach has led to many failures in the management of the fisheries; vigilance is required so that the same flaw is not repeated in the management of aquaculture.

Most current aquaculture business models do not consider or recognize the economic value of the biomitigative services provided by biofilter s, as there is often no cost associated with aquaculture discharges/effluents in land-based or open-water systems. 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 financial incentive tools such as NTC and CTC, may therefore be required to clearly recognize the benefits of the extractive components of IMTA systems. Better estimates of the overall costs and 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 [43].

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. 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 [23, 44] and the USA [45] indicate that the general public is in favor of practices based on the "recycling concept." Consumers' perceptions and attitudes may also 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 consumers come to accept eating products cultured in the marine environment in the same way they accept eating products from recycling and organic agricultural practices, for which they are willing to pay a higher price for the perceived higher quality or ethical premiums? After all, regulations require mushrooms to be specifically grown on farmyard manure and animal excrements to receive organic certification (European Community Regulations No 2008R0889 - Article 6). Will a greater appreciation of the sustainable ecological value of the IMTA 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. The differentiation of IMTA products through traceability and eco-labeling will also be key for their recognition and command of premium market prices.

Some have argued that the adoption of IMTA in the western world is slow. For example, on the east coast of Canada, there were obviously no IMTA sites in the Bay of Fundy in 2001 when IMTA research started. Nine years later, 8 of the 96 finfish sites in southwest New Brunswick have the combination salmon (or cod)/mussels/kelps and 8 other sites have been amended to develop IMTA. This is a respectable conversion of almost 16% in 9 years. Moreover, it would not be reasonable to anticipate an instant conversion, as the industry needs to develop markets to absorb the cocultured biomass: this also takes time and can only be progressive.

Future Directions: The Path Forward

Several IMTA projects, worldwide, 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 commercial scale to further 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. Emerging responsible aquaculture approaches must generate net economic benefits for society if they are to be advocated. 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.

It has taken decades to reach current finfish aquaculture production levels and learn new species husbandry. A major rethinking is, however, needed regarding the definition of an "aquaculture farm " by reinterpreting the notion of site-lease areas and regarding how it works within an ecosystem, in the context of a broader framework. Within Integrated Coastal Zone Management (ICZM), integration can range from the small scale (a leased site with its spatial limits) to a Bay Management Area (BMA) and to the larger scale of a region connected by the functionalities of the ecosystem. Amending regulations to allow a new type of aquaculture systems will not occur overnight. This should, however, not discourage the finfish aquaculture industry from practicing IMTA, as even small amounts of cocultured species production are useful at the initial stage of development.

Selecting the right combination of species will be critical. They will have to be appropriate for the habitat, the available culture technologies and labor forces, and the environmental, climatic, 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. Their ecological interactions and synergies within an IMTA system will have to be identified and understood to take full advantage of them. Their commercialization should not generate insurmountable regulatory hurdles.

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 biomitigative services rendered by the extractive species. Economic analyses will have to recognize and account for the values of the environmental/societal services of extractive crops to estimate the true value of these IMTA components. Economic analyses will need to be part of the overall modelling of IMTA systems, as they get closer to commercial scale and their economic benefits and costs, as well as their 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. They will have to include the pricing and marketing potential and impact of organic and other eco-labelling s, the value of biomitigative 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 of aquaculture (including food safety, food security, and consumer attitudes toward buying sustainable seafood products). This would create economic incentives to encourage aquaculturists to further develop and implement sustainable marine agronomy practices such as IMTA, and would increase the societal acceptability of aquaculture by the general public. Seaweeds and invertebrates produced in IMTA systems should be considered as candidates for a variety of regulatory measures that internalize these benefits. For example, nutrient and carbon trading credits (NTC and CTC) could be used to promote nutrient removal, CO_2 sequestration, oxygen provision, and coastal eutrophication reduction 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.

Nutrient extractive aquaculture appears to be a viable ecological engineering option for managing/internalizing some of 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. 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, environmental nongovernmental organizations, 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 Research & Development, outreach and technology transfer, and NTC and CTC incentives), then the development of IMTA will be encouraged.

