

# Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture

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## Abstract

Integrated multi-trophic aquaculture (IMTA) seeks to diversify fed aquaculture (e.g. finfish or shrimps) with extractive aquaculture, recapturing the inorganic (e.g. seaweeds) and organic (e.g. suspension- and deposit-feeders) nutrients from fed aquaculture for their growth. The combination fed/extractive aquaculture aims to engineer food production systems providing both biomitigative services to the ecosystem and improved economic farm output through the co-cultivation of complementary species. Major rethinking is needed regarding the definition of an 'aquaculture farm' and how it works within an ecosystem. The economic values of the environmental/societal services of extractive species should be recognized and accounted for in the evaluation of the full value of these IMTA components. Seaweeds and invertebrates produced in IMTA systems should be considered as candidates for nutrient/carbon trading credits. While organic loading from aquaculture has been associated with localized benthic impacts, there have also been occurrences of increased biodiversity and abundance of wild species in response to moderate nutrient enrichment and the use of infrastructures as substrates. To develop efficient food production systems, it will be important to understand and use the duality of nutrients (essential when limiting/polluting when in excess) to engineer systems producing them in moderation so that they can be partially recaptured while maintaining their concentrations optimal for healthy and productive ecosystems. Measures of species diversity, colonization rates, abundance, growth and ecosystem functions with respect to nutrient partitioning and recycling, species interactions and control of diseases could represent valid indicators for the development of robust performance metrics.

**Key words:** biodiversity, biomitigation, integrated multi-trophic aquaculture (IMTA), nutrient trading credits, positive aquaculture impacts.

## Introduction

Integrated multi-trophic aquaculture (IMTA) is 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

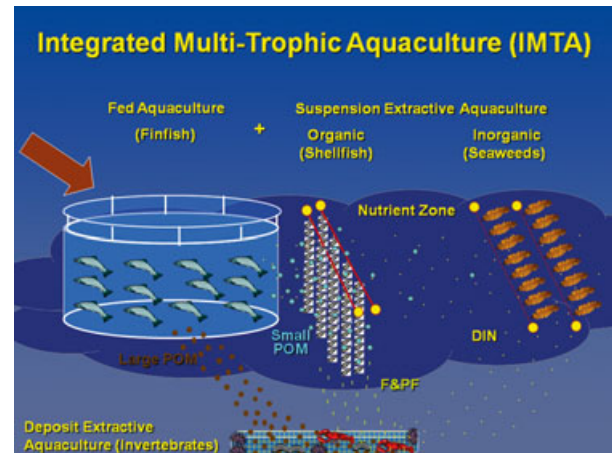
other crops, and to take advantage of synergistic interactions between species (Chopin *et al.* 2001, 2008; Troell *et al.* 2003; Neori *et al.* 2004). Farmers combine fed aquaculture (e.g. finfish or shrimps) with extractive aquaculture, which utilizes the inorganic (e.g. seaweeds or other aquatic vegetation) and organic (e.g. suspension- and deposit-feeders) excess nutrients from fed aquaculture for their growth. The aim is to ecologically

engineer systems for environmental sustainability (biomigrative services for improved ecosystem health), economic stability (improved output, lower costs, product diversification, risk reduction and job creation in coastal and rural communities) and societal acceptability (better management practices, improved regulatory governance and appreciation of differentiated and safe products) (Chopin *et al.* 2010).

This aquaculture practice is based on a very simple principle: ‘the solution to nutrification is not dilution, but extraction and conversion through diversification’, which is, in fact, another way of expressing the principle of conservation of mass, as formulated by Lavoisier (1789): ‘Nothing is created, nothing is lost, everything is transformed’. It is interesting to note that this famous quote is, in fact, an adaptation of the formulation of Anaxagoras of Clazomenae (c. 500 BC–428 BC): ‘Nothing is born nor perishes, but things already existing combine and then separate again’.

The IMTA concept is extremely flexible. It is the central/overarching theme on which many variations can be developed. It can be applied to open-water or land-based systems (sometimes called aquaponics), marine or freshwater systems, and temperate or tropical systems. What is important is that the appropriate organisms to be co-cultured are chosen at multiple trophic levels based on their complementary functions in the ecosystem, as well as for their economic value. Integration should be understood as cultivation in proximity, not considering absolute distances but connectivity in terms of ecosystemic functionalities (Barrington *et al.* 2009).

