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Prospects for Integrated Multi-Trophic Aquaculture (IMTA) in the Open Ocean

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As the demand for seafood is rising worldwide and the availability of appropriate sheltered nearshore sites is more and more reduced, the aquaculture industry is looking at expanding into more exposed and open ocean locations. Open ocean development will not be unlimited, however, as the vast oceanic systems have their functional and resource limitations. It will be important to develop the right design of open ocean aquaculture operations, that includes extractive species to carry out the biomitigating functions of the systems. It is expected that, because of economies of scale, the open ocean farms of tomorrow will be larger than the present nearshore farms. Higher levels of waste will be generated due to their inherent assimilative inefficiencies. Instead of taking the position that hydrodynamic conditions in open ocean environments will be appropriate for dispersion and reduced environmental impacts (but at a significant cost of lost food), the aquaculture sector should capitalize on the by-products of fed aquaculture to recapture what is food and energy for extractive aquaculture and engineer efficient integrated multi-trophic aquaculture (IMTA) systems.

The challenges will be numerous from the biological, environmental, economic, technological, engineering, regulatory and societal perspectives. Appropriate extractive species will have to be selected based on their biology and the culture methods and harvesting technology will have to be adapted to exposed conditions. High value-added markets will be needed to justify their culture within expensive infrastructures, as they generally have a lower value than fish. The profitability of open ocean IMTA systems will have to be demonstrated. Early bio-economic models of nearshore IMTA indicate that economic diversification and reduction of risks are keys to increasing the profitability of these systems over finfish monoculture. The same arguments can probably be used for open ocean IMTA operations. Moreover, if the environmental, economic and societal services and benefits of IMTA are properly estimated and internalized, they will provide significant incentives for cultivating extractive species. These species could be considered for nutrient trading credits in the global economy, as the aquaculture sector moves to become more efficient and sustainable, possibly by becoming a partner with the large wind power generation and biofuel projects of the future.

Introduction

The global seafood market is at a crossroad. While landings by capture fisheries have leveled off, and many fish stocks have reached their plateau or collapsed, demand for seafood has been rising steadily, leading to the rapid expansion of aquaculture.[1] A significant increase in aquaculture output will require expansion into more exposed, open ocean, locations, as the relatively sheltered nearshore sites appropriate for aquaculture, such as in the Bay of Fundy, have already been developed and not many others are available.

Moving to the open ocean has also been considered as a means for moving away from environmental and public perception issues in the coastal zone, already sought out by many stakeholders. This move, however, should not be seen as an "out of sight, out of mind" attitude, as open ocean developments will also be under scrutiny by a more and more educated public. Even though wastes will be more diluted through larger dispersion fields, it is likely that these operations will need, economically, to be much larger than farms in nearshore waters. This implies more wastes will be generated, particularly when one considers that animals are generally poor converters of food into somatic tissues. The solution to nutrification should not, as has been the case throughout history in most western countries, be dilution. Even if greater residual currents, deeper water and lower nutrient baselines are anticipated to reduce impacts from open ocean operations through wider dispersion plumes of nutrients, as compared to similarly-sized nearshore operations, there is a point when open ocean ecosystems will eventually reach their assimilative carrying capacities. We thought the sea was so immense that we did not need to worry about fisheries limits, and this is not the case. We thought the "Blue Revolution" of aquaculture development was benign, and this is also not the case. Why should we think that open ocean aquaculture, the "last frontier", will be without its own borders/limits? Moreover, our rudimentary knowledge about linkages between open ocean and nearshore systems could also result in unpleasant surprises.

