What is important is that the appropriate organisms are chosen based on the functions they have in the ecosystem, their economic value or potential, and their acceptance by consumers. While IMTA likely occurs due to traditional or incidental, adjacent culture of dissimilar species in some coastal areas (Troell *et al.*, 2003), deliberately designed IMTA sites are, at present, less common. Moreover, they are presently simplified systems, like fish/seaweed/shellfish. In the future, more advanced systems with several other components for different functions, or similar functions but different size ranges of organic particles, will have to be designed (Chopin, 2006).

The aim is to increase long-term sustainability and profitability per cultivation unit (not per species in isolation as is done in monoculture), as the wastes of one crop (fed animals) are converted into fertilizer, food and energy for the other crops (extractive plants and animals), which can in turn be sold on the market. Feed is one of the core operational costs of finfish aquaculture operations. Through IMTA, some of the food, nutrients and energy considered lost in finfish monoculture are recaptured and converted into crops of commercial value, while biomitigation takes place. In this way all the cultivation components have an economic value, as well as a key role in services and recycling processes of the system, the harvesting of the three types of crops participating in the export of nutrients outside of the coastal ecosystem.

IMTA is considered more sustainable than the common monoculture systems – that is a system of aquaculture where only one species is cultured – in that fed monocultures tend to have an impact on their local environments due to their dependence of supplementation with an exogenous source of food and energy without mitigation (Chopin *et al.*, 2001). For some twenty years now, many authors have shown that this exogenous source of energy (e.g. fish food) can have a substantial impact on organic matter and nutrient loading in marine coastal areas (Gowen and Bradbury, 1987; Folke and Kautsky, 1989; Chopin *et al.*, 1999; Cromey, Nickell and Black, 2002), affecting the sediments beneath the culture sites and producing variations in the nutrient composition of the water column (Chopin *et al.*, 2001).

Integration of different species in one culture unit can reduce these impacts because the culture of the species that do not require exogenous feeding may balance the system outputs through energy conversion, whereby the waste of one species becomes the food for another (Chopin *et al.*, 2001). For example, the wastes given off from the culture of salmon, e.g. uneaten fish food, fish faeces and excreted nitrogen (N) and phosphorus (P), can be assimilated by shellfish (organic processors) and seaweed (inorganic processors), thereby reducing the amount of waste given off from a fish farm and turning it into fodder for another species which is also of commercial value.

This practice of IMTA can help reduce environmental impacts while also creating other economically viable products at the same time. It is this dual-benefit which should make IMTA attractive to fish farmers, while making the aquaculture system more acceptable to environmentalists and the general population.

Considering the potential for increased profitability, it is amazing to realize how very little the aquaculture sector has diversified in some countries or in significant producing regions. For example, the salmon aquaculture in Canada represents 68.2 percent of the tonnage of the aquaculture industry and 87.2 percent of its farmgate value (Chopin and Bastarache, 2004). In Norway, Scotland and Chile, the salmon aquaculture represents 88.8 percent, 93.3 percent and 81.9 percent of the tonnage of the aquaculture industry, and 87.3 percent, 90.9 percent and 95.5 percent of its farmgate value, respectively (Chopin *et al.*, 2008). Conversely, while Spain (Galicia), produces only 8 percent of salmon in tonnage (16 percent in farmgate value), it produces 81 percent of its tonnage in mussels (28 percent in farmgate value). Why should one think that the common old saying "Do not put all your eggs in one basket", which applies to agriculture and many other businesses, would not also apply to aquaculture? Having too much production concentrated in a single species leaves a business vulnerable to issues of sustainability because of low prices due to oversupply, and the possibility of catastrophic destruction of one's only crop (diseases, damaging weather conditions). Consequently, diversification of the aquaculture industry (especially at the local and regional levels) is imperative to reduce the economic risks and maintain its sustainability and competitiveness.

The traditional view of diversification often means producing another product along the same lines of the first, that would fit into the existing production and marketing systems. In finfish aquaculture in North America and Northern Europe, this has usually meant salmon, cod, haddock or halibut. However, from an ecological point of view, these are all "shades of the same colour". No synergies are created; rather, these situations compound the impacts on the system. True ecological diversification of aquaculture means farming at more than one trophic level, i.e. switching from another species of finfish to another group of organisms of lower trophic level (e.g. shellfish, seaweeds, echinoderms, polychaetes, bacteria, etc.), more resembling a natural ecosystem. Staying at the same ecological trophic level will not address some of the environmental issues because the system will remain unbalanced due to the non-stable distribution of energy and non-diversified resource needs and outcomes.

Product diversification should also mean looking at seafood from a different angle. Aquaculture products on the market today are very similar to those obtained from the traditional fishery resources, and are, thus, often in direct competition. While this may be part of the market forces at work, the opportunity exists to diversify from the fish filets, or mussels and oysters on a plate in a restaurant, to a large untapped array of bioactive compounds of marine origin (e.g. pharmaceuticals, nutraceuticals, functional foods, cosmeceuticals, botanicals, pigments, agrichemicals and biostimulants, and industry-relevant molecules). Consequently, research and development on alternative species should no longer be considered as R&D on alternative finfish species, but rather on alternative marine products. Moreover, diversification should be viewed as an investment portfolio, with short-term, long-term, high risk and low-risk components, and with long-term growth and stability as the main objectives.

There is a paradoxical situation when looking at current worldwide food production. In agriculture, 80 percent of the production is made up of plants and 20 percent of animal products (meat, milk, eggs, etc.), while in aquaculture, 80 percent of the production is animal biomass and 20 percent is plant biomass (Chopin and Reinertsen, 2003). Considering only mariculture, the worldwide production in 2004 was made up of 45.9 percent seaweeds, 43.0 percent molluscs, 8.9 percent finfish, 1.8 percent crustaceans, and 0.4 percent of varied other animals (FAO, 2006a). Consequently, in many parts of the world, aquaculture is not synonymous to finfish aquaculture, as so many people in affluent western countries believe. Based on the need for balancing the cultured species functions within the surrounding ecosystem functions, marine herbivores, carnivores and omnivores cannot be cultivated while neglecting marine plants – as efficient biofilters, a crop on their own, or a food component for other organisms – if we are to make the "Blue Revolution" (*sensu* Costa-Pierce, 2002) "greener". Several species of seaweeds cultivated under the right conditions, especially near sources of high levels of nitrogen as in proximity to finfish farms, can be excellent sources of proteins, important amino acids and unsaturated oils. We need to be aware of the other food production systems in the rest of the world if we want to understand our present prevailing system and correctly position it in perspective with other systems. Seaweeds and micro-algivores (e.g. filter feeding shellfish and herbivorous fish) represent 59 percent of the world aquaculture production, followed by the production of 30 percent of omnivores and detritivores. In tonnage, the three leading aquacultured species are the seaweed *Laminaria japonica*, and two micro-algivores, the Pacific cupped oyster, *Crassostrea gigas*, and the silver carp, *Hypophthalmichthys molitrix*. Vocal public opposition to aquaculture has been generated by "high value" salmonids and other carnivorous marine fish and shrimp, which, in fact, represent only 10.7 percent of the world mariculture production (but 40.8 percent of its value).

From the above numbers for mariculture, one may be inclined to think that at the world level, the two types of aquaculture, fed and extractive, are relatively balanced. However, because of the predominantly monoculture approach, these different types of aquaculture production are often geographically separate, and, consequently, rarely balance each other out on the local or regional scale. For example, in Eastern Canada, fed salmon aquaculture is primarily located in the Bay of Fundy in Southern New Brunswick and in Southern Newfoundland, while extractive mussel and oyster aquaculture is located in the Northumberland Strait and the Lower Gulf of St. Lawrence, along the coastlines of Prince Edward Island and Northeastern New Brunswick, and in Eastern Nova Scotia and Northeastern Newfoundland. In Japan, aquaculture is mostly carried out with various bays dedicated to either shellfish, seaweed or finfish aquaculture. There are, however, examples in China of bays managed according to the IMTA approach (Chopin and Sawhney, 2009).

While IMTA may seem like a new concept to western farmers, this approach to farming and aquaculture has long been in use in Asian countries. Japan and China have used this technique for the co-culture of rice and fish for millennia (Neori *et al.*, 2004). Even if the cultured species are different, why, then, is this common-sense solution not more widely implemented, especially in the western world? The reasons for this generally center around social customs and practices that we are already familiar with, even if common sense tells us that we should modify them. Human society does not change quickly unless there are compelling reasons to. The conservative nature of our marine food production industries is a good example of the relative slowness with which changes are adopted, especially when dealing with a complex aquatic environment, which we mostly see only the surface of, and have difficulty understanding the processes taking place beneath it over considerable distances and volumes.

Western countries are regularly reinventing the wheel. Research on integrated methods for treating wastes from modern mariculture systems was initiated in the 1970s (Ryther, DeBoer and Lapointe, 1978). After that period, the scientific interest in IMTA stagnated, and it was not until the late 1980s and early 1990s (Indergaard and Jensen, 1983; Buschmann, López and Medina, 1996; Kautsky, Troell and Folke, 1996; Chopin *et al.*, 1999) that a renewed interest emerged, based on the common-sense approach that the solution to nitrification is not dilution but conversion within an ecosystem-based management perspective. This interest has likely been an indirect result of the increased demand for aquaculture products. In 2004, aquaculture production from mariculture was 30.2 million tonnes, representing 50.9 percent of the global aquaculture (FAO, 2006a), which has steadily increased each year since the 1950s, at a rate of roughly 10 percent (FAO, 2006a). This increase has in turn, resulted in intensified cultures, decrease in available habitat (space available for cage sites/aquaculture leases), and increased environmental impacts on the immediate ecosystem. IMTA is a method whereby production can be intensified, diversified and yet remain environmentally responsible – thereby ensuring a sustainable aquaculture industry. Multi-trophic integration appears to be a logical next step in the evolution of aquaculture.

This trend in the global recognition of the need for more advanced ecosystem-based aquaculture systems has begun to show up in the scientific world through the aquaculture conference circuit. For example, in recognition of this growing interest, the Aquaculture Europe 2003 Conference in Trondheim, Norway, whose theme was "Beyond Monoculture", was the first large international meeting (389 participants from 41 countries) with IMTA as the main topic. In 2006, at the joint European Aquaculture Society and World Aquaculture Society Conference in Florence, Italy, IMTA was recognized as a serious research priority and option to consider for the future development of aquaculture practices.

The objectives of the present paper are:

- To review the current status (production systems and scales, environmental, economic and social benefits, etc.) and future potential of IMTA in regions situated in temperate marine waters, using the best published and personal contact information available.
- To outline the requirements for further expansion of IMTA in the world's marine temperate waters.