Our variation on the IMTA concept, in the Bay of Fundy on the east coast of Canada and in Kyuquot Sound on the west coast of Canada, has been systems combining initially the cultivation of a fed component (Atlantic salmon, *Salmo salar*, and Pacific sablefish, *Anoplopoma fimbria*, as finfish species) with an inorganic extractive component (the kelps, *Saccharina latissima* and *Alaria esculenta*, as seaweed species recapturing dissolved nutrients and carbon dioxide while providing oxygen) and an organic particulate extractive component (suspension-feeding shellfish such as mussels, *Mytilus edulis*, *M. trossulus* and *M. galloprovincialis*, scallops, *Patinopecten yessoensis*, and oysters, *Crassostrea gigas*, recapturing small organic particles). As we are taking this initial system from the experimental to the commercial scale, we are also adding an organic settleable extractive component near the bottom (deposit-feeding invertebrates such as sea urchins, *Strongylocentrotus droebachiensis*, sea cucumbers, *Parastichopus californicus*, or sea worms, *Nereis virens*, recapturing larger organic particles and suspension-feeding invertebrates such as sea cucumbers, *Cucumaria frondosa*, capturing re-suspended particulates) (Fig. 1).



**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 faeces and pseudo-faeces (F&PF) from suspension-feeding organisms. The bioturbation on the bottom also regenerates some DIN, which becomes available to the seaweeds.

There would be a fifth component to consider, the microbial component, of which not much is known presently.

### Rethinking what an ‘aquaculture farm’ should be and how it operates within an ecosystem

Instead of focusing on monospecific technological solutions, we will have to shift our aquaculture approach towards developing food production systems that consider species interactions, as pure mono-aquaculture is rarely the case and is more an abstract human concept. We already see a transition within capture fisheries away from single species stock assessment. There is an international emerging consensus that ecosystem-based fisheries management is essential for sustainable fisheries and that an ecosystem approach that takes into account target and non-target species, their interactions, as well as the ecosystem must be incorporated into the management planning process (Link 2010). Learning from the mistakes in the capture fisheries, we need to ensure that aquaculture management does not fall into the same cracks, and consider the cultivation of multiple species in proximity and their interactions with each other and with wild species.

As we are practising IMTA, we are starting to understand some species interactions, which could prove to be positive from the perspective of disease controls. For

example, in laboratory experiments, it has been shown that blue mussels are capable of inactivating the infectious salmon anaemia virus (ISAV) in Atlantic salmon (Skår & Mortensen 2007). Blue mussels, and other shellfish such as scallops (*Placopecten magellanicus*), can ingest copepodids, the planktonic and infectious stage of sea lice, *Lepeophtheirus salmonis* (Shawn Robinson, pers. comm., 2010; Molloy *et al.* 2011). Consequently, shellfish rafts could be placed strategically to serve as a kind of sanitary/biosecurity cordon around fish cages to combat some diseases. Using biofilters, such as shellfish, could enable some biological control of pathogen and parasite outbreaks, hence reducing the number of costly chemical treatments.

A major rethinking will also be needed regarding the definition of an 'aquaculture farm' by reinterpreting the notion of site-lease areas and regarding how it works within an ecosystem and in the broader context of integrated coastal zone management (ICZM), where integration can range from the small scale (a leased site with its spatial limits) to the larger scale of a region connected by the functionalities of the ecosystem.

If organic particles released by the fed component settle quite rapidly, dissolved inorganic nutrients travel longer distances; consequently, the understanding of their impacts and their mitigation should be approached and modelled differently. When aquaculture sites are located close to one another, the incursions of the nutrients released from different sites may overlap, especially in regions with significant tidal currents, and the site origin of the nutrients is not that important for biomitigating organisms such as seaweeds (Reid *et al.* 2011). The nutrient sequestration has, then, to be considered at the bay management level (as for diseases) and seaweed cultivation sites could be conceived as nutrient scrubbing stations (moreover earning nutrient trading credits, see below). Particulate nutrient removal by suspension- and deposit-feeder IMTA components needs to be much more specifically site targeted as the excess and undigested organic matter will accumulate under and close to fish cages (Reid 2011). It will also be important to consider that during their lives, the organisms of these two IMTA components will have also contributed to transform some of the organic material back to inorganic forms, hence contributing to the inorganic extractive component, which will need also to be considered at this level, underlining how intricate the different nutrient removal niches are and the difficulty in quantifying and modelling them.

### **Wastes or limiting: the difficult balancing act of nutrients in coastal ecosystems**

Nutrients are necessary in aquatic environments and for the organisms living in them. For example, the following