This suggests that mitigating approaches should also be used in open ocean operations. Thus, conversion into other crops of commercial value, not dilution, should be applied to open ocean development as well as to nearshore environments.[2] Trophic diversification is required from an environmental and economic perspective, with "service species" from lower trophic levels (mainly seaweeds and invertebrates) performing the ecosystem balancing functions while representing value-added crops. Various approaches have been suggested to improve the deficiencies of the "Blue Revolution".[3] One such responsible practice is the development of flexible integrated multi-trophic aquaculture (IMTA) systems for a greener "Turquoise Revolution". The IMTA concept is based on an age-old, common sense, recycling and farming practice in which the by-products (wastes) from one species become inputs for another: fed aquaculture (fish or shrimp) is combined with inorganic extractive (seaweed) and organic extractive (invertebrate) aquaculture to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and societal acceptability (better management practices). IMTA is also a practical approach that provides additional revenues, as food and energy (which represent approximately 60% of the operating costs of nearshore finfish farms) can be recaptured and converted into crops of commercial value, instead of lost by dilution in a finfish monoculture.

Open Ocean IMTA—Realities and Constraints

It is important to clarify that open ocean, or offshore, aquaculture is not a question of distance from the coast, but one of moving from sheltered to more exposed habitats, which in some parts of the world can be found within less than 3.7 km (2 nautical miles) from land, whereas other aquaculture sites 18.5 km (10 nautical miles) offshore, but in inner seas, are still experiencing conditions described as sheltered.

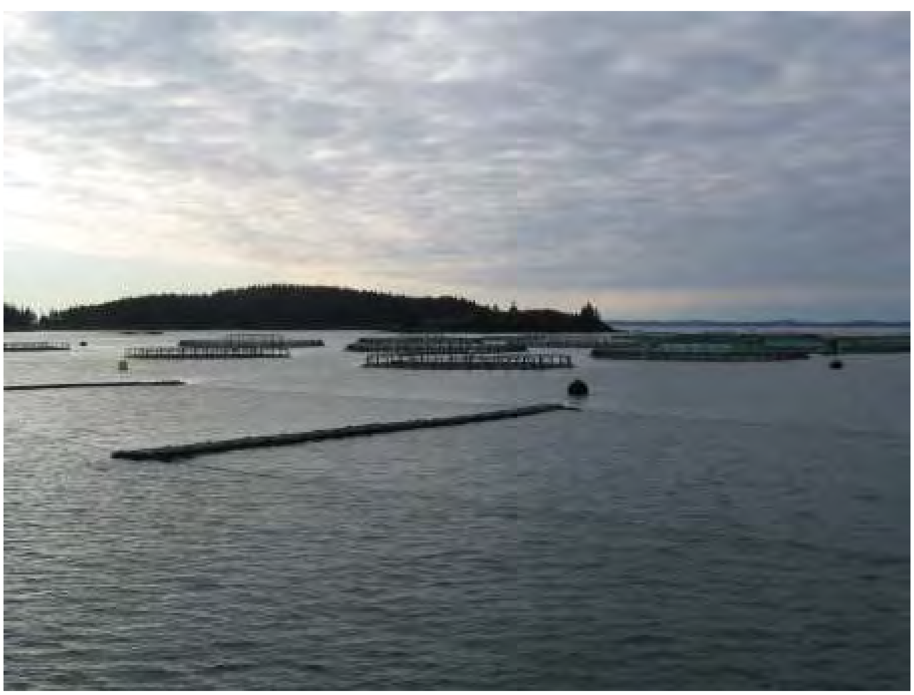
Over the last 20 years, there has been renewed interest in IMTA systems in the western world.[4] They, however, have remained at the experimental or small commercial scale (Fig. 1). It is difficult to extrapolate from limited nearshore IMTA experience to the unknown of open ocean IMTA commercial operations. Open ocean large-scale multi-trophic sea-ranching and suspended cultures do exist in China,[5] but their relevance to western socio-economic models is questionable.

At the present time, designs of finfish open ocean operations can be grouped into two categories: submerged and surface operations. In the first scenario, the distribution of nutrients will be different from that at shallower nearshore sites. The bulk of the nutrients will be released at a relatively greater depth. Organisms of the organic extractive component can be submerged to some extent, but seaweeds being photosynthetic organisms need to remain relatively close to the surface (based on light availability). If open ocean sites do not experience upwellings, such ascensional movements will have to be engineered. Surface open ocean designs will be simpler and more efficient regarding the functioning of the extractive species. Moreover, designs involving a one-point mooring system will enable the extractive species to always be in the zone of nutrient dispersion. In Canada, the first into the open ocean aquaculture field will probably be the salmon industry, so engineering will have to be developed to accommodate this effort.