REVIEW OF CURRENT IMTA SYSTEMS

The IMTA concept is extremely flexible. It can be applied to open-water and land-based systems, and marine and freshwater systems (sometimes then called "aquaponics" or "partitioned aquaculture"). What is important is that the appropriate organisms are chosen based on the functions they have in the ecosystem and, moreover, for their economic value or potential. What is quite remarkable, in fact, is that IMTA is doing nothing other than recreating a simplified, cultivated ecosystem in balance with its surroundings instead of introducing a biomass of a certain type expecting this can be cultivated in isolation of everything else.

Moreover, IMTA goes beyond environmental sustainability; it provides economic diversification and reduces economic risk when the appropriate species are chosen, and it increases the acceptability of the overall aquaculture sector by using practices evaluated as responsible by the industry, the regulators and the general public.

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

North America

Canada

In Canada, aquaculture of salmonids (salmon and trout), groundfish (cod and haddock), and shellfish (oysters, scallops and mussels) has been ongoing for many years. Canada produced, in 2004, 96 774 tonnes of salmonids and 37 925 tonnes of shellfish, with a respective value of US$298 056 000 and US$48 834 000 (Table 1). Most of the aquaculture systems in Canada are intensive monocultures. The blue mussel (*Mytilus edulis*) dominates the shellfish production with 60 percent of the volume, while oysters (*Crassostrea virginica* and *Crassostrea gigas*) make up 33 percent. Seaweeds (e.g. *Laminaria, Saccharina, Alaria, Ascophyllum, Fucus, Furcellaria, Palmaria* and *Chondrus*), although not cultivated in aquaculture systems, have been harvested as wild crops. The seaweeds are used primarily as sources of alginates, carrageenans, agrichemicals (biostimulants and fertilizers), animal feed supplements and ingredients, edible sea vegetables, nutraceuticals and botanicals for the health and beauty industries (DFO, 2001; Chopin and Bastarache, 2004). Acadian Seaplants Limited, based in Dartmouth, Nova Scotia, is a world leader in the development of land-based seawater tank cultivation of seaweeds (*Chondrus crispus*) with a unique commercial cultivation operation in Charlesville, Nova Scotia.

Within the past eight years, IMTA projects have been developed on both the Atlantic and Pacific coasts. On the Atlantic coast, in the Bay of Fundy, a project integrating the culture of salmon (*Salmo salar*), blue mussels (*Mytilus edulis*) and kelps (*Saccharina latissima*, previously described as *Laminaria saccharina*, and *Alaria esculenta*) has been ongoing since 2001 (Chopin and Robinson, 2004) and the results

TABLE 1

Quantity (in tonnes) and value (in US$ x 1000) of marine aquaculture products by country in 2004

Country	Aquatic plants		Crustaceans		Molluscs		Diadromous fishes		Marine fishes		Total	
	tonnes	US$	tonnes	US$	tonnes	US$	tonnes	US$	tonnes	US$	tonnes	US$
Canada	n/a	n/a	n/a	n/a	37 925	48 834	96 774	298 056	n/a	n/a	134 699	346 890
Chile	19 714	13 800	n/a	n/a	96 922	340 119	564 043	2 384 151	255	2 397	680 934	2 740 467
Finland	n/a	n/a	n/a	n/a	n/a	n/a	10 586	40 406	n/a	n/a	10 586	40 406
France	37	16	n/a	n/a	208 535	506 672	925	4 590	6 728	66 593	216 225	577 871
Ireland	n/a	n/a	n/a	n/a	43 092	53 423	14 349	64 727	25	280	57 466	118 430
Norway	n/a	n/a	21	395	3 796	2 746	627 581	1 656 146	5 404	21 997	636 802	1 681 283
Portugal	n/a	n/a	n/a	n/a	2 681	12 978	n/a	n/a	3 194	21 830	5 875	34 808
South Africa	2 845	1 252	30	419	1 680	26 477	n/a	n/a	n/a	n/a	4 555	28 148
Spain	n/a	n/a	46	666	236 708	97 346	158	462	23 294	144 512	260 206	242 986
Sweden	n/a	n/a	n/a	n/a	1 435	794	1 316	4 871	n/a	n/a	2 751	5 665
United Kingdom	n/a	n/a	n/a	n/a	32 500	64 278	159 879	479 985	440	3 888	192 819	548 151
United States	n/a	n/a	4 731	20 958	221 717	164 352	15 127	56 575	1 362	6 292	242 937	248 178
Total	22 596	15 068	4 828	22 438	886 991	1 318 019	1 490 738	4 989 969	40 702	267 789	2 445 855	6 613 283

Source: FAO (2006b).

support the establishment of IMTA systems in this region. Innovative kelp culture techniques have been developed and improved both in the laboratory and at the aquaculture sites. Increased growth rates of kelps (46 percent; Chopin *et al.*, 2004) and mussels (50 percent; Lander *et al.*, 2004) cultured in proximity to fish farms, compared to reference sites, reflect the increase in food availability and energy. Nutrient, biomass and oxygen levels are being monitored to estimate the biomitigation potential of an IMTA site. Salmonid solid and soluble nutrient loading is being modelled as the initial step towards the development of an overall flexible IMTA model. The extrapolation of a mass balance approach using bioenergetics is being juxtaposed with modern measures of ecosystem health such as exergy. Over eight years, none of the therapeutants used in salmon aquaculture have been detected in kelps and mussels collected from the IMTA sites; levels of heavy metals, arsenic, PCBs and pesticides have always been below Canadian Food Inspection Agency, USA Food and Drug Administration, and European Community Directive regulatory limits. A taste test at market size conducted on site grown versus reference mussels showed no discernable difference (Lander *et al.*, 2004). *Alexandrium fundyense*, the dinoflagellate responsible for producing paralytic shellfish poisoning (PSP) toxins, occurs annually in the Bay of Fundy and mussels can accumulate these toxins above regulatory limits in the summer/early fall. However, PSP toxins concentrations in mussels decreased readily as the blooms of *Alexandrium fundyense* diminished. Domoic acid, released by the diatom *Pseudo-nitzschia pseudodelicatissima*, was never above regulatory limits over the eight years. All of these results indicate that, with the proper monitoring and management, mussels and seaweeds from the IMTA operations can be safely harvested as seafood for human consumption (Haya *et al.*, 2004).

Two attitudinal studies towards salmon farming in general, and IMTA in particular, were conducted (Ridler *et al.*, 2007). The first survey found that the general public is more negative towards current monoculture practices and feels positive that IMTA would be successful (Robinson *et al.*, in press). The second attitudinal survey, a focus group study (Barrington *et al.*, 2008), showed that most participants felt that IMTA has the potential to reduce the environmental impacts of salmon farming (65 percent), improve waste management in aquaculture (100 percent), benefit community economies (96 percent) and employment opportunities (91 percent), and improve food production (100 percent), and the industry competitiveness (96 percent) and overall sustainability (73 percent). All felt that seafood produced in IMTA systems would be safe to eat and 50 percent were willing to pay 10 percent more for these products if labelled as such, which open the door to developing markets for differentiated premium IMTA products, either environmentally labelled or organically certified.

Preliminary data of a bio-economic model (Ridler *et al.*, 2007), in which net present value (NPV) calculations are conducted over 10 years to portray long-term variability, show that the addition of seaweed and mussel to salmon farming is more profitable and helps reduce risks through diversification. The project is now scaling up the experimental systems and working on an appropriate food safety regulatory and policy framework for the development of commercial scale IMTA operations with its two industrial partners, Cooke Aquaculture Inc. and Acadian Seaplants Limited. Presently, five amended salmon sites of Cooke Aquaculture Inc. are reaching commercial scale development for both seaweeds and mussels.

Site selection for the best compromise between site characteristics, species selection, and markets demands will be key to optimizing these IMTA operations. Further scaling-up of cultivation systems (seaweed and mussel rafts), species diversification, economic analysis and development of niche markets will be implemented. Scaling-up to commercial level will also allow the investigation into the impacts of IMTA on the carrying capacity of the coastal environment, water and benthos quality, potential for disease transfer, and animal and plant health at a realistically large scale to validate the early assumptions developed, and results obtained, through modelling with Monte Carlo simulations (Reid *et al.*, in press).

There have been concerns that co-cultured organisms, such as shellfish and seaweeds, could be "reservoirs" for diseases affecting fish. Interestingly, a recent study by Skar and Mortensen (2007) and our own unpublished data indicate that carefully chosen additional species in an IMTA setting have the potential for some disease control. Mussels (*Mytilus edulis*) are capable of reducing loads of the infectious salmon anaemia virus (ISAV) in the water. The mechanism is not yet completely elucidated; however, there is, consequently, the potential that appropriately placed mussels around salmon cages could act as a possible biofilter for disease reduction or prevention. All the possible interactions between co-cultured species have certainly not all been investigated, but what was initially perceived as a potentially problematic situation is now regarded as an unexpected positive interaction.

Concurrent with the positive results of the IMTA system on the east coast, a project concerning the feasibility of finfish-shellfish-seaweed culture has recently gotten underway on the west coast, in the waters of British Columbia (BC) off Vancouver Island (Cross, 2004a, b). Beginning in 2006, researchers plan to assess whether growing a range of species – including shellfish (mussels, oysters and scallops), kelps (*Saccharina latissima*), sea cucumbers, and sea urchins – can help reducing the environmental impacts of salmon and sablefish (or black cod, *Anoplopoma fimbria*) farming (S. Cross, pers. comm.). This work has been inspired by earlier preliminary investigations into the culture of Pacific oyster, *Crassostrea gigas*, with Chinook salmon, *Oncorhynchus tshawytscha*, on the BC coast. Jones and Iwama (1991) found that oysters grew three times the amount in shell height and growth rate when integrated with salmon farms than at reference sites. This increase in weight and growth of the co-cultured species is a positive side effect and holds obvious economic benefit for farmers.

The future of Canadian aquaculture is currently at a crossroad. Important to consider is Canada's historical dependence on traditional fisheries and the impact that the cod moratorium made on the cultural landscape, particularly in Newfoundland (Schrank, 2005). The East coast of Canada seems ripe for aquaculture development as the region struggles with high unemployment: 13.2 percent in Newfoundland and Labrador, 11.2 percent in Prince Edward Island, 8.0 percent in Nova Scotia and 7.2 percent in New Brunswick, whereas the national unemployment rate was at 5.9 percent in November 2007 (Statistics Canada, 2007). On the West coast of Canada, the salmon industry encounters environmental NGO's opposition (Hamouda *et al.*, 2005). The unique ability of IMTA systems to encourage sustainable aquaculture should be considered as a valuable tool when managing Canadian aquaculture. While aquaculture is developing on the East coast (particularly in Newfoundland), IMTA systems should be used to prevent potential environmental damage as this important employment area is growing; similarly, IMTA systems should be used on the West coast to mitigate environmental damage and to help quell public opposition.