nutrients are considered essential for all algae: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), magnesium (Mg), copper (Cu), manganese (Mn), zinc (Zn) and molybdenum (Mo). Sulfur (S), potassium (K) and calcium (Ca) are required by all algae, but can be replaced partially by other elements. Sodium (Na), cobalt (Co), vanadium (V), selenium (Se), silicon (Si), chlorine (Cl), boron (B) and iodine (I) are required only by some algae (Lobban & Harrison 1994). However, like many ingredients for life, these need to be present in the right amounts and proportions, which generally means in moderation and within the assimilative capacity of the system. Ecosystem health and, consequently, biodiversity are influenced by nutrient concentrations and ratios. This is largely because the concentrations of limiting nutrients (typically N in marine systems and P in freshwater systems; Ryther & Dunstan 1971) frequently dictate the level of primary productivity. High nutrient concentrations may result in excessive primary productivity (eutrophication), where resultant algal blooms ultimately die, sink and strip dissolved oxygen from the water column upon decomposition. In extreme cases, the decomposition of organic material, whether from algae or direct anthropogenic sources (e.g. sewage) will cause so called 'dead zones' (Dodds 2006). 'Dead zones' have been a common re-occurring problem in the past half century, linked largely to the delivery of reactive nitrogen and terrestrial phosphorus to the oceans, which has increased threefold from pre-industrial agricultural times (Díaz *et al.* 2009). It is such negative impacts of excessive nutrients that are, unfortunately, so often associated with nutrients in general. However, low concentrations of nutrients may also have negative effects on ecosystem health, resulting in oligotrophic environments, with similarly low productivity and limited food sources. In fact, in some aquatic environments, such as freshwater highlands, the removal of nutrients is a significant concern, and methods to recycle phosphorus in a carefully controlled and ecologically sensitive way to restore sufficient fisheries production level, have been advocated (Stockner *et al.* 2000). Herein lays the paradox of nutrients. Too much or too little is 'bad', and arguably the relationship between nutrient concentrations and ecosystem health is perhaps more a quantity issue than a substance issue.

One of the biggest challenges in quantifying effects to ecosystem health, are considerations of scale and this is also true of nutrient availability. Most ecosystem services are delivered at the local scale, but their supply is influenced by regional or global-scale processes and, frequently, benefits accrued at one scale may result in costs at another (Carpenter *et al.* 2006). Ocean eutrophication from run-offs of agriculture fertilizers (Beman *et al.* 2005) is arguably an example of this. Ironically, fertilizers are

added to augment nutrient levels insufficient in the soil, as a means to increase crop productivity. In many parts of the world this results in large nutrient imbalances (more nutrients are added than removed within crops in, for example, the USA and China), with the 'extra' nutrient run-offs directed to surrounding waters (Vitousek *et al.* 2009) and ultimately the coastal zone. Issues of scale, transfer of costs to other regions and sensitivity (i.e. trophic levels) of the receiving environment require consideration.

The nutrient paradox, then, may be manifested at the management level as well. Should policies be applied to relevant scales? Should they be applied at the source of an impact, the receiving body or both (the total watershed)? In the case of nutrients, where addition or removal can be either positive or negative depending on the type of environment, scale of effects, assimilative capacity of the ecosystem and background concentrations, overreaching policies may be insufficient. For example, the application of nutrient trading credits (NTCs; see below) as an incentive to remove/reduce nutrients to mitigate or prevent eutrophication may have merit. However, would NTCs also be necessary/applicable to cases where moderate enrichment stimulates productivity and biodiversity in the environment? Credit systems (of carbon or other compounds) are often advocated for abatement policies where negative impacts have or could develop. Triggering positive impacts should also be recognized and, consequently, could also generate credits. It should, therefore, be kept in mind that advocacy of nutrient removal (e.g. via IMTA) or moderate nutrient enrichment (e.g. via fed aquaculture at an appropriate scale and complemented or not with IMTA) will be a function of optimizing ecosystem health at the scale or environment of interest.

### Recognizing and valuing the ecosystem services provided by extractive aquaculture

In recent years, large international conferences have focused on global warming, CO<sub>2</sub> emissions and carbon trading credits. Another key concern related to global ecosystem health, however receiving arguably less attention, is the increased nutrification of coastal ecosystems. It is, therefore, also important to introduce the concept of 'nutrient trading credits' (NTC). Inorganic and organic extractive aquaculture, independently or as components of IMTA systems, can play a key role in the sequestration of these nutrients. If various abatement measures exist for reducing nutrients on land, there are only a few removal options once they enter coastal ecosystems.

One often forgotten function of seaweeds is that they are excellent nutrient scrubbers (Chopin *et al.* 2001). If we estimate an average composition for seaweeds of

around 0.35% N, 0.04% P and 3% C, and NTCs which should be around US\$10–30 kg<sup>-1</sup>, US\$4 kg<sup>-1</sup> and US\$30 t<sup>-1</sup> for N, P and C, respectively (Chopin *et al.* 2010), the ecosystem services of cultivated seaweeds (15.8 million tons) are worth at least US\$592.5 million–US\$1.698 billion, hence as much as 23% of their present commercial value (US\$7.4 billion; Chopin 2011).

Similar calculations could be made for the organic extractive component of IMTA, paying particular attention to the sequestration of carbon with shellfish. Ferreira *et al.* (2009) estimated that the ecosystem goods and services provided by shellfish aquaculture towards reducing eutrophication in the coastal waters of the European Union should amount to 18–26 billion € per year.