Open ocean waters may have lower nutrient concentrations than nearshore waters and the presence of the fed component should improve the growth of the extractive species, which would otherwise have difficulty there in large amounts, due to the relative lack of food and energy. This will certainly be highly geographically specific. For example, mussels have grown quickly in open ocean operations off New Hampshire,[6] and have very high meat yields, suggesting they are not food limited.

Contrary to fish, which are pelagic, most extractive organisms are benthic and are often either attached to a substrate or living within it. The success in aquaculture is to make these organisms attach to artificial substrates: attachment or entwining by holdfast to ropes and nets for seaweeds, by byssus to ropes or socks for filter feeders such as mussels, or by burrows for polychaetes. An important aspect for open ocean IMTA to determine is if such organisms will be able to withstand the hydrodynamic forces at these sites. This has rarely been tested and demonstrates the need for specialized equipment.[7,8]

Figure 1. Small commercial scale IMTA site in the Bay of Fundy, Canada, where seaweeds (*Saccharina latissima* and *Alaria esculenta*, front), blue mussels (*Mytilus edulis*, first line of cages) and salmon (*Salmo salar*, other cages in the background) are cultivated **(photo by T. Chopin).**



The inorganic extractive component: seaweeds

For open ocean systems, the primary goal will probably be the maximization of seaweed areal yield and not nutrient reduction efficiency (which is a more typical approach of land-based recirculation systems). Therefore, a significant fraction of the dissolved nutrients may remain in the seawater, but there will still be a net removal of nutrients when the seaweed biomass is harvested.

Most seaweed culture methods have been designed for sheltered conditions (suspended ropes, suspended nets or off-bottom monolines).[9] Moving to exposed conditions will require a complete rethinking of the culture techniques, infrastructures and possibly species. Materials of higher resistance and improved anchoring systems will be needed. Selective thinning of the seaweed biomass is a common harvesting method that implies frequent visits to the sites; in the open ocean context this will have logistical implications.

Even if increased water transparency (reduced turbidity) in open ocean waters permits culturing seaweeds in deeper waters, they will still be cultivated near the surface and over a relatively large area, as seaweed cultivation is almost a two dimensional system using a small vertical dimension of the water column as compared to fish and organic extractive organisms.

The organic extractive component: filter and deposit feeders

Pilot projects have demonstrated the technical feasibility and rapid growth rates for blue mussels (*Mytilus edulis*) grown in open ocean environments.[6,10] The deployment of mussels in the deeper, less turbulent environment found in open ocean conditions resulted in thinner shells and more meat.[10] Mussels deployed at a summer flounder (*Paralichthys dentatus*) open ocean cage site had an average growth rate of 1 mm/wk and meat yields (percent cooked meat weight divided by total cooked weight) ranging from 44 to 58%.[6] These are encouraging results and suggest mussels would be good candidates for open ocean IMTA operations.

Modelling results from nearshore IMTA systems show that while filter feeders are excellent biomitigating organisms for the extraction of small organic particulate matter, deposit feeders will also need to be added to the systems for better efficiency at recapturing the food and energy entrapped in the larger particles.

With the development of open ocean IMTA in waters of considerable depth, the cultivation of bottom deposit feeders could present challenges making that component economically prohibitive if they are grown on the sea bottom. Mid-water systems of suspended trays, or other artificial reef structures, below the fish cages will need to be developed and will require significant effort in engineering design and testing. As with the inorganic extractive component, equipment and infrastructure for the organic extractive component will need to be rethought and dimensioned to the conditions prevailing in open ocean situations.