Caution: Let's Not Promise the Moon and Let's Be Conscious of Societal Constraints, Particularly in the Western World

During the last few years, there has been a renewed interest in the mariculture of seaweeds and their uses, something that should make phycologists and ecologists rejoice, as this group of organisms, never clearly systematically circumscribed, has been misunderstood, unappreciated and under/misused over the centuries. There is now an opportunity to explain what seaweeds are, and the many applications, benefits, and services they can provide. However, how can people do that appropriately and responsibly, without "promising the moon" that they will not necessarily attain, and risking another "purgatory period" in between each energy crisis?! Seaweeds (and algae in general) made the news in the 1970s-1980s; they are back in the news now (2000s-2010s). If people are not careful to distance themselves from charlatanistic claims, which abound in the media and even in certain scientific circles, they could be in a situation of not developing a sustained public interest and use of these organisms, but be in another phase of denial until the next fad cycle (2030s-2040s?), which is not productive for the acquisition of still much needed scientific knowledge, nor the teaching of our discipline or the placement of our in-between fashion students. While everyone wants the seaweed sector to develop, some biotechnological issues and societal constraints, particularly in the Western World, should be recognized and a responsible and gradual implementation strategy for the long term should be adopted.

The western marine biology community has been dominated by people who have received a mostly zoological training from kindergarten to high school, very often reinforced by a monospecific (or monogrouping) specialization at university, instead of receiving and developing an ecosystem approach to knowledge and issue solving, which are then sadly missing when concepts of ecosystem-based management, species cocultivation , and interdisciplinarity are mentioned. Not surprisingly, the knowledge of seaweeds and their functions and services in/to the ecosystem is reduced and remains at universities and research institutions that have been wise in keeping their diverse expertise, instead of succumbing to fad cycles, which, then, force them to periodically reinvent the wheel. The consequence is that every time one wants to raise the possibility of using seaweeds in research and development and commercialization (R&D&C), one has to go through a lonely period of "preaching in the desert" before facts and common sense start to prevail.

One key, common, and deeply rooted misunderstanding to shake from the minds of people is that there is more than fish in the ocean! Over the centuries humans have been quite minimalist in their meat choices: four mammals (cow, pig, sheep, and goat) and four poultry (chicken, turkey, duck, and goose), hence, Paul Greenberg's idea of four fish (salmon, sea bass, cod, and tuna) for the title of his book [8]. However, the ocean cannot function with only fish, and the seafood solutions cannot come from within only this group of organisms. Maybe the problem resides deeply among the English-speaking people with this overuse of "fish": fish is a noun, which can even encompass shellfish and seaweeds in its general use, and fish is a verb… if you go harvest seaweeds along the shore you could be paradoxically fishing seaweeds, which for a Cartesian French-speaking person does not make much sense! In French, there is "poisson" as a noun and "pêcher" as a verb, even if both come from "pisces" in Latin. So, when a French person "va à la pêche," it is not necessarily to get a fish, but also to go "à la pêche aux moules" (mussels), "aux oursins" (sea urchins), or "aux algues marines" (seaweeds, for which many languages also have a higher opinion, as marine algae, instead of weeds of the sea!). To function, IMTA requires, in fact, not four components but five: the fed organisms (e.g., fish or shrimps), the extractive inorganic component (e.g., seaweeds or other aquatic vegetation), the extractive small organic component (e.g., suspension feeders such as shellfish), the extractive large organic component (e.g., deposit feeders such as sea-urchins, sea cucumbers, or sea worms), and certainly a fifth component, the microbial component, of which presently not much is known. So, if people want aquaculture to work, they have to stop being obsessed with fish aquaculture! Paradoxically, it is interesting to know that fish aquaculture , of which so much is heard, represents, in fact, only 9% of the total mariculture (aquaculture in the marine environment). Shellfish aquaculture represents 43%. Seaweed aquaculture represents even more (46%), but 99.8% of it is carried out in Asia, hence the ignorance in the western world [46, 47].