The recognition of such significant biomitigative, or ecosystem services and their association with a system of nutrient trading credits, which still has to be put in place at a national or international level, should represent financial incentive tools to encourage mono-aquaculturists to contemplate IMTA as a viable marine agronomy (or aquanomy) option to their current practices. If we want to calculate correctly the full value of IMTA, we have to make sure that its value is not equated only to the value of the direct sale of the co-cultured species, but also includes the above credits and that a monetary value is also given to the following benefits it provides:

- Recapturing feed and energy otherwise lost and their conversion into other commercial crops. Feed represents around 60% of a finfish aquaculture operation; if that feed can be used more thoroughly and, in fact, several times, substantial savings could result even from small improvements in overall system feed conversion efficiency (juxtaposing all species production in the system with feed used).
- Increasing profitability and reducing risk through crop diversification. Ridler *et al.* (2007) demonstrated that IMTA results in a higher net present value (NPV) over 10 years compared with salmon monoculture. Mussels and seaweeds provide alternative uncorrelated sources of income, thereby softening the damaging effect of salmon losses when they occur and providing greater economic resilience to the overall operation. This should have impacts with bankers and insurers, and on government regulations and policies.
- Increasing the societal acceptability of aquaculture. We have conducted several attitudinal surveys with different groups (Shuve *et al.* 2009; Barrington *et al.* 2010); each one has demonstrated a greater acceptance of IMTA over conventional fish monoculture.
- Differentiating and eco-certifying IMTA products, which can command premium market prices. The IMTA salmon of our industrial partner, True North Salmon Company, is now commercialized as Wise



Source™ Salmon by the largest food distributor in Canada, Loblaw Companies Ltd., Brampton, Ontario, Canada. The IMTA salmon can only be differentiated if grown together with the extractive components, which should be credited for the premium price on salmon, on top of their intrinsic sale value.

### Changing consumers' perceptions and attitudes towards wastes and nutrients

Nutrients should not automatically be equated to wastes, especially in the western world. Consumers' perceptions and attitudes may have to change regarding recycling and recapturing at sea. After all, there is the good old saying 'What is waste for some is gold for others' entrenched in our common sense wisdom. Transposed to agronomy (and aquanomy), we could say 'What is waste for some species is nutrients for others'. Surprisingly, this seems to be readily accepted on land and for agricultural practices; why is it not at sea and for aquacultural 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 premium price for a perceived higher quality or ethical standard? For example, regulations require mushrooms to be grown specifically on farmyard manure and animal excrements to receive organic certification (European Community Regulations No 2008R0889 – Article 6). Confusion has been instilled in the perceptions of the consumer: people are accustomed to associating farmyard manure and animal excrements with organic agricultural farming. So, why such association cannot be transposed to IMTA, as a form of organic aquacultural farming, duly recognized through differentiation, eco-certification or eco-labelling and commanding premium market prices for its products?

### Positive environmental impacts of aquaculture and IMTA

Organic loading to the benthos from aquaculture produces similar effects to that of other sources. It is well known that as organic enrichment on soft bottoms increases, biota typically transition from a high biodiversity, to a greater abundance of more 'pollution' tolerant species (Pearson & Rosenberg 1978) until anoxia ultimately occurs. A good summary of the general effects of excessive benthic marine organic enrichment was given by Hargrave *et al.* (2008). Increased organic carbon flux to the benthos is ultimately accompanied by increases in total free sulphides with corresponding decreases in oxygen, pH, redox potential ( $E_{\text{NHE}}$ ) and biodiversity. The

Shannon-Weiner index, Hurlberts index, the infaunal trophic index, mean number of taxa and number of arthropod classes all report a decrease in biodiversity along with increases of organic carbon flux. It is important to note, however, that this transition illustrates resultant effects of increasing sulphides and decreasing oxygen as a response to organic flux. An organic flux that would be arguably 'excessive' would suggest that the rate of carbon flux exceeds the relative rate of assimilation. Under some conditions of moderate enrichment, it is, however, possible to observe significant biodiversity accompanying high abundance. Pearson and Rosenberg (1978) referred to this as the ecotone point or transitional zone, although this zone may be very spatially discrete. This may explain why in many aquaculture studies, which include measures of benthic biota, there are often at least some data reporting increased biodiversity relative to background levels, regardless of the study's overall conclusions.

It is important to note that it is difficult to measure positive impacts and to get a true picture because monitoring protocols, performance measures and metrics are mostly designed to identify negative impacts. However, under the right condition, right assimilative capacities and right scales, aquaculture practices can increase environmental and economic productivity and biodiversity.