Aquaculture can be a valuable socio-economic tool, particularly in the coastal communities of the provinces of New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland and Labrador. These provinces have all been traditionally tied to the fishing industry. As wild capture fisheries are becoming less profitable and stocks dwindle, aquaculture can be a means by which people can maintain their cultural identities as folk who live off the sea. This industry has the potential to limit out-migration by providing jobs directly and indirectly related to the marine industry sector. A preliminary economic scenario for the New Brunswick side of the Bay of Fundy showed that IMTA could provide CDN$44.6 million in extra revenue and 207 new jobs in a sector presently worth CDN$223 million and already employing 1683 people directly and 1322 indirectly (Chopin and Bastarache, 2004; Chopin *et al.*, 2008).

United States of America

In 2004, the United States produced 221 717 tonnes of shellfish, 16 489 tonnes of fish and 4 731 tonnes of shrimp, with a respective value of US$164 352 000, US$62 867 000 and US$20 958 000 (Table 1). In the Northern United States, culture of mussels and salmon are common, while in the Southern United States culture of shrimp is more suited to the warmer climate. Like most aquaculture operations in North America, the majority of the culture units are intense monocultures.

Interest in IMTA has been primarily fuelled in the United States as a means of treating the wastewater from intensive culture of shrimp. Sandifer and Hopkins (1996) outlined a method of farming shrimp with herbivorous mullet and oyster, whereby the mullet and oyster feed on the wastewater of cultured shrimp, thereby acting as biofilters and recycling feeders. The researchers designed their IMTA system so that the solid removal from the shrimp effluent would be enhanced and deposition would also be reduced, while cultivating two other valuable species – oyster and mullet. Although this is currently a land based system, the authors have suggested that this system could be utilized in estuarine areas in the Southern United States (e.g. South Carolina to Texas). This model should be considered by shrimp farmers when managing their farm.

More recently, researchers in the American Northeast have been investigating the potential of the red alga *Porphyra* (also known as nori) to be used in integrated finfish-algal aquaculture system. Carmona, Kraemer and Yarish (2006) studied six species of *Porphyra* (*P. amplissima, P. purpurea, P. umbilicalis, P. haitanensis, P. katada* and *P. yezoensis*) and concluded that *P. amplissima, P. purpurea* and *P. umbilicalis* were excellent candidates as bioremediators in IMTA systems. These species are all native to coastal waters of the NE United States (e.g. Maine to Massachusetts) and should therefore be considered excellent candidates for integration with existing salmon or mussel farms or in land-based facilities with flounder or cod (project between the University of New Hampshire and Great Bay Aquaculture, LLC; C. Neefus, pers. comm.).

Chopin *et al.* (1999) stated that the culture of *Porphyra* in the Gulf of Maine and Bay of Fundy (the Atlantic Coast of the United States and Canada) may be limited by low levels of inorganic nutrients in the water. However, if this alga was grown in an integrated system with finfish for example, this problem may be mitigated. If the production of *Porphyra* is to expand from Asian waters to other countries such as Canada and the United States, IMTA systems may have to be employed in order to meet the biological demands of the seaweeds. This effort may be well rewarded if a niche can be found in the sushi-market, where profit returns can be high. Referring to Table 2, the value of the nori market was worth US$1.34 billion in 2004 (Chopin and Sawhney, 2009). The market for all edible seaweeds in North America is estimated at US$35 million.

The company Söliv International, a manufacturer of skin care products, has developed a land-based IMTA system in collaboration with the University of Washington in Seattle (Dr. Robert Waaland). Situated in Manchester, Washington State, they are cultivating the red alga *Chondracanthus exasperatus* (also known as Turkish towel) in tanks receiving seawater from Pacific halibut (*Hippoglossus stenolepsis*) and black cod (*Anoplopoma fimbria*) culture tanks. *Chondracanthus exasperatus*, with a maximal production of 725 kg wet weight per month, is used in formulations of cosmetic products.

Big Island Abalone Corporation, a tenant at the Natural Energy Laboratory of Hawaii Authority (NELHA), commercially produces Kona Coast Abalone™ (Japanese Northern Ezo abalone, *Haliotis discus hannai*) fed with patented red algae believed to be derived from a strain of Pacific dulse (*Palmaria mollis*). Each month, the 10-acre aquafarm grows, in large tanks, 70 tonnes wet weight of the red algae needed to produce 8 tonnes wet weight of abalone, which are shipped live to Japan, Hawaii and mainland United States. The Kona Coast of Hawaii's Big Island was chosen because

TABLE 2
Main components of the world's seaweed industry and their value (in US$) for 2004

Industry component	Raw material (wet tonnes)	Products (tonnes)	Value (US$)
Sea-vegetables	8.59 million	1.42 million	5.29 billion
Kombu (*Laminaria)*	4.52 million	1.08 million	2.75 billion
Nori (*Porphyra*)	1.40 million	141 556	1.34 billion
Wakame (*Undaria*)	2.52 million	166 320	1.02 billion
Phycocolloids	1.26 million	70 630	650 million
Carrageenans	528 000	33 000	300 million
Alginates	600 000	30 000	213 million
Agars	127 167	7 630	137 million
Phycosupplements	1.22 million	242 600	53 million
Soil additives	1.10 million	220 000	30 million
Agrichemicals (fertilizers, biostimulants)	20 000	2 000	10 million
Animal feeds (supplements, ingredients)	100 000	20 000	10 million
Pharmaceuticals, nutraceuticals, botanicals, cosmeceuticals, pigments, bioactive compounds, antiviral agents, brewing, etc.	3 000	600	3 million

Source: Chopin and Sawhney (2009).

it receives more sunlight per year than any other coastal location in the United States; secondly, through NELHA's deepwater pipe, Big Island Abalone Corporation has access to a constant supply of cold, nutrient-rich seawater, pumped from a depth of around 900 m in the Pacific Ocean. Lastly, Hawaii's location, midway between Asia and North America, enables the company to ship fresh, live abalone to markets on both continents.

Buttner and Leavitt (2003) reported an interesting study undertaken with lobster fishers along the Massachusetts coast, where lobster fishing was integrated with oyster cultivation. By modifying traditional lobster traps to incorporate trays for eastern oysters (*Crassostrea virginica*) the authors found that oysters could survive, grow, and augment the income of lobster fishers without affecting lobster captures rates. This pilot project promoted acceptance of aquaculture among commercial fishers, local communities, and regulatory agencies in the region. The authors also felt that this idea could easily be adapted to other bivalve species. This concept of lobster-bivalve co-culture is an interesting adaptation of the IMTA concept and illustrates the flexibility of the concept to suit particular communities' resources and needs, although, in this particular case, the nutrient capture and retention are minimal.

South America

Chile

The culture of salmon is widespread along the entire coastline of Chile's Region X and moving rapidly to Region XI. Chile is one of the world leaders in production of farmed salmon. In 2005, the value of exported farmed salmon was near US$ 2 million and production has nearly doubled since 2000 (FAO, 2006a). Chile ranks among the top ten aquaculture producers in the world, and produces 4 percent of the global aquaculture value (US$2.82 billion) (FAO, 2006a). In 2004, Chile produced 564 298 tonnes of fish, 96 922 tonnes of shellfish and 19 714 tonnes of seaweed, with a respective value of US$2 386 548 000, US$340 119 000 and US$13 800 000 (Table 1).

Species of finfish being commercially cultivated include *Salmo salar*, *Oncorhynchus mykiss*, *Oncorhynchus tschawytscha*, *Oncorhynchus masou*, *Oncorhynchus kisutch* and *Scophthalmus maximus* (Buschmann *et al.*, 1996). The three most economically important salmonids are *Salmo salar*, *Oncorhynchus kisutch* and *Oncorhynchus mykiss*. Besides the culture of salmon, monocultures of mussels (*Mytilus chilensis* and *Choromytilus chorus*), scallops (*Argopecten purpuratus*) and oysters (*Tiostrea chilensis* and *Crassostrea gigas*) are commonplace (Buschmann *et al.*, 1996).

There is much potential for a seaweed culture industry in Chile. The algae *Gracilaria chilensis*, *Gigartina skottsbergii*, *Sarcothalia crispata*, *Porphyra columbina*, *Callophyllis variegata*, *Chondracanthus chamissoi*, *Lessonia trabeculata*, *Lessonia nigrescens, Macrocystis pyrifera* and *Durvillaea antarctica* are commonly grown and collected in Chile (Buschmann *et al.*, 2001; 2005; 2006). To date, *Gracilaria chilensis* is the only species cultured on a commercial level (Buschmann *et al.*, 2005; 2006).

With the strong intensification trend of salmon aquaculture in Region X and further salmon sites expansion in Region XI, and following the tendencies in northern hemispheric countries, there have been increasing concerns about potential cumulative environmental impacts since the second half of the 1990's (Soto and Norambuena, 2004; Leon, 2006). Some authors have stressed the need to adopt integrated management measures to control these impacts, highlighting the relevance of maintaining a balance between further aquaculture development and environmental conservation through the development of IMTA systems (Buschmann *et al.*, 2006). The recent confirmation of the presence and spreading of the ISA virus in Chile should be seen as a warning signal for overstocked salmon monocultures.

IMTA started in the late 1980's in Chile, but is still fairly small. The first attempt considered the development of land-based intensive marine systems using pumped seawater to intensively culture trout (*Oncorhynchus mykiss*). The fish effluents were then used for the cultivation first of oyster (*Crassostrea gigas*) and second of the agar producing alga *Gracilaria chilensis*, which both were able to significantly reduce nitrogen and phosphorus. The first trials were successful and demonstrated that an IMTA approach was an additional way for developing a more sustainable aquaculture approach. It now consists of seaweed-finfish culture sites, where the algae *Gracilaria chilensis* and *Macrocystis pyrifera* are co-cultivated with salmon (Troell *et al.*, 1997). IMTA units are promising as thus far research has shown that biomass productivity of *Gracilaria chilensis* increased by 30 percent when grown with salmon, and it also has a higher agar quality (Buschmann *et al.*, 2005). Currently cultivated *Gracilaria* is used as feed for abalone and for the extraction of agar. Other algae that are economically valuable include *Ulva* and *Macrocystis*, from which organic fertilizers are being developed at a commercial level (Buschmann *et al.*, 2005). These species hold promise for further development and could also be used in IMTA systems due to their economic value (Table 3), established market niche, and suitability for growth in the climate.