It is also important to understand that sustained successful ventures rarely happen overnight and that more than a 3 year grant is generally necessary to successfully take a concept along the R&D&C continuum. For example, the IMTA program on the east coast of Canada is starting to collect the fruits of its tireless efforts as it enters its 15th year of activities, which so far could be divided into four periods: (1) the "preaching in the desert" period from 1995 to 2000 [48], (2) the R&D proof of concept period from 2001 to 2006, (3) the R&D&C pilot scale period from 2006 to 2012, overlapping with (4) the R&D&C industrial-scale and networking period with the establishment of CIMTAN since 2009. People, consequently, have to stay away from claims of solving hunger in the world, converting everybody into frequent direct "seaweedivores," 100% biomitigation (which, in fact, is not necessarily the goal), renewing energy at unbelievable rates that defy the rules and equations governing photosynthesis , and all that within the next 5 years with the almighty, miraculous seaweeds and micro-alga e!

If there is no shortage of interesting ideas that work at the small demonstration scale, the problems generally appear when scaling up is contemplated and people start to realize what the consequences will be and, especially, the realistic, or unrealistic, deployment footprints required to implement these experimental ideas to commercial-market scales, which should make sense from environmental, economic, and production perspectives and also have an acceptable societal impact.

People should also stay away from the cliché that around 71% of this planet is covered by oceans and that, consequently, there is a lot of space for aquaculture development. If aquaculture will most probably expand into more exposed and open ocean locations in the future, due to the reduced availability of new and appropriate sheltered nearshore sites, it is doubtful that one will see farms in the middle of the Atlantic, Pacific, and Indian Oceans, due to simple logistics and weather issues. Moreover, the present international law of the sea is not that comforting for privately owned equipment (farms in this case) found at sea. The vagueness of territorial jurisdictional competence in the Exclusive Economic Zone (EEZ) in different countries, and certainly in international waters, has been a major impediment to progress of the so-called offshore aquaculture . Moving to the open ocean has been considered a means for moving away from environmental and public perception issues in the coastal zone. However, this move should not encourage an "out of sight, out of mind" attitude, as open ocean development will also come under scrutiny by a more and more educated public. Even if greater residual currents, deeper waters, and lower nutrient baselines are expected to reduce impacts from open ocean operations through wider dispersion plumes of nutrients, as compared to similarly sized nearshore operations, there will be a point when reasonably accessible and manageable open ocean ecosystems will eventually reach their assimilative carrying capacities. Why should one think that open ocean aquaculture, the "last frontier," will be without its own border/limits? Despite the sea being so immense, one is now learning the hard way the concept of overfishing … Instead of taking the position that in open ocean environments the hydrodynamic conditions will be appropriate for dispersion (a way of exporting problems, not solving them) and reduced environmental impacts (but at a significant cost in lost food), the open ocean aquaculture sector will also have to capitalize on recapturing the by-products of fed aquaculture and, hopefully, engineer, right from the beginning, efficient open ocean IMTA systems with their built-in biomitigative functions. The solution to nutrification in the open ocean environment, like in the nearshore environment, should not be dilution, but extraction and conversion through diversification. Why repeat what was done with the development of nearshore aquaculture (fish aquaculture development in the 1970s and IMTA development in the 2000s) with open ocean aquaculture (moving the fish to the open ocean in the 2010s … oh, the extractive species should have also been moved in the 2050s!)? These open ocean systems will also require trophic diversification from an environmental and economic perspective, with "service species" from lower trophic levels (mainly seaweeds and invertebrates) performing ecosystem balancing functions while representing value-added crops [49, 50]. Open ocean IMTA should not be an afterthought for 2050.