In a review of aquaculture studies reporting benthic effects of organic deposition and published since 2000, we found that:

- Some studies reported measures where in some areas the benthic biodiversity near aquaculture sites increased relative to background levels (Karakassis *et al.* 2000; Brooks 2001; Dimech *et al.* 2002; Kempf *et al.* 2002; Brooks & Mahnken 2003; Macleod *et al.* 2006; Apostolaki *et al.* 2007; Kutti *et al.* 2007; Borja *et al.* 2009; Papageorgiou *et al.* 2009).
- Some studies reported some measures of increased species abundance and/or biomass (typically pollution tolerant species) but not necessarily increases in biodiversity (Karakassis *et al.* 2000; Brooks *et al.* 2003; Edgar *et al.* 2005; Felsing *et al.* 2005; Klaoudatos *et al.* 2006; Dimitriadis & Koutsoubas 2008; Borja *et al.* 2009; Nickell *et al.* 2009; Vidovic *et al.* 2009).
- Some studies reported either a decrease or no increase in biodiversity (Danovaro *et al.* 2004; Felsing *et al.* 2005; Gao *et al.* 2005; Aguado-Giménez *et al.* 2007; Fabi *et al.* 2009; Grego *et al.* 2009; Nickell *et al.* 2009; Tomassetti *et al.* 2009; Vidovic *et al.* 2009).

These aforementioned studies had a variety of objectives, occurred in a variety of environments and, consequently, employed a variety of sampling protocols. Moreover, these studies were often conducted at different geographical scales and analysing different levels of aquaculture intensification. Therefore, direct comparison

between them is not possible and we should be cautious of rapid generalizations regarding the effect of organic loading from aquaculture. However, a pattern appears to emerge: where a depositional gradient of organic material is not excessive and does not promote anoxia or hydrogen sulphide generation, there is the potential for positive contributions to biodiversity. As in many activities, 'doing it in moderation', and with the right practices, is often the appropriate approach. Managing aquaculture to avoid deleterious effects is one thing. Managing aquaculture deposition to promote increases in biodiversity or increased abundance of desirable species is another. Nevertheless, this is one of the conceptual objectives of open-water IMTA. While this aim has been typically implemented with cultured species at the site level, there are lessons to be learned studying conditions where aquaculture enriches natural biota and augments the success of feral species to assist with site design. For example, polychaetes have mitigated benthic effects under fish cages (Tsutsumi *et al.* 2005), while also providing an opportunity for 'aquaculture ranching'. In and around an artificial benthic reef, cultured species such as sea urchins (*Strongylocentrotus droebachiensis*) and giant sea scallops (*Placopecten magellanicus*), along with sea cucumbers (*Cucumaria frondosa*), longhorn sculpin (*Myoxocephalus octodecemspinosus*), winter flounder (*Pseudopleuronectes americanus*), rock gunnel (*Pholis gunnelis*), lumpfish (*Cyclopterus lumpus*), sea stars (*Asterias vulgaris*) and a variety of crabs and amphipods, have thrived in high enrichment conditions due to a multi-fold increase in elevated surface area, compared with a soft mud bottom (Robinson *et al.* 2011).

### Wild fish assemblages at aquaculture sites

The effects of organic loading to the benthos on species abundance and biodiversity of epibenthic and sessile species are arguably relatively easier to measure than with pelagic species. However, over the past several years there have been numerous examples of feral fish benefiting from the presence of fish cages. In some cases the effect has been so pronounced as to increase fisheries landings in oligotrophic seas (Machias *et al.* 2006). The reason for such enhancement may be either stimulation of localized productivity and consequent trophic transfer, direct consumption of fish farm organics, or the provision of a 'safe zone' from fishing pressure.

One experiment suggests a typical route of trophic transfer. Rainbow trout cages were established in a small oligotrophic lake with a well documented feral lake trout population (Mills *et al.* 2008). After the second year of rainbow trout farming, the lake trout growth and condition increased. There was no change in lake trout condition in

a similar adjacent control lake, without rainbow trout cages. The improvement in lake trout growth and condition was probably related to increases in fathead minnow and pearl dace, which in turn had responded to rainbow trout farm 'fertilizer' input. Since fathead minnows eat algae (Scott & Crossman 1973) and freshwater algae respond to phosphorus loading, this implies a typical route of trophic transfer.

This is, however, not always the case. Håkanson (2005) investigated changes to the ecosystem structure of lake Bullaren (Sweden) resulting from rainbow trout fish cage emissions and discovered significant increases in the lake biomass of wild fish, without corresponding increases in algal volume. This apparent circumvention of the expected trophic pathway, where secondary productivity is a function of primary productivity, may seem counter intuitive. However, these findings were related to the fact that wild fish directly consumed the fish farm organics (i.e. feed spill and faeces), thereby creating a specific foodweb pathway.

Marine research in this area has also been conducted. Fernandez-Jover *et al.* (2008) estimated that at some southwestern Mediterranean farms of sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) wild fish consumed up to 10% of feed pellets used. Twenty different juvenile fish species were found to settle these fish farms, where food pellets from the farm appeared to affect the food chain, modifying the fatty acid profiles of farm-associated zooplankton and juveniles of *Liza aurata* and *Oblada melanura* (Fernandez-Jover *et al.* 2009). It was suggested that the results from this study demonstrated that aquaculture organics can directly influence the body composition of wild juvenile fish that recruit to sea-cage fish farms. At other fish cages in the Mediterranean Sea, 80% of the particulate organic matter leaving the net-pens may have been consumed by wild fish before settling on bottom sediment (Vita *et al.* 2004). Significant changes in the nutrient quality of the organic matter exported were attributed to fish farm organic consumption by wild fishes. Vita *et al.* (2004) concluded that wild fishes play an important role in recycling organic matter of the sediment, and regulate the benthic community structure. Similar conclusions were also reached with an Australian study where wild fish have been reported as potential important consumers of cage aquaculture waste materials (Felsing *et al.* 2005).