TABLE 3

Profitability analysis using the net present value (NPV in US$) and internal rate of return (IRR in percent) of a culture system simulating three different net salmon productions (200, 400, 600 tonnes) and four different fish stocking densities (15, 30, 45, 60 kg/m^3), in three scenarios: a) without internalizing the total environmental costs, b) considering the internalization of the total environmental costs, and c) considering the internalization of the total environmental costs reduced by the nutrient scrubbing capacity of *Gracilaria chilensis* and its conversion into another commercial marine crop (n.p. = no profit)

Fish net production (kg/m^3)	Fish stocking density (tonnes)	NPV (US$)			IRR (%)		
		a	b	c	a	b	c
200	15	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
	30	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
	45	455 692	n.p.	39 982	24.1	n.p.	15.8
	60	685 939	n.p.	270 230	30.0	n.p.	20.8
400	15	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
	30	814 852	n.p.	n.p.	21.9	n.p.	n.p.
	45	1 965 197	n.p.	1 133 772	34.3	n.p.	25.7
	60	2 498 356	339 186	1 666 931	42.2	19.2	32.2
600	15	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
	30	2 065 330	n.p.	818 195	26.2	n.p.	19.4
	45	3 743 201	505 167	2 496 785	40.0	18.6	30.3
	60	4 569 269	1 330 517	3 322 135	47.8	25.4	37.5

Source: Chopin *et al*. (2001).

IMTA sites have remained at a small scale level, primarily because the explosive growth of salmon aquaculture prevented the adoption of alternative farming strategies, like IMTA, as the industry had no immediate incentive to modify a very successful financial story. It has not been easy to adopt an IMTA approach in Chile. Like oriental countries, Chile has a long tradition of shellfish and seaweed consumption; however, the price for these goods is very low, therefore, they cannot be suggested as an interesting business for investors. To encourage the farming of these organisms, novel uses of seaweeds are being developed (A. Buschmann, pers. comm.). Present licensing regulations also offer no incentives for the adoption of IMTA practices, especially as it does not encourage partnership between site owners involved in producing different crops, or their association within one site. It is unlikely that the owner of a large intensive salmon farm will invest and make the effort of growing seaweeds and mussels unless regulations would stipulate that the implementation of IMTA practices would allow to increase the number of fish being raised at the site or would lower penalties related to environmental effects levied by the authorities. Most parameters monitored for the environmental assessment of salmon farming focused on the state of the bottom under the cages and ignored issues encountered in the water column and watershed (e.g. nutrients), where IMTA could have a significant effect. If regulations were to address concerns of cumulative impacts and eutrophication at larger scale (fjords, channels, or whole bays), instead of focusing on local bottom effects, farmers would then become more inclined to adopt IMTA, especially if the implementation of such practices can be associated with recognition through certification systems or eco-labelling.

Other IMTA initiatives, both at freshwater and marine aquaculture sites, have been experimentally pursued. For example, the use of artificial reefs around and below salmon cages to enhance ecosystem restoration and to increase the production of crabs and other fish have been attempted (Soto and Mena, 1999; Soto and Jara, 2007).

An interesting situation has emerged in southern Chile with the recent development of mussel (*Mytilus chilensis*) cultivation. Mussel long lines can now be found between salmon cages in channels and fjords due to space limitations in the region. The decisions regarding the design and location of sites were, however, not based on scientific data for prevailing currents, suspended matter and nutrient circulation, oxygen availability, etc. and the IMTA concept was not explicitly considered, despite the fact that it has been documented that natural mussel beds near salmon farms can utilize these nutrients and particulate matter (Soto and Jara, 2007). Better pre-planning of these coastal zones, by inclusion of the IMTA principles, would represent much better management practices.

The development of abalone cultivation is presently emerging in Chile, adding an extra pressure on natural resources of seaweeds as a source of feed. A pilot scale farm (4-5 ha) is already producing the brown alga *Macrocystis pyrifera* and has demonstrated its technical and economic feasibility. Linking salmon aquaculture (the source of nutrients for seaweeds) with seaweed aquaculture (the source of food for abalone) and abalone aquaculture (the final recipient of the food and energy passed along) could represent another interesting IMTA system.

One potential problem with the integrated culture of seaweed-salmon farms is the spread of the invasive species *Codium fragile* ssp. *tomentosoides*. This invasive alga competes for nutrients with *Gracilaria* (Neill *et al.*, 2006), which could reduce biomass and agar quality. The spread of this alga needs to be monitored and controlled if possible to prevent losses to the industry.

The development of IMTA systems in Chile should be a high priority with the government and industry officials. Due to the high production volumes and rapid expansion of the salmon culture industry (FAO, 2006a), the risk of environmental degradation is high if salmon effluents are not managed and mitigated. IMTA systems can help prevent environmental degradation, while supporting an industry with high employment potential, which is an important socio-economic issue in a country that seeks to reduce unemployment. The possibility of allowing small shellfish and seaweed farmers to couple their efforts with large salmon farmers is an option which remains mostly unexplored, but which should help spreading the benefits of aquaculture to all stakeholders within a more ecosystemic perspective.

Europe

Spain and Portugal

In 2004, mariculture in Spain produced 236 708 tonnes of molluscs and 23 452 tonnes of fish, with a respective value of US$97 346 000 and US$144 974 000 (Table 1). Mariculture in Portugal produced 3 194 tonnes of fish and 2 681 tonnes of molluscs, with a respective value of US$21 830 000 and US$12 978 000 (Table 1).

IMTA research along the Atlantic coast of the Iberian Peninsula is primarily focussed on using algae (mainly Rhodophyta) with fish (mainly turbot, *Scophthalmus maximus*, and sea bass, *Dicentrarchus labrax*).

Of the seaweeds, much research is being done regarding the use of *Gracilaria bursa pastoris*, *Chondrus crispus*, *Palmaria palmata* (Matos *et al.*, 2006; Martínez *et al.*, 2006), *Porphyra dioica* (Pereira, Yarish and Sousa-Pinto, 2006), *Asparagopsis armata* (Mata *et al.*, 2006; Schuenhoff, Mata and Santos, 2006), *Gracilariopsis longissima* (Hernández *et al.*, 2006), *Ulva rotundata, Ulva intestinalis* and *Gracilaria gracilis* (Martínez-Aragon *et al.*, 2002; Hernández *et al.*, 2002) as biofilters for use in IMTA units.

All these authors show that many of these macroalgal species are excellent candidates for biofilters and wastewater effluent mitigation: all these species have excellent growth rates, photosynthetic rates and inorganic nutrient removal rates – all characteristics which make for good candidates in IMTA units – growth rates being important for biomass production and increased profit; photosynthetic rates being interesting for increasing the availability of oxygen at aquaculture sites; inorganic nutrient removal rates being important for effluent mitigation.

Using this knowledge, researchers have begun experimental studies where algae have been integrated with sea bass and turbot. Matos *et al.* (2006) found that of the three species tested (*Gracilaria bursa pastoris, Chondrus crispus* and *Palmaria palmata*) *Gracilaria bursa pastoris* had better yields and higher N uptake efficiency and was thus recommended as the best candidate for integration with sea bass or turbot. *Ulva rotundata*, *Ulva intestinalis* and *Gracilaria gracilis* have been co-cultivated with sea bass and found to be efficient biofilters of phosphates (PO_4^{3-}) (Martínez-Aragon *et al.*, 2002) and ammonium (NH_4^+) (Hernández *et al.*, 2002) from the wastewaters.

Borges *et al.* (2005) investigated a small scale IMTA unit of fish (sea bass, *Dicentrarchus labrax*, and turbot, *Scophthalmus maximus*), clams (*Tapes decussatus*) and three microalgal species (*Isochrysis galbana, Tetraselmis suecica* and *Phaeodactylum tricornutum*). Their purpose was to determine if the microalgal species could be efficiently reared from the effluents from the fish, which would be ultimately fed to clams in a shellfish culture unit. The authors found that all three algal species grew well in the effluent, and that the algae contributed to effluent purification while contributing to extra income at no increased cost. The microalgae all reduced the amount of NH_4^+, NO_{3-} and PO_4^{3-} from the effluent. The resulting microalgal production was designed to be either sold or fed to shellfish as supplemental feed. The study estimated that the algal system would produce enough food to feed 1 000 to 2 000 clams per day.

Once the algae are harvested, farmers have many options on how to use their additional product. One of the areas already mentioned is the use as food supplements for other cultured species such as fish and shellfish. Valente *et al.* (2006) investigated the potential for *Gracilaria bursa pastoris, Gracilaria cornea* and *Ulva rigida* as dietary ingredients for juvenile sea bass (*Dicentrarchus labrax*). The authors found that *Gracilaria bursa pastoris* and *Ulva rigida* could contribute up to 10 percent, and

Gracilaria cornea up to 5 percent, of the diet for juvenile sea bass, thus providing another use for macroalgae grown in IMTA systems in Portuguese waters.

France

In 2004, mariculture in France produced 208 535 tonnes of shellfish, 7 653 tonnes of fish and 37 tonnes of seaweeds, with respective values of US$506 672 000, US$71 183 000 and US$16 000 (Table 1). Most aquaculture units in France are intensive monocultures. The majority of the work on IMTA systems in France is concerned with the use of marine ponds to treat fish effluents, and all are at the experimental stage. More specifically, researchers (Pagand *et al.*, 2000; Metaxa *et al.*, 2006) are investigating the use of high rate algal ponds (HRAP) to treat sea bass (*Dicentrarchus labrax*) effluents and other researchers (Lefebvre, Barillé and Clerc, 2000) are investigating the use of oysters to treat sea bass effluent in a research initiative known as the European Genesis project.

Metaxa *et al.* (2006) found that when *Ulva* and *Cladophora* were used in HRAP the wastewater had significant reductions in the dissolved inorganic N and P. The authors also noted that the algae had no effect on fish growth. An important observation made by these researchers is that the uptake of N and P by the algae was greater in summer than winter; therefore farmers should consider seasonal effects on algal growth conditions and water effluent treatment in integrated units.

Pagand *et al.* (2000) found that when Ulva (as *Ulva* and *Enteromorpha*) was used in HRAP the wastewater effluent had higher levels of dissolved oxygen and lower concentrations of nutrients and suspended solids than the water in reference tanks. No toxic algae were observed, and, as in the previous study, the authors noticed a profound seasonal effect on algal growth and production.