Open ocean, biofouling and the IMTA advantage

A key issue that will have to be considered with open ocean cage culture systems is biofouling. Open ocean sites will not remain monocultures. Similar to their nearshore counterparts, organisms will settle and grow on the structures. This colonization concept has been amply demonstrated on offshore oil and gas platforms in the North Sea and off California.[11-16] These platforms have been described as some of the largest artificial structures in the marine environment,[14] and as such can carry significant loads of species that have settled from drifting larval forms. One platform was estimated to shed over 1 m^3 of mussels per day, through normal processes, that supported large numbers of sea stars on the bottom.[11]

Open ocean aquaculture sites will also create large structures on which drifting species attach. Biofouling will add to the stress loads on the structures by increasing the friction coefficients, hampering the inspection of the components and potentially accelerating the corrosion of some of the structural elements, hence creating physical damage to some parts.[15] For remote open ocean aquaculture sites that will not be visited for daily inspection, this could have some important operating consequences. The oil and gas industry, having faced these issues over the last few decades, has developed various antifouling strategies (*e.g.* cathodic systems) that will have to be adapted to the open ocean aquaculture industry.

Some studies have demonstrated that the succession of species settling on offshore oil and gas platforms are the same ones that settle on nearshore aquaculture cage sites.[11,15,16] The blue mussel is the dominant species and occupies most of the surface area of the structures. Sea anemones, such as *Metridium senile*, often eventually dominate the lower levels with various tube worms. Some of our observations on the IMTA system in the Bay of Fundy show that high densities of intentionally grown mussels can significantly reduce the settlement of other pelagic larvae (likely through ingestion). High densities of intentionally grown seaweeds can also significantly reduce the settlement of other algae on ropes (likely for the simple reason of being first to occupy the substrate and excluding the others by winning the early competition for space). These observations emphasize the point that if something is going to grow on your culture structures anyway, you might as well design the system for it to happen with species of commercial value to try to turn a biofouling nuisance into an IMTA advantage.

Species interactions and potential role of IMTA in disease reduction

Another biological issue to be considered is the interactions between species at the sites. Like offshore oil and gas platforms, open ocean aquaculture infrastructures will act as predator refuges for various species of fish and invertebrates, making them similar to fish aggregating devices (FADs) used in commercial fishing operations.[12] If disease agents are present, this will represent one vector that will need to be checked and hopefully controlled, perhaps through the use of vaccines.

Interestingly, recent studies[17] and our own unpublished data indicate that carefully chosen species in an IMTA setting have the potential for some disease control. Mussels are capable of reducing loads of the infectious salmon anemia virus (ISAV) in the water. Consequently, appropriately placed mussels around salmon cages could act as a possible biofilter for disease reduction or prevention.

Economics of open ocean IMTA

Economic feasibility studies on open ocean IMTA are rare. Some cost estimates have been made for a finfish/mussel system off New Hampshire, USA;[18] they are, however, based on hypothetical data with little allowance for risks and their management, which will be critical in determining profitability. Economic feasibility studies on nearshore IMTA are limited.[2,19,20] They demonstrate that integrating mussels and seaweeds with existing salmon monocultures can increase the profits of salmon farmers. This increase in profitability is compounded over time and grows with increased production and stocking densities.

IMTA is also an excellent tool for reducing and managing risks. A diversified portfolio of species will increase the resilience of the operation by absorbing price fluctuations of one species or the accidental catastrophic destruction of another. While some extractive species (*e.g.* mussels) may have a lower market price than fish species, especially in western-type aquaculture which favors carnivorous fish, others may be more valuable (*e.g.* scallops and polychaetes). However, the volumes that can be cultivated are often lower, resulting in a lower gross profit. To compensate for the higher costs of cultivating extractive species within high-tech open ocean infrastructures, their use and applications in high valued-added markets—such as in direct human food consumption (sea vegetables), nutraceuticals, cosmetics, bioactive compounds—will have to be systematically sought out.

If the costs of environmental degradation could be recognized and quantified, then the value of extractive species would increase and their "environmental and societal services" could be factored in, giving an advantage to farmers implementing IMTA. If there were limitations to nutrient emission, a farmer could expand finfish production if extractive species were also farmed, based on a system of nutrient (nitrogen, phosphorus, etc.) trading credits, similar to that of carbon trading credits, which would internalize the nutrient discharge mitigating properties of the extractive species. Better estimates of the environmental and economic benefits of IMTA to society could represent significant incentives for its implementation.