Wild fish assemblages at fish cages may also result in part from protection against fishing. At fish cages of sea bream and sea bass in an oligotrophic coastal bay in the Aegean Sea, the overall abundance of the fish assemblage increased by a factor of 4 (Machias *et al.* 2006). Most of the wild fish recorded around the fish cages were not known to consume feed pellets. The authors suggested an

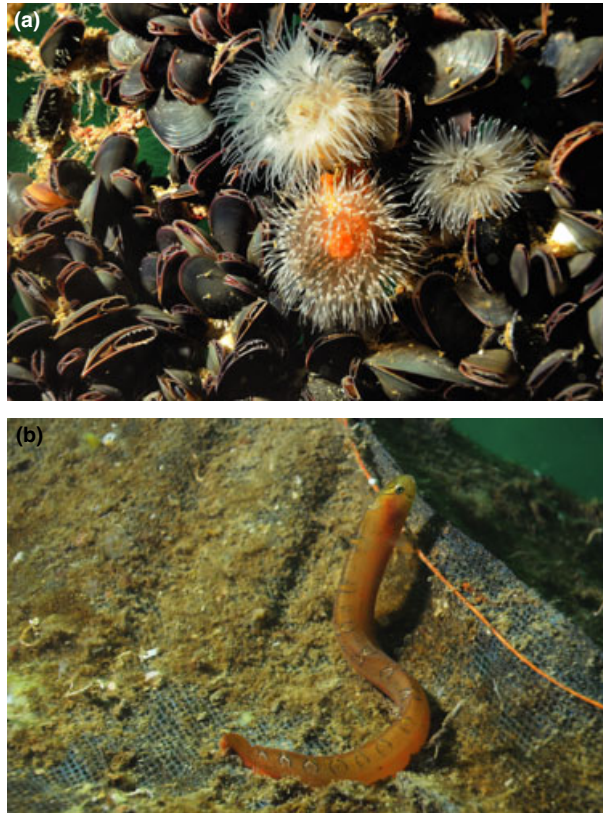
increase in primary production or a local reduction of fishing pressure due to the occupation of part of the marine coastal space by the fish farms as the probable reasons for the population increase. Submerged physical structures that provide some measure of habitat are well known to act as fish aggregating devices, even in the absence of an anthropogenic feed source.

Nevertheless, consumption of cultured fish fecal material by feral fish can be a significant 'export pathway'. This should not be surprising as faeces in natural aquatic systems are often very abundant, represent a repackaging of available organic matter, and are readily transported (Wotton & Malmqvist 2001). It is not uncommon for fish faeces to be consumed by other fish from different trophic levels (Bailey & Robertson 1982; Robertson 1982).

### Engineering biodiversity into IMTA

As indicated in the preceding section, many wild species can inhabit aquaculture sites and the surrounding area. There may be some degree of benefit from escaped nutrients associated with fed-aquaculture. These benefits are measurable (Rensel & Forster 2007) and indicate a clear nutrient effect for increased colonization and growth. To many, the response from wild species, also known as biofouling, is considered a nuisance to the industry. Through the concept of IMTA, this fouling can be used as a tool to not only measure nutrient availability but also the potential for nutrient recapture and recycling.

Nutrient availability is not the only factor to consider. The role of suitable habitat is also evident if IMTA is to engineer biodiversity for improved economic and environmental performance. Present fish aquaculture infrastructures, consisting of steel, plastic, ropes, nets, buoys, etc. offer already habitable substrates that would not normally be available in open waters. Within several weeks there is a typical colonization by a variety of organisms including mussels, sea cucumbers, anemones, tunicates, nudibranchs, hydrozoans and algae (Fig. 2a). These species either feed by capture of fine particulates or feed through absorption of dissolved nutrients and light. For this reason (as well as economic ones), species such as mussels and kelps are already important biodiversity components that have been applied to the IMTA approach. The introduction of three dimensional structures at IMTA sites is thought to present a significant opportunity to increase biodiversity due to increase surface area (Robinson *et al.* 2011). Colonization of new substrates initiates a succession of species, such as sea stars, urchins, fish and crustaceans (Fig. 2b), that are either attracted to newly available prey or the more diverse habitats provided by the colonized substrates. Over time, a complex community of species is created, representing different trophic