Oysters are actively cultured in France, particularly in the Marennes-Oléron Bay. To assess the suitability of oysters to IMTA systems, Lefebvre, Barillé and Clerc (2000) investigated the ability of oyster (*Crassostrea gigas*) to clean sea bass (*Dicentrarchus labrax*) effluent. The authors found that *Crassostrea gigas* has the ability to feed on the detritus/waste of the fish farm effluent. This is one way that farmers can recapture the lost organic product of intensive fish farming, and grow another economically valuable species.

Although these studies are pond or tank based, they are all relevant to the marine-based aquaculture systems in coastal waters of France, specifically the aquaculture of sea bass. Therefore their importance to the development of IMTA systems, particularly the benefits of integrating macroalgae and oysters, in coastal waters should be justly noted.

United Kingdom of Great Britain and Ireland

Aquaculture in the United Kingdom (essentially Scotland's west coast) and Ireland primarily consists of monoculture units, with emphasis on salmonids and mussels. In Western Europe, the United Kingdom is second to Norway in aquaculture growth and makes up 17 percent of the region's salmon production (FAO, 2006a). In 2004, the United Kingdom produced 160 319 tonnes of fish and 32 500 tonnes of shellfish, with respective values of US$483 873 000 and US$64 278 000 (Table 1). Ireland produced 43 092 tonnes of shellfish and 14 374 tonnes of fish, with respective values of US$53 423 000 and US$65 007 000 (Table 1). There is some research on IMTA in Scottish and Irish waters.

The growth and production of mussels (*Mytilus edulis*) with salmon (*Salmo salar*) in Scottish sea lochs was investigated by Stirling and Okumuş (1995). They found that mussels integrated with salmon had higher growth rates and had less depleted tissue reserves over the winter than those grown without salmon. This study suggests that mussels can be integrated with salmon in Scottish waters for increased economic viability.

More recently, researchers at the Scottish Association for Marine Science (SAMS), in Oban, have been working with the salmon companies Loch Duart Limited and West Minch Salmon, as well as with the mussel producer Loch Beag, to initiate pilot projects investigating the potential for IMTA along Scotland's west coast (M. Kelly, pers. comm.). Currently, there are several projects underway. These include: integration of Atlantic salmon, *Salmo salar*, with the sea urchins, *Psammechinus miliaris* and *Paracentrotus lividus*, and the seaweeds, *Palmaria palmata, Laminaria digitata, Laminaria hyperborea, Saccharina latissima* and *Sacchoriza polyschides*; integration of organically farmed salmon with the oyster, *Crassostrea gigas*, and the king scallop *Pecten maximus*; and co-cultivation of the sea urchin *Paracentrotus lividus* and the mussel *Mytilus edulis* (M. Kelly, pers. comm.). Results thus far are encouraging. Both sea urchin species are growing well next to salmon, and seaweed performance is positive, but varies according to species and site hydrography (M. Kelly, pers. comm.). Research using stable isotopes with *Palmaria palmata* shows that this species can utilise dissolved nitrogen of salmon farm origin. The current challenges facing IMTA in Scotland are primarily economical, as new market routes for the co-products (e.g. sea urchins) remain to be established (M. Kelly, pers. comm.). However, with the full support of industry and co-operative efforts of academic researchers and government, these hurdles should soon be overcome. The regulatory framework, as it relates to IMTA, also remains to be tested in Scotland.

Aquaculture, both mono-specific and integrated, is currently underway in Ireland. Irish farmers have taken advantage of the abundance of commercially viable seaweed. Kraan and Barrington (2005) report on the success of a commercially viable farm that cultivates *Asparagopsis armata* in County Galway. As shown by Schuenhoff, Mata and Santos (2006), *Asparagopsis armata* is an excellent biofilter of fish farm effluent and it also has high economic value when harvested for the antibiotic and cosmetic industry (Santos, 2006). Therefore, *Asparagopsis armata* should be considered an excellent species for integration with fish farms in the United Kingdom and Ireland.

Besides the commercial cultivation of *Asparagopsis armata*, there are three other seaweeds currently being farmed in Ireland: *Palmaria palmata, Alaria esculenta* and *Chondrus crispus*. There are also monoculture sites growing cod (*Gadus morhua*), salmon (*Salmo salar*), oysters (*Crassostrea gigas*) and mussels (*Mytilus edulis*), which, due to the intensity of the operations, are nearing carrying capacity at their current locations (S. Kraan, pers. comm.). Moreover, some of these species (e.g. mussels and seaweeds) are already being cultured, albeit independently, in the same bay (Roaring Water Bay, County Cork). Consequently, Ireland seems ready for IMTA and it should only be a small step to integrate these existing systems, once consensus is reached between industry officials and state agencies (S. Kraan, pers. comm.). Researchers at the Irish Seaweed Centre (ISC) at the National University of Ireland, Galway, have recently been meeting with fishers' groups in County Kerry. Since the banning of salmon drift net fishing in 2007, the fishers have been looking to supplement their income. In consultation with the ISC, they were planning on establishing an IMTA operation incorporating seaweed with mussel and scallop farms in Bantry Bay and Brandon Bay, Co. Kerry, in 2007, with the possibility of expanding into cod and sea bass operations in 2008.

The ISC, in conjunction with 2 commercial companies and a state agency are currently planning a large project in Bantry Bay, which was scheduled to start in late 2007 (S. Kraan, pers. comm.). This IMTA system will integrate 4 different species on 3 different trophic levels (2 algal species, shellfish and finfish). *Laminaria digitata* will be integrated into a salmon farm. This kelp will then be used as feed for an abalone farm in which *Porphyra* sp. will be grown with the abalone effluent. *Porphyra* will be used as a back up supply for feeding abalone when access to the kelp farm is restricted due to weather conditions. Excess *Porphyra* will be used for other commercial purposes and for experimental feed design for farmed finfish, possibly salmon in the proposed IMTA system. In this integrated-looped system, the macroalgae are internalized food sources for shellfish and finfish, while simultaneously acting as effluent biomitigators, increasing the sustainability of the entire operation.

Norway, Sweden and Finland

Much like in the United Kingdom, aquaculture in the Scandinavian countries of Norway, Sweden and Finland is largely focussed on monocultures of salmonids and mussels. A review of the existing literature shows that there are no commercial harvests of cultured seaweed in these countries, nor are there any commercial IMTA systems. Norway is by far the leader in salmon aquaculture in Europe, producing 71 percent of the region's Atlantic salmon (FAO, 2006a). The Norwegian aquaculture industry produces large amounts of salmon and rainbow trout, to a lesser extent cod, halibut, turbot and eel, and shellfish – mussels, oysters and scallops (Maroni, 2000). In 2004, Norway produced 632 985 tonnes of fish and 3 796 tonnes of shellfish, with a respective value of US$1 678 143 000 and US$2 746 000 (Table 1).

The Swedish and Finnish aquaculture industries are substantially smaller than that of Norway. The Swedish aquaculture industry produces rainbow trout, salmon, eel, arctic char, blue mussel and crayfish (Ackefors, 2000). The Finnish aquaculture industry produces primarily rainbow trout and salmon (Varjopuro *et al.*, 2000). In 2004, Sweden produced 1 435 tonnes of shellfish and 1 316 tonnes of fish, with a respective value of US$794 000 and US$4 871 000 (Table 1). Finland produced 10 586 tonnes of fish, with a value of US$40 406 000 (Table 1).

These countries, especially Norway, experienced a large boom in salmon and trout monoculture in the late 1980's and throughout the 1990's (Maroni, 2000). As a result of this rapid and largely unchecked expansion, disease and parasite outbreaks were common. To help control this situation the government began to strictly control the salmon culture industry and as a result have some of the most detailed records of farm activity in the world (Maroni, 2000). Licence applications have strict outlines and environmental monitoring programs are in place.

With such stringent industry control on environmental monitoring, and the large volume of monocultured fish, Norway could be an excellent candidate for IMTA systems. The biofiltration ability of seaweeds, along with the presently cultured shellfish species, would aid in meeting the government mandate towards environmentally sustainable farming. While Norway has a long history of seaweed harvesting (especially of kelps for alginates), there is no commercial seaweed culture in Norway. Many economically valuable species exist in Scandinavian waters (e.g. *Laminaria, Saccharina, Porphyra, Gracilaria, Palmaria, Chondrus*, etc.) and it would be interesting to integrate these species with salmon farms to help aquaculture become more sustainable.

The availability of resources for fish feed, suitable locations in the coastal zone, pathogen control and environmental impacts have all been regarded as possible constraints for the continued growth of the Norwegian salmon aquaculture industry (K. Reitan, pers. comm.). While Norway has aimed to produce 2.5 million tonnes of farmed salmon by 2030, researchers and industry are aware that these constraints must be addressed in order for their industry to maintain a high level of production and quality.

To help deal with these constraints, Norwegian researchers have initiated two projects. The first project is currently investigating possible pathogen transfer between blue mussels and salmon (Skar and Mortensen, 2007). The second project is a 5-year (2006-2010) pilot IMTA project. In this project, researchers are investigating which technologies are best used to determine site and species appropriateness, as well as which apparatus are best for the growth and harvest of alternate species. Currently, researchers have integrated blue mussels at salmon farms, and are planning to expand into seaweeds such as *Laminaria* and *Gracilaria* at these sites (K. Reitan, pers. comm.).

Investigators have highlighted two main points that require improvement to ensure the success of IMTA in this region: the adaptation of technology for growth of the alternate species (i.e. mussels and seaweeds), and the reduction of labour intensive activities, particularly during harvesting (K. Reitan, pers. comm). Improvements in both these areas will ensure economic efficiency of IMTA. Although at this point in time there is no commercial scale IMTA in Norway, it may only be a few years (after 2010) until researchers have developed the appropriate technology and systems to bring this practice to commercial scale. Regulations regarding distances between farms and types of organisms will also have to be revisited for their appropriateness vis à vis IMTA.