For some, the ecological, engineering, economic, and social challenges remaining to be solved may be daunting. However, our 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. There are no simple solutions, but one thing is certain - the human population is increasing on this planet and as people get richer, and their standards of living increase, they want more meat and dairy products in their diet, the temptation of the "western diet," while, ironically, Westerners aspire to change their diets! Will terrestrial agriculture be able to continue to supply most of this food? A balanced and responsible diet is required, and some of this food will have to come, increasingly, from aquatic food production systems, be them in seawater, brackish water, or freshwater. As was the case on land, where the acquisition of food by hunter/gatherer societies had to evolve toward agricultural practices, humans will have to accept an evolution in seafood procurement. It has to be understood, particularly in the western world, that "the modern global supermarket has a basic internal ecology" [8]. The average consumer is not a "foodie" and is not that interested in or cannot afford local, seasonal, less-than-100-miles food if not rich enough or not living within a region graced by a clement climate year long. The modern supermarket wants guaranteed supply on a 12 month basis, with limited variability in seasonality and quality. Most of the time, agricultural products can provide that comfort, barring the occurrence of an unexpected disease, contamination, drought, flood, economic protectionism, or political barrier. The seafood counter is a much more variable department to manage, at the present time, with a convoluted succession of many intermediates before seafood arrives on ice at a supermarket. It is interesting to note that the aquaculture industry's ability to provide 12 month availability of its products, moreover of consistent quality, is improving.

People are presently witnessing the emergence of a plethora of organizations developing their own standards and eco-label/certification schemes as they jockey for position in the global marketplace. The problem is that there are presently too many possible horses to ride and nobody really knows which one(s) will cross the finish line and, consequently, which one(s) to bet on as worth being associated with. One can only wonder what will happen when so many fisheries and aquaculture operations will be eco-certified. If everything is certified, nothing will be certified … and certification will lose its aura the same way some argue organic labelling is losing its significance, after having been used and overused. All that, of course, to the great confusion of the consumers, who cannot follow this contradictory debate/competition among standard setters, and may decide to simply stay away from seafood all together when, in fact, seafood products are healthy [51]. One of the problems is that some of these standards are passing or failing grades, with no incentives for continuous improvement from a minimal baseline to be decided, followed by a tiered approach. Some argue that it would give accreditation to companies at a very low level. However, putting the bar so high is not a recipe for gradual improvement of everybody involved, to progress and gradually reach the ultimate goal, although admittedly not overnight. If 20% of the global farmed seafood producers are certified at the highest threshold, what happens to the remaining 80% and the chance of incentivizing them to improve their practices? What happens when, in a bay management area, several aquaculture companies have taken the appropriate measures to be certified, but a "black sheep" (should it be a black cod?!) makes the whole certification scheme crumble once the hydrodynamics of the bay are considered? By analogy, in which the vector this time is not water but wind, one sees the same dilemma in parallel agriculture situations where conventional and organic agriculture practices are separated by illusionary buffer zones. On one hand, one can understand the desire by suppliers and retailers to see a hard to meet certification scheme so as to differentiate themselves from the others (most probably amounting to the privilege of displaying a sticker or logo on the packaging); on the other hand, too high a certification carrot, or moving goalposts, may not be the best strategy if progress toward overall better and more responsible aquaculture practices is the goal. The market will ultimately decide who remains in the competition and which logo(s) will be trusted by the general public, but there still are several years of confusion ahead.

Agricultural development has been associated with significant changes in landscape and land use; one can expect that the evolution of sourcing one's seafood more and more through aquaculture will also trigger significant "seascape " and "sea use" modifications, all the way to one's deepest human social structures and governance. The transformation from hunters/gatherers to farmers happened many centuries ago on land. Humans are in the middle of this transformation at sea and that is maybe why they are so uncomfortable with this evolution they are part of, and not able to sit back and analyze without being emotional. It is up to them to be a link in the chain, which will hopefully lead to fishing and aquaculture practices done right, enabling them to become herders and farmers of the sea. It should not be forgotten that they 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 market and marketing issues and the biological, environmental, economic, technological, engineering, and regulatory issues of aquaculture developments , the basic question will be that of societal acceptance. Are humans ready to evolve in their 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 and birds, 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-hungry human population? Despite all the campaigns, boycotts, documentaries, books, seafood pocket guides, scare tactics, sustainable/local/seasonal movements among affluent restaurant goers in weather clement regions and western world well offs, one can only admit that the global human population continues to grow and eat more seafood than ever per capita per year. So, where does that leave people? Paul Greenberg wrote that very often people consider fish as "a crop, harvested from the sea that magically grew itself back every year. A crop that never required planting" [8]. But are they investing in the principal, being in fisheries or in aquaculture, to only harvest the interests every year so as to not reduce/eat the capital for long-term sustainability? Are people ready to put some savings aside in the form of Marine Protected Areas (MPAs) , not only for their natural beauty, but also for their functions in the ecosystem such as breeding grounds, nursery habitats, and food production areas? It seems that the concept of zoning the sea, or what is now called, in a softer terminology, "marine spatial planning" (MPS) , is finally starting to be legislated in some countries, notably in the UK and the USA.