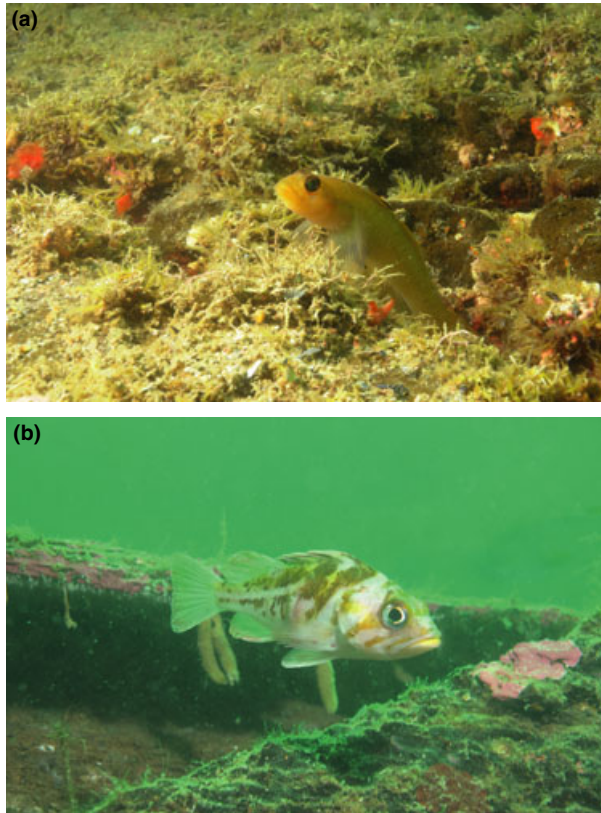


**Figure 2** Examples of wild 'near-field' species inhabiting an IMTA aquaculture site in Kyuquot Sound, British Columbia, Canada. (a) Mussels (*Mytilus galloprovincialis*) and plumose anemones (*Metridium* sp.) established and thriving within an aquaculture structure. (b) A crescent gunnel (*Pholis laeta*) caught sleeping on a pearl net for IMTA scallops (*Patinopecten yessoensis*).

levels that occupy the niche space offered by the aquaculture system. In the adjacent shorelines, a diversity of fish, large crustaceans and other marine life can be observed (Fig. 3) and suggests that these areas are not devoid of life and are both sources of wild species colonization and wild species response to the aquaculture infrastructure.

It is important that we understand the natural processes in biodiversity that take place around aquaculture sites if we want to design efficient IMTA systems. The Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) has begun to investigate the nature and spatial extent of wild species colonization and how it could be used to guide IMTA innovation and also quantify IMTA performance. If nutrients and conditions for colonization and growth are better near a fed cage site, then one might expect to observe a combination of higher rates of colonization, higher rates of growth and increased species diversity. We can determine what wild species are utilizing from the nutrients available from an aquaculture





**Figure 3** Examples of wild ‘far-field’ species in shoreline areas adjacent to an IMTA aquaculture site in Kyuquot Sound, British Columbia, Canada. (a) Blackeye gobi (*Coryphopterus nicholsi*). (b) Copper rockfish (*Sebastes caurinus*).

site, and, if monitored over time, how effective IMTA nutrient recapture and recycling can be.

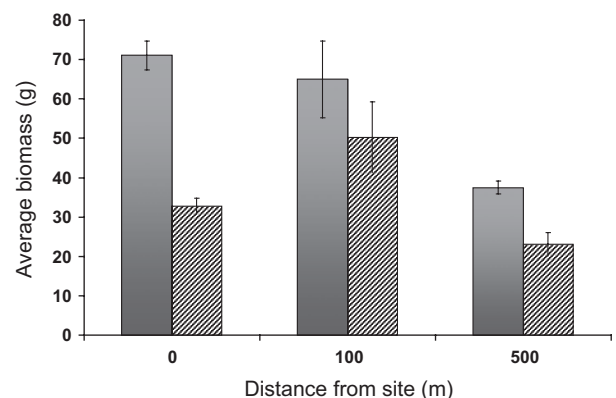
As part of a multi-year project, standardized biodiversity collectors, constructed of plastic plates (Fig. 4), have been deployed for periods of 9–14 weeks during the summer months of peak colonization and growth. This simple apparatus has begun to offer some interesting insights into the nature of nutrient availability and the complexity of establishing robust performance measures in the field. The collectors when positioned in areas that are both near and far from existing aquaculture sites, offer a controlled artificial substrate upon which one can measure the rate of colonization, growth and diversity of wild species. Most collector plates offer suitable substrates for biocolonization and several taxa typically dominate early settlement in all areas. Within a few weeks, species such as vase tunicates, bryozoans and hydrozoans visibly establish themselves. While the species composition is dependent on geographic area, these taxa are consistently first to be detected. The colonisation of other species such as molluscs, algae, nudibranchs, echinoderms and crustaceans



**Figure 4** One of a series of collector plates deployed at depths of 5 and 10 m next to an IMTA aquaculture site in Kyuquot Sound, British Columbia, Canada. This collector has been in the water for 9 weeks and has been quickly colonized by vase tunicates and hydrozoans.

seem to be much more variable, depending on depth and location relative to currents or settlement areas. Early colonizers in themselves may not necessarily offer commercial opportunities for IMTA, but they can serve as a rapid metric for conditions suitable to growth and production.