Southern Africa

South Africa

In 2004, South Africa produced 2 845 tonnes of seaweeds and 1 680 tonnes of shellfish, with respective values of US$1 252 000 and US$6 477 000 (Table 1). South African mariculture is focused on the abalone industry, particularly the Midas ear abalone, *Haliotis midae* (Bolton *et al.*, 2006), as well as on the Pacific oyster (*Crassostrea gigas*) in the Knysna region of the Cape and the Mediterranean mussel (*Mytilus galloprovincialis*) in the Saldahna Bay area. This industry has grown rapidly over the past ten years, expanding from Port Nolloth to Port Elizabeth along the west coast of the region where suitable rocky habitat exists (Troell *et al.*, 2006). However, a bottleneck for this rapidly expanding industry has been the availability of a consistent and convenient food source. Over 6 000 tonnes of kelp, *Ecklonia maxima*, are harvested annually on the South African west coast for abalone feed, and some kelp beds are now reaching sustainable limits of exploitation. As a result, *Ecklonia maxima* has been the subject of a parallel aquaculture industry with many systems now developed as integrated abalone-kelp culture units (Troell *et al.*, 2006). This kelp is grown alongside the abalone and is harvested as a food source for the molluscs. This on-land integrated culture unit, with shallow raceways, is widely viewed as the preferred method of production for the abalone industry, and the way of the future for the industry (Bolton *et al.*, 2006). A growing body of evidence suggests that a mixed diet of kelps and other seaweeds can induce growth rates at least as good as with artificial feed, can improve abalone quality and reduce parasite loads. Seaweeds grown in abalone wastewater have an increased nitrogen content, resulting in value-added seaweeds with over 40 percent protein dry weight content and, hence, of excellent quality to feed abalone.

According to Bolton *et al.* (2006), besides *Ecklonia maxima*, *Ulva* has also been grown in integrated culture units with abalone. However, when the abalones were fed a diet of *Ulva*, an off-taste and sulphur-like smell was observed in the canned abalone, thus decreasing market value. It is known that *Ulva* can increase the levels of dimethyl sulphide in abalone; therefore it is not the preferred feed choice. This off taste in abalone has not been observed in *Ecklonia maxima* fed abalone. Farmers should thus consider the effects of taste the various seaweed species may have on their final shellfish products to avoid product depreciation.

Besides *Ulva* and *Ecklonia*, the seaweeds *Gelidium* and *Gracilaria* are both harvested from wild populations along the coast of South Africa (Troell *et al.*, 2006). These seaweeds could also be used as candidates for IMTA systems. The integrated cultivation of *Gracilaria* with salmon, and its economic value, have already been demonstrated in Chile (Buschmann *et al.*, 2001; 2005; 2006), making it an obvious choice for IMTA in any country where it exists naturally.

The general benefit from IMTA, i.e. reduction of nutrient release to the environment, is also true for integrated seaweed-abalone culture. Furthermore, as seaweeds remove ammonium from the seawater and add oxygen, the abalone wastewater passing through seaweed ponds can be partially re-circulated back to the abalone tanks, thus potentially reducing pumping costs. The ability to operate in re-circulation mode is important as red tides occasionally occur along the South African coast. Moreover, some coastal areas experience heavy traffic of tanker boats, which represent potential risks for oil spills. It has been shown that a farm can operate successfully at 50 percent re-circulation, and even higher recirculation (up to 100 percent) can be sustained for shorter periods. This can, of course, be optimized, depending on what the main objective is with re-circulation. The re-circulation through seaweed tanks/ponds also has the potential to raise water temperature, which can stimulate abalone growth in areas of cold coastal waters. Compared to many other aquaculture operations, there is currently no real environmental pressure from abalone wastewater release in South Africa. Wastes from abalone operations are different from those of fish, with significantly lower concentrations of both nitrogen and phosphorus. This implies that the seawater in the seaweed tanks needs to be fertilized to sustain seaweed growth. This additional input of nutrients would not be needed if seawater from fish tanks were to be used (this has been tested with success). The development of IMTA in South Africa has, in fact, been driven by other incentives, such as future limitation of wild kelp harvesting and the proven economic benefits from improved abalone growth and quality with seaweed diets.

There is also strong socio-economic pressure on the South African government to create more jobs in the area, which has high unemployment and poverty levels (Troell *et al.*, 2006). The further expansion and permanent job creation potential of this industry, as well as indirect related jobs, in remote coastal communities, is very attractive. Thus there is much support for this practice of co-cultivating kelp with abalone, from government, industry and the general population.

There may also be incentives to move IMTA concepts into the mussel growing industry in Saldahna Bay. Studies have shown that the large mussel culture rafts are impacting the benthos in the Bay, suggesting that stocking densities are too high for natural assimilation of the organic load to the bottom (Stenton-Dozey, Probyn and Busby, 2001).

Asia

China

The level of IMTA development in the marine temperate waters of China is not easy to apprehend, as published information on IMTA in that country is difficult to find or access. Describing the development of IMTA in China is really beyond the scope of this review; it would, however, deserve a review on its own, written by Chinese authors or by people with a rare and prolonged insight in the history of aquaculture in that vast country.

IMTA in China will be covered succinctly below by reporting on two examples of variations on this practice approach: suspended multi-species aquaculture, generally in shallow nearshore waters, and multi-species large scale sea ranching in more offshore and deeper waters (J. Fang, pers. comm.). The reader should note the large scale of these enterprises.

An example of suspended multi-species aquaculture is what is being developed in Sungo Bay, in the East of the Shandong Peninsula. Scallops (*Chlamys farreri*, 2 100 tonnes fresh weight in 2005) and oysters (*Crassostrea gigas*, 110 000 tonnes fresh weight) are cultivated, on the same long line system, with the kelp, *Laminaria japonica* (80 000 tonnes fresh weight). The cultivation zone extends to 8 km offshore with a water depth of around 20-30 m. The co-cultivation of abalone (*Haliotis discus hannai*, 1 000 tonnes fresh weight) with *L. japonica* is also being developed, with abalones kept in lantern nets hanging vertically from the long lines, while kelps are grown on ropes maintained horizontally between long lines so that the abalones can feed on the kelps by manual feeding. Once the kelps have been harvested, the abalones are fed with dried kelps.

An example of multi-species large scale sea ranching is taking place near Zhangzidao Island, 40 miles offshore in the northern Yellow Sea (water depth from 10 to 40 m). Sea ranching is usually practised for the enhancement of natural stocks, but the scale and intensity at which it is practised in some Chinese waters means, in fact, that one is really talking about aquaculture on natural substrates. The Zhangzidao Fishery Group Co., Ltd., is authorized to farm up to approximately 40 000 ha, and presently cultivates 26 500 ha of the scallop, *Patinopecten yessoensis*, 10 000 ha of the arkshell, *Scapharca broughtonii*, 660 ha of the sea cucumber, *Apostichopus japonicus*, and 100 ha of the abalone *Haliotis discus hannai.* The company has been in existence for more than 10 years. The total harvest in 2005 reached 28 000 tonnes, valued at more than US$60 million (US$18 million in net profit). To improve ecological conditions and the sustainability of the operation, the company is now thinking of developing seaweed cultivation and the construction of artificial reefs in more offshore environments. To date, about 13 300 ha have been optimized in this way.

MAJOR REQUIREMENTS FOR THE EXPANSION OF IMTA

In order to ensure the further development of IMTA systems in marine temperate waters, several steps should be taken to move IMTA from the experimental concept to the full commercial scale.

Establishing the economic value of IMTA systems and their co-products

One such requirement would be to ensure that the added elements (e.g. seaweeds, shellfish, echinoderms and polychaetes) to an already existing monoculture unit (e.g. fish farm) make the systems at least as profitable or even more. Several projects in different parts of the world, like those presented above, have now accumulated enough data and information to support the biological demonstration of the IMTA concept. The next step is the scaling up of the experimental systems to make the biological demonstration at a commercial scale, and to document the economic and social advantages of the concept, which will be key to convincing practitioners of mono-specific aquaculture to move towards IMTA practices.

IMTA farms should be planned and engineered as complete systems, rather than as clusters of different crops, to maximize the benefits of the complementing ecological functions of the different species toward the profitability of the entire operations. Economic analyses need to be inserted in the overall modelling of IMTA systems as they get closer to commercial scale and their economic impacts on coastal communities are better understood. It will, then, be possible to add profitability and economic impacts to the comparison of the environmental impacts between IMTA and monoculture settings. These models will need to be sensitized for the most volatile parameters and explicit assumptions so as to develop models for IMTA systems with built-in flexibility to be tailored to the environmental, economic and social particulars of the regions where they will be installed. They could be modified to estimate the impact of organic and other eco-labels, the value of biomitigation services, the savings due to multi-trophic conversion of feed and energy which would otherwise be lost, the reduction of risks by crop diversification and the increase in social acceptability of aquaculture (including food safety, food security and consumer attitudes towards buying sustainable seafood products).

An indirect effect of establishing the economic value of IMTA systems to a community will result in the increase stewardship of the coastal zone. Because the system has to work as a whole, there will be direct economic benefits flowing to the community for keeping the ecosystem healthy. In a practical sense, this means reviewing infrastructure projects from an environmental point of view will be important to the town's finances. The increased cost of monitoring and management should be more than made up by the returns from the local IMTA industry with their increased value in food quality and safety.

Developing bio-economic models for IMTA systems

Chopin *et al.* (2001) demonstrated how integrating seaweeds (*Gracilaria*) with salmon farms can help increase profits while internalizing environmental costs. Assuming an average price for salmon of US$4.8 kg, Table 3 shows how salmon farm profits (at different production levels and stocking densities, based on Chilean fish farms) increase without internalizing the total environmental costs (scenario a) and present situation throughout the world). Assuming the costs of effluent mitigation are US$6.4 to 12.8/kg for nitrogen and US$2.6 to 3.8/kg for phosphorus (based on treatment costs in Swedish sewage treatment plants), scenario b) of Table 3 shows that, if laws or regulations were implemented to have aquaculture operations responsibly internalizing their environmental costs, a significant reduction of their profitability would occur. Scenario c) of Table 3 shows that by integrating the culture of the nutrient scrubber and commercial crop *Gracilaria* (at a conservative price of US$1 per kg [dry]), the environmental costs of waste discharges are significantly reduced and profitability is significantly increased. Although profitability in Table 4 is not as high as in Table 5 in the short term, it gains stability and sustainability for the culture system and reduced environmental and economic risk in the long term, which should make financing easier to obtain (Brzeski and Newkirk, 1997).

Another economic model using integrated salmon-mussel farms was developed by Whitmarsh, Cook and Black (2006) using base line data from farms on the west coast of Scotland. Table 5 shows that the NPV of a salmon-mussel IMTA system is greater than the combined NPV of salmon and mussel monoculture, assuming 20 percent greater production rate of mussels due to proximity to fish cages and a discount rate of 8 percent. Enhanced mussel productivity translates into a measurable financial benefit,

TABLE 4

Scenarios for salmon monoculture versus kelp/mussel/salmon IMTA in the Bay of Fundy, Canada. Ten year run NPV discounted at 5 percent and 10 percent (in US$)

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

Source: Ridler *et al.* (2007).