Discussion

Open ocean aquaculture will be an expensive venture. Its profitability remains to be demonstrated, especially when facing increasing prices for energy, fishmeal and fish oil; the high costs of engineering, construction, and reliable safety and monitoring systems; the cost of a specialized labour force; and risk uncertainties and the even lower commodity prices fish will reach (reduced profitability margins have already been experienced by the nearshore industry). Niche markets may justify the high fixed costs of open ocean aquaculture, but whether finfish such as salmonids can be cultivated profitably in open ocean systems remains to be proven.

IMTA could add to the profitability of open ocean systems through economic diversification and risk reduction. To reduce the entry costs and share the costs of developing technical solutions, open ocean aquaculture, including IMTA, should team up with other sectors considering open ocean development, such as the development of wind energy generation. In fact, the infrastructures developed for these other open ocean ventures could be amenable to becoming the pivotal anchoring systems of IMTA.

Open ocean aquaculture should, in fact, consider the IMTA option from the beginning if it does not want a repeat of what happened with intensive finfish nearshore aquaculture, where criticism necessitated the development of

Figure 2. Large commercial scale IMTA of kelps (*Saccharina japonica*), scallops (*Chlamys farreri)* and oysters (*Crassostrea gigas*) in Sungo Bay, Shangong Province, China **(photo courtesy of M. Troell).**

biomitigating practices such as IMTA. Including IMTA at the early stages, and not as an afterthought 30 years later, will lead to creating appropriate designs for environmental sustainability, economic stability and increased societal acceptability. As mentioned above, the bulk of nutrients will be at greater depth with submerged fish cages. Designing current turbines could create local upwellings, bringing nutrients closer to the surface; they could also double as electricity generators for the sites (also supplemented by wave, wind and solar power). Wave-energy breakers could also be designed around aquaculture sites to provide protection and to channel local currents to the turbines.

The spatial scale covered by the extractive species, particularly the seaweeds, will have to be large in IMTA open ocean systems (Fig. 2). This aspect has not really been addressed so far, nor have solutions been developed. Combining IMTA farms with wind power generating farms could be a means for reducing their cumulative footprint. Gigantic projects for the production of biofuel with terrestrial crops have been proposed in several countries, but the implications have not been clearly thought out. The price of some staple food crops used in traditional agriculture has already risen considerably due to competition for their uses as energy crops. To reach the American government's target of 30% displacement of gasoline with biofuels by 2030 using corn or switch-grass would require over 40.5 million hectares (100 million acres) of farmland,[21] equivalent to 1.7 times the total area of the provinces of New Brunswick, Newfoundland, Nova Scotia and Prince Edward Island (*i.e.* Atlantic Canada), or a little more than the state of California. Issues of irrigation on a planet already suffering from water availability problems, and of competition for land or deforestation occurring to make room to cultivate crops for biofuel production, have been ill-approached or ignored. Using organisms already living in water could be the real answer to address the above interdependencies, which have not been perceived or have been ignored so far. Kelps are, in fact, amongst the fastest carbon assimilators on the planet, with yields of up to 44.5 tons/hectare (18 tons/acre) compared to 11.2 and 24.7 tons/hectare (4.5 and 10 tons/acre) for corn and switch-grass, respectively.[21,22] The conversion efficiency of kelps is promising (0.43 g ethanol per gram of kelp carbohydrate).[23] The aquaculture sector should consider being involved in the elaboration of these large biofuel projects as a valuable partner, already having a lot of know-how and experience with regard to cultivation and infrastructure development.

Beyond the biological, environmental, economic, technological, engineering and regulatory issues of such developments, the basic question will be that of societal acceptance. Are we ready to industrialize 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, migration routes for marine mammals, recreational uses, and then finally deal with the concept of zoning some portions of the oceans (marine spatial planning) for large multipurpose integrated food and renewable energy parks (IFREP)?

As Jules Verne wrote more than 130 years ago, "tout ce qui est impossible reste à accomplir" (all that is impossible remains to be accomplished)...!

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