At the IMTA site on the west coast of Canada, collector plates were recently deployed at depths of 5 and 10 m and at distances of 0, 100 and 500 m from the sablefish cages. Collectors that accumulated the most biomass were not always the ones closest to the cages (Fig. 5) and presumably closest to the source of nutrients. At a depth of 5 m, the greatest biomass accumulation was observed next to the fish cages, with a slight decrease at 100 m and a significant reduction at 500 m ( $n = 35$ ,  $df = 2$ ,



**Figure 5** Biomass accumulation expressed in mean accumulated weight per collector ( $n = 12$ ). Collector plates were deployed in Kyuquot Sound, British Columbia, Canada, at fixed distances (0, 100 and 500 m) away from an active IMTA site and at depths of 5 (grey) and 10 (diagonal bars) m for a period of 9 weeks. Error bars,  $\pm$ standard error of the mean.



$F$ -ratio = 11.483,  $P < 0.005$ ). At a depth of 10 m, the greatest biomass accumulation occurred at a distance of 100 m ( $n = 36$ ,  $df = 2$ ,  $F$ -ratio = 5.889,  $P < 0.05$ ). There was also a consistent reduction in biomass accumulation with increased depth at each distance, with significant differences observed at distance of both 0 and 500 m. Not surprisingly, these early findings suggest that proximity to a nutrient source is not the only factor to consider in order to successfully engineer biodiversity into IMTA. For example, temperature was significantly higher ( $P < 0.05$ ) at 5 m ( $11.88 \pm 0.04$ ) than at 10 m depth ( $10.93 \pm 0.03$ ). Other environmental factors such as light, depth for colonization of spores, gametes and larvae, currents, salinity and native species are also site specific aspects to consider in order to objectively quantify wild species response and nutrient performance within an IMTA site.

These collectors serve as just one example of how wild species response surrounding an aquaculture site can be investigated. As indicated earlier, there is as much to learn about wild species biodiversity responses in the subtidal benthic communities, which tend to be exposed to high volumes of nutrient settlement, and along the adjacent intertidal zone and shore line.

### Increasing the resilience of aquaculture to climate change by the species and economic diversification provided by IMTA

It is now generally accepted that climate change is occurring and that this will have significant implications for the marine environment and, consequently, aquaculture. As this is likely to have species specific effects, it has been proposed to diversify species production as a form of insurance that offers adaptation possibilities under different climate change scenarios, especially unexpected events such as diseases or market issues (De Silva & Soto 2009). The diversified nature of IMTA will, by default, accommodate this. In some areas of the world where 'incidental IMTA' occurs, through the proximate location of farms culturing different species types (Duarte *et al.* 2003), the regional aquaculture industries may have greater potential for resilience.

### Conclusion

Integrated multi-trophic aquaculture proposes to biomitigate and diversify fed mono-aquaculture practices by combining them with extractive aquaculture to realize benefits environmentally, economically and societally. In order to achieve this, a major rethinking will be needed regarding the definition of an 'aquaculture farm' by reinterpreting the notion of site-lease areas and regarding how it works within an ecosystem and in the broader

context of integrated coastal zone management (ICZM). Biomitigative solutions, such as IMTA and its extractive components, should become an integral part of coastal regulatory and effluent/nutrient management frameworks.

A fundamental principle of IMTA is to mimic natural ecological processes in order to reduce environmental impacts by benefitting from improved use of nutrient loading, species interactions and diversified commercial products. Communications on waste management issues to stakeholders and the public would benefit from discussing nutrients in the context of optimal concentrations for the receiving ecosystem, given, on one hand, their essential nature and, on the other hand, their behaviour as pollutants only under excessive concentrations.

This engineering of biodiversity requires that we understand how it responds and changes within the 'near-field' and 'far-field' aquaculture environment so that objective and robust performance metrics can be developed. These changes could be observed in species diversity, colonization rates, abundance, growth, and ecosystem functions with respect to nutrient partitioning and recycling, species interactions and control of diseases. The 'near-field' and 'far-field' subtidal and intertidal areas are not devoid of life and each habitat offers IMTA researchers an opportunity to learn from the natural communities' responses to aquaculture and how the IMTA approach can mimic and benefit from them. These tools and metrics are yet to be developed and their practicality evaluated before they become useful in selecting a suite of indicators, acceptable to technical experts and advisors, the aquaculture sector, decision makers and regulatory agency managers, and the general public (Rice & Rochet 2005; Ward *et al.* 2011). Once adopted, they will be useful in assessing and monitoring the environmental, economic and societal benefits of IMTA, as a more responsible and diversified approach to aquaculture.

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