TABLE 5

Financial performance (in UK£) of salmon and mussel aquaculture, considered independently or in an IMTA system

Indicator	Salmon monoculture	Mussel monoculture	IMTA	Integration benefits
Normal production (tonnes per annum)	600	77	-	15.4
Price (UK£ per tonne)	1 900	1 100	-	-
Annualized equivalent cost (UK£ per tonne)	1 723	583	-	-
NPV (UK£)	922 114	353 328	1 425 685	150 243

Source: Whitmarsh, Cook and Black (2006).

TABLE 6

Net present value (NPV in UK£) of salmon/mussel IMTA investment: sensitivity to variations in mussel productivity enhancement and salmon price trends

Mussel productivity enhancement (percent)	Integration benefits (UK£)	Constant salmon price (UK£)	Salmon price falls at 1 % per annum (UK£)	Salmon price falls at 2 % per annum (UK£)
0	0	1 275 442	477 455	-242 795
10	75 121	1 350 564	552 577	-167 673
20	150 243	1 425 685	627 698	-92 552
30	225 364	1 500 807	702 820	-17 430

Source: Whitmarsh, Cook and Black (2006).

which can be recognized as a genuine “economy of integration”. Table 6 describes the sensitivity of the NPV of IMTA under three different assumptions about salmon prices. Integration is economically profitable if the price of salmon remains constant or drops by 1 percent per annum; however, a drop of 2 percent per annum would result in a negative NPV for IMTA, making it a financially unattractive investment. It should be noted, however, that the non-viability of the aquaculture operation was due to the salmon prices rather than the value of the associated species, in this case mussels.

The IMTA project in the Bay of Fundy, Canada, is presently developing a bio-economic model (Ridler *et al.*, 2007). Economic estimates (with risk scenarios) have been undertaken comparing the profitability of a kelp/mussel/salmon IMTA system with salmon monoculture. Initially a capital budgeting model was designed for a hypothetical salmon monoculture cage operation using parameters for the Bay of Fundy. To this were added fixed and operating costs of mussel and kelp cultivation, and potential additional revenues from these two species. Profitability (NPV) was estimated by projections over ten years using discount rates of 5 percent and 10 percent. To take risk into consideration, three scenarios were run, and each scenario was given a probability of occurrence. The best scenario, Scenario 1, has salmon harvested every second year, with a mortality rate of 11 percent. This would give a total of five successful harvests in the ten year span with a probability of occurrence of 20 percent. The worst scenario was Scenario 2. It followed the same rules as the first, except it had only four successful harvests, because in one harvest all fish were assumed destroyed. This scenario is plausible because of infectious salmon anaemia or winter chill. This scenario was assigned a 40 percent probability. Scenario 3 was intermediate between 1 and 2. It had four successful harvests and one harvest in which only 30 percent of the fish survived. This scenario was also given a 40 percent probability. The NPV for these scenarios are shown in Table 4. Additional revenues from mussels and seaweeds more than compensate for additional costs with a resulting higher NPV for IMTA than for salmon monoculture. The increase in NPV is significant at 24 percent. As one would expect with diversification, IMTA results in higher NPV. Mussels and seaweeds provide alternative uncorrelated sources of income, thereby softening the damaging effect of salmon losses. Even under the worst case scenario (2), IMTA provided a positive NPV at both discount rates. Just one bad harvest can have a negative impact on the entire 10 year run of a monoculture salmon farm, whereas IMTA effectively reduces the risk. The natural factors that affect salmon mortality may not necessarily affect mussels and kelps. For instance, salmon experience winter chill at -0.8°C, while mussels and kelps can survive much colder temperatures (e.g. mussels live in the intertidal zone that can experience drops to -40°C); similarly, kelps are temperate cold water organisms and, in fact, most of kelp growth occurs from winter to late spring). Therefore, the addition of these co-products can reduce risk (it is unlikely that all three species will be affected simultaneously) and maintain profitability.

These economic models (Chopin *et al.*, 2001; Whitmarsh, Cook and Black, 2006; Ridler *et al.*, 2007), all based on different IMTA operations (using data from Chile and Sweden, Scotland, and Canada), indicate that integrating mussels and seaweeds with existing salmon monocultures can increase the profits of salmon farmers while remaining environmentally responsible. Also, this increase in profitability is compounded over time, grows with increased production and stocking densities, and is using only conservative estimates for seaweed market value. Assuming no major market changes or die-offs, the outlook for IMTA is certainly promising.

Exploring additional economic value for IMTA coproducts

Besides the commonly cultured finfish, shrimps and bivalves, the economic value of seaweeds, echinoderms, crustaceans and polychaetes should also be considered for IMTA.

Aquatic plants represent 23.4 percent of the tonnage and 9.7 percent of the value of the global (marine, brackishwater and freshwater) aquaculture production, estimated at 59.4 million tonnes and US$70.3 billion in 2004. Considering only mariculture (50.9 percent of the global aquaculture, estimated at 30.2 million tonnes and US$28.1 billion), aquatic plants represent 45.9 percent of the tonnage and 24.2 percent of the value. Molluscs represent 43.0 percent, fish 8.9 percent, crustaceans 1.8 percent, and other aquatic animals 0.4 percent (FAO, 2006a). The seaweed aquaculture production (92 percent of the world seaweed supplies) is estimated at 11.2 million tonnes and US$ 5.7 billion (99.7 percent being provided by Asian countries). Approximately 220 species of algae are cultivated; however, 6 genera are providing 94.8 percent of the seaweed aquaculture production (*Laminaria* [kombu; 40.1 percent], *Undaria* [wakame; 22.3 percent], *Porphyra* [nori; 12.4 percent], *Eucheuma/Kappaphycus* [11.6 percent] and *Gracilaria* [8.4 percent]), and 4 genera are providing 95.6 percent of its value (*Laminaria* [47.9 percent], *Porphyra* [23.3 percent], *Undaria* (17.7 percent) and *Gracilaria* [6.7 percent]).

According to Santos (2006), until recently, the most commonly used seaweeds for biofiltration in Europe belonged to the genera *Ulva* and *Gracilaria*. Although their husbandry is well established, their market value is low, as they are used primarily as feed or fertilizer. Therefore alternative species of seaweeds with higher market value are being explored. For example, *Asparagopsis armata* has a high value due to its ability to concentrate halogenated organic metabolites, which can be used for fungicides, antibiotics and skin cosmetics, with the possibility of patents (Lognone *et al.*, 2003). Therefore to ensure further expansion of IMTA, further research into alternative species must continue or be initiated. As well, new markets for these products should be sought out to further safe guard economic reward.

As shown in Table 2, seaweeds can be highly profitable, assuming growing conditions are optimal and market niches have been established. While there exists a wide range in seaweed use (e.g. from fertilizer to human consumption), the value and quality of the product also have a wide range. These points are important to consider when determining product value.

Other species in an IMTA system, invertebrates and herbivores in general, also have high economic value. As shown in Table 1, molluscs (particularly bivalves) have well established market value. Other mid-trophic animals such as echinoderms, crustaceans and polychaetes are also economically valuable. Ross, Thorpe and Brand (2004) showed how sea urchins and crabs can be grown with scallops to prevent biofouling on nets, which in turn help reduce maintenance costs and improve growth rates of scallops. These co-products can also be sold. For example, sea urchin gonad (“roe” or “uni”) is popular in Asian sushi restaurants where it can demand prices in the range of US$6 to US$200 per kilogram, depending on quality (Robinson, Castell and Kennedy, 2002; Robinson, 2004). Therefore to ensure maximal gonad growth and quality, the stage of gametogenesis (among other factors) must be considered before harvesting (Robinson, Castell and Kennedy, 2002). However, as wild stocks of sea urchins are in decline, and the demand from Japanese markets still exists, aquaculture of sea urchins is viewed in a positive light and research into sea urchin (particularly that of the green sea urchin, *Strongylocentrotus droebachiensis*) growth and husbandry is ongoing (Pearce, Daggett and Robinson, 2004; Robinson, 2004; Daggett, Pearce and Robinson, 2006). There is much room for growth in the sea urchin aquaculture industry. In 2004, the global fishery for sea urchins (*Strongylocentrotus* spp. and *Paracentrotus lividus*) was 32 606 tonnes, while commercial aquaculture that same year was reported at only 7 495 tonnes (FAO, 2006b). This occurred in Asia (7 491 tonnes of *Strongylocentrotus* spp. worth US$22 473 000) and Europe (4 tonnes of *Paracentrotus lividus* worth US$47 000) (FAO, 2006b). In Chile, the sea urchin *Loxechinus albus* has been overexploited for domestic and export markets (Moreno *et al.*, 2007). The largest harvest was recorded in 2002 (60 000 tonnes). It declined to 37 000 tonnes in 2005, with an export of 3 000 tonnes worth US$61 000 000 (FAO, 2006b). There are presently several efforts to develop sea urchin aquaculture in Chile due to the imminent collapse of the fishery in all regions but the 12th; however, farmed sea urchins remain more expensive than wild harvested ones.

Another echinoderm that has strong market demand from Asian markets is the sea cucumber. Sea cucumbers, particularly the species *Holothuria scabra* and *Stichopus japonicus*, have been heavily exploited by the traditional fisheries, and as a result of strong market demand, sea cucumber aquaculture is on the rise (Hamel and Mercier, 1997; Purcell, Blockmans and Agudo, 2006; Purcell, Patrois and Fraisse, 2006). In 2004, Asia produced 53 315 tonnes of cultured *Stichopus japonicus* worth US$159 943 000 (FAO, 2006b). Although commercial scale sea cucumber aquaculture is currently restricted to Asia, there is a pilot project underway on the Pacific coast of Canada culturing *Parastichopus californicus*. Traditional fisheries are located globally, capturing a total of 23 439 tonnes, with 4 973 tonnes from North America and 15 470 tonnes from Asia (FAO, 2006b). Sea cucumbers are naturally found in temperate waters, and with a high market demand and value, are excellent candidate species for IMTA. In Chile, there are pilot projects to cultivate *Athyonidium chilensis* and *Apostichopus japonicus* for export markets.