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 into large multipurpose integrated food and renewable energy parks (IFREP) could be a means for reducing their cumulative footprint, while integrating green energy with food and fuel production and processing [52]. Our business models will have to change from "one species - one process - one product" to a streamed bioeconomic chain, or web, approach among different industry sectors for the production, on one hand, of a wide range of bio-based, high-valued food and feed products/ingredients/supplements, specialty fine and bulked chemicals, agrichemicals, biostimulants, pharmaceuticals, nutraceuticals, functional foods, cosmeceuticals, botanicals, pigments and, on the other hand, lower-valued commodity energy carrying molecules/biofuels, all of them produced within reduced footprint requirements. The synergies and the services rendered by cultivating organisms of different trophic levels in an integrated manner will have to be understood and valued. The physiological, biochemical, and production performances of the different organisms will have to be improved to make the systems even more efficient, profitable, and competitive. The aquaculturists and different multi-sector end users will need to become interdisciplinary in their approach and learn to collaborate and share/integrate the biomass cultivation and processing steps (production, harvesting, pretreatment and transportation, separation and fractionation, and sequential biomass processing), while aiming at the lowest resource and energy inputs. Culture diversification into species that might otherwise be inappropriate for food markets fits well within the sustainability and management concept of IMTA. Functionalities will have to be maintained, as much as possible, along the process for optimal use/valorization of the multipurpose biomass, and not necessarily the maximization of just one end product, as some coproducts will, in fact, reveal themselves as the real drivers of the emerging integrated sequential bio-refinery (ISBR) concept [53], extended to macro-algae instead of only considering micro-algae . Market volumes/values, biomitigative services, and public acceptance will have to be included and fit into the models.

If the "Not In My BackYard" (NIMBY) and the "Build Absolutely Nothing Anywhere Near Anything" (BANANA) attitudes continue to prevail, especially in the western world, then humans will not be able to secure their food, chemicals, and energy in an intricately interconnected ecosystem responsible manner, despite all the rhetoric heard today regarding alternative technologies and solutions (the so-called "greenwash "). Self-sufficiency of humans will not be ensured but will become dependent on other food, chemicals, and energy "masters," who may no longer be in the Middle East but instead in the Far East (99.8% of the 15.8 million tons of cultivated seaweeds come from China, Indonesia, the Philippines, Korea, and Japan [46, 47]). It is time to walk the talk and recognize the implications - notably regarding marine spatial planning and our societal production and food habits - of the policies elaborated for the future.

The 1960s were the time of the "Green Revolution " on land, but some would question if it was really "green" (increased dependence on synthetic fertilizers and irrigation to increase crop yields per hectare at the expense of long-term soil health and yields per unit of input; increased dependence of indebted farmers on multinational producers of seeds, increasingly genetically modified, and which have not always delivered the touted benefits). It was thought that the sea was so immense that one needed not to worry about fishery limits, but now it is known that it is not always the case with many examples of overfishing of some populations. The 1980s were the time of the "Blue Revolution" of aquaculture development at sea, but it is also known that it is not always "green." It is, consequently, time to make the "Blue Revolution " greener; it is time for the "Turquoise Revolution" to move aquaculture to a new ERA of Ecosystem Responsible Aquaculture at sea and on land, in seawater and freshwater, and in temperate and tropical regions.

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