Traditional lobster and crab fisheries are also highly lucrative. In 2004, globally, 232 922 tonnes of wild lobster were caught in traditional capture fisheries (FAO, 2006b). Commercial aquaculture of the spiny lobster that same year was reported at only 39 tonnes (FAO, 2006b). This occurred in North America (1 tonne worth US$5 000) and Asia (38 tonnes worth US$655 000) (FAO, 2006b). If these animals could be integrated with existing fed-aquaculture operations, it could not only provide profit for the farmers, but it could also relieve pressure on dwindling wild populations and help clean the benthic environment of the aquaculture sites. While much research is being done on the culture of the spiny and rock lobsters, *Panulirus* sp. and *Janus* sp. (common in tropical waters; Phillips and Liddy, 2003; Phillips, Smith and Maguire, 2004), there is much work yet to be done on the culture of the temperate water lobsters, *Homarus americanus* and *Homarus gammarus* (Nicosia and Lavalli, 1999; Tlusty, Fiore and Goldstein, 2005) and their integration in IMTA systems. In the Bay of Fundy, Canada, it is common to see lobster boats setting their traps at the periphery of salmon aquaculture sites. In the majority of cases, there is a good relationship between the farmers and the fishers and the divers that service aquaculture sites will often retrieve lobster traps that have become entangled in the mooring lines and give them back to the fishers (S. Robinson, pers. comm.).

Polychaetes are another invertebrate group that can play a key role in IMTA. These worms are often found in benthic regions under aquaculture sites, and can play an important role in organic sediment bioremediation (Lu and Wu, 1998). Polychaetes (*Sabella spallanzanii*) have been successfully co-cultured with the alga *Cladophora prolifera* as bioremediators for aquaculture wastewater treatment in the Mediterranean

Sea (Pierri, Fanelli and Giangrande, 2006). In a review on polychaete aquaculture, Olive (1999) recommended the potential for polychaetes to be used as feed for fish brood stock. Olive (1999) also drew attention to the niche that polychaetes have in the recreational fishing industry. Interestingly, some polychaetes (*Nereis* spp. "ragworms" and *Arenicola* spp. "lugworms") have high value as bait in the sea angling sport and leisure industry. These marine worms are commonly sold in bait shops in the United Kingdom, Ireland and the Netherlands. Olive (1999) reported that the European baitworm industry is worth about €200 million (US$262 million), and according to FAO (2006b), while no commercial harvest of cultured polychaetes was reported in 2004, there was a wild harvest of 500 tonnes of polychaetes. With a high value as fishing bait, the potential as a food supply for fish brood stock, and their role as a sediment bioremediator (Tsutsumi *et al.*, 2005), polychaetes integrated with existing aquaculture operations could be beneficial for fish farmers. Moreover, the haemoglobin of *Arenicola marina* has been reported as a potential substitute for human red cells (Zal, Lallier and Toulmond, 2002), and could be a promising alternative at a time of worldwide blood shortage.

Besides uses as bioremediators, biofouling agents, bait, fishmeal and human consumption, invertebrates and herbivorous fishes can also be used to meet the market demand for aquaria and laboratory specimens. In 2001, the global export value of ornamentals was US$350 million (Hardy, 2003). Although marine ornamentals only consisted of 4 percent of the volume, they were worth 20 percent of the value (Chapman *et al.*, 1997). While most ornamentals are captured in the wild or grown in aquaria, the potential for co-culturing ornamentals with other aquaculture species could hold lucrative economic benefits for farmers, if they chose to exploit this market niche.

It will also be important to assemble interdisciplinary and complementary teams combining the expertise of cultivating and providing marine biomass (of different and consistent composition and quality through IMTA practices) with the expertise of identifying and characterizing bioactive compounds. This will position differentiated IMTA products for high added-value applications in promising niche market opportunities, and, consequently, make the whole IMTA approach even more attractive and profitable.

Selecting the right species

When establishing which species to use in an IMTA system, one must carefully consider the suitability of the species in a particular habitat/culture unit. In order to ensure successful growth and economic value, farmers should:

- Use local species that are well within their normal geographic range and for which technology is available. This will help to prevent the risk of invasive species causing harm to the local environment, and potentially harming other economic activities. These species have also evolved to be well adapted to the local conditions.
- Use species that will complement each other on different trophic levels. For example species must be able to feed on the other species' waste in order for the newly integrated species to improve the quality of the water and grow efficiently. Not all species can be grown together efficiently. Particulate organic matter and dissolved inorganic nutrients should be both considered, as well as the size range of particles, when selecting a farm site.
- Use species that are capable of growing to a significant biomass. This feature is important if the organisms are to act as a biofilter that captures many of the excess nutrients and that can be harvested from the water. The other alternative is to have a species with a very high value, in which case lesser volumes can be grown. However, with the latter, the biomitigating role is reduced.
- Use species that have an established or perceived market value. Farmers must be able to sell the alternative species in order to increase their economic input. Therefore, they should establish buyers in markets before investing too heavily.

- Use species for which regulators and policy makers will facilitate the exploration of new markets, not impose new regulatory impediments to commercialization.

Understanding habitat specificity

Each farm site has its own unique oceanographic and biological characteristics. These factors will affect the performance of the species being grown. Therefore, when establishing aquaculture leases, site managers should know the flushing rates, nutrients and oxygen levels, temperature and salinity ranges, ice conditions, etc., for each site. The addition of infrastructures to cultivate different species can alter the oceanographic and biological conditions of a habitat to a certain extent. Therefore site managers should be mindful of the changes in oxygen levels, flow rates, particulate organic matter and dissolved inorganic nutrient levels, etc. when species are added or removed from an IMTA system. For example, the addition of seaweeds and shellfish can alter the O_2 and CO_2 concentrations for short periods of time at an aquaculture site that is naturally limited in O_2 at different times of the year (e.g. the fall in the Bay of Fundy, Canada). Using GIS tools could facilitate the identification of sites amenable to IMTA practices by offering the best compromise of characteristics which will be acceptable to different species with different requirements.

Promoting effective government legislation/regulations and incentives to facilitate the development of IMTA practices and the commercialization of IMTA products

Establishing effluent regulations conducive to the development of IMTA

The development and adoption of technology often depends highly on the level of legislative pressure from a nation's government, itself reacting to pressures from consumers, ENGOs and the public at large. If environmental legislation remains 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 profit obtained from additional product growth and regulatory incentives. Therefore, if government puts legislative pressure on the proper management of wastewater effluent, openly supports the use of biomitigation for effluent management, and put in place the appropriate corresponding financial tools (funding for IMTA R&D, outreach and technology transfer and tax incentives), the development of IMTA will be encouraged.

It is also important to note that present aquaculture business models do not consider and recognize the economic value of the biomitigation services provided by biofilters, as there is no cost associated with aquaculture discharges/effluents in open seawater-based systems. Regulatory and financial incentives may therefore be required to clearly recognize the benefits of the extractive components of IMTA systems (shellfish and seaweeds). A better estimate of the overall cost/benefits to nature and society of aquaculture waste and its mitigation would create powerful financial and regulatory incentives to governments and the industry to jointly invest in the IMTA approach. For example, Denmark, after the initial development of finfish aquaculture in the 1970-80's, is now reconsidering more finfish aquaculture development, but the condition for that to occur is proper planning for biomitigation and the recommended use of biofilters, such as seaweeds and shellfish, is being considered. This means that the use of extractive species would become part of the license requirements to operate in Denmark, and that the nutrient reduction services provided by these organisms would finally be recognized and valued for their ecosystem functions. These services need to be quantified; for example, in Denmark, the remediation costs for one kilogram of nitrogen is estimated at €33 (Holdt, Moehlenberg and Dahl-Madsen, 2006). If laws or regulations were implemented to have aquaculture operations responsibly internalize their environmental costs, a significant reduction of their profitability would occur. As previously mentioned, a study in Chile showed that by integrating the culture of the algal nutrient biofilter *Gracilaria*, environmental costs of waste discharges are significantly reduced and profitability is significantly increased (Chopin *et al.*, 2001). The introduction of a nutrient tax, or its exemption through the implementation of biomitigative practices, would make the economic demonstration of the validity of the IMTA approach even more obvious. Moreover, by implementing better management practices, the aquaculture industry should increase its social 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.

Lifting fish farm moratoria on the condition that biomitigative practices such as IMTA are implemented

Many countries (e.g. Norway, Sweden and South Africa) have moratoria on the further expansion of fish farms. This could limit the immediate development of IMTA. However, as the positive benefits of this type of culture system become further known from the work of academic and industry pioneers in this field (e.g. Canada), it is likely those other countries will also adopt this practice. The adoption of IMTA may allow the further expansion of aquaculture farms and economic opportunities in coastal regions due to the sustainability and ecological balancing of this type of production system. Therefore, to ensure further expansion of aquaculture, countries could consider lifting the moratoria on fish farms, on the condition that they show initiative towards sustainable development, through biomitigation, as is already the case in Sweden (Lindahl *et al.*, 2005).

Putting in place enabling legislation for commercialization of IMTA products

For IMTA to develop to a commercial scale, appropriate regulatory and policy frameworks need to be put in place. Present aquaculture regulations and policies are often inherited from previous fishery frameworks and reasoning, which have shown their limitations. To develop the aquaculture of tomorrow, the present aquaculture regulations and policies need to be revisited. Adaptive regulations need to be developed by regulators with flexible and innovative minds, who are not afraid of putting 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 be 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 net-pens. This paragraph was never written with IMTA in mind, but it impinged seriously its development. After four years (2004-2008), it has finally been amended so that IMTA practices can legally develop to commercial scale based on recent, reliable and relevant data and information provided by the IMTA project in the Bay of Fundy and similar projects in other parts of the world. While four years may appear to be a long period of time for some, it is a relatively short delay when one recognizes the regulations and legislations that needed to be reviewed and considered through such governmental type processes involving several federal and provincial departments. However, when developing a new aquaculture practice in a particular country, regulatory issues should be addressed right from the beginning to avoid delays when new products are ready to go to market.

Recognizing the benefits of IMTA and educating stakeholders about this practice

Once government, industry and the general population will become aware of the positive impacts of IMTA, they are likely to be more inclined to encourage the establishment of these culture systems.

The benefits of IMTA include:

- The mitigation of effluents through the use of biofilters (e.g. seaweeds and invertebrates), which are suited to the ecological niche of the farm. → *Effluent biomitigation.*
- Prevention or reduction of disease among farmed fish can be provided by certain seaweeds due to their antibacterial activity against fish pathogenic bacteria (Bansemir *et al.*, 2006), or by shellfish reducing the virulence of ISAV (Skar and Mortensen, 2007; S. Robinson, pers. comm.). → *Disease control.*
- Increased overall economic value of an operation from the commercial by-products that are cultivated and sold. → *Increased profits through diversification.*
- Potential for differentiation of the IMTA products through eco-labelling or organic certification programmes. → *Increased profits through obtaining premium prices.*
- Economic growth through employment (both direct and indirect) and product processing and distribution. → *Improving local economy.*
- Product diversification may offer financial protection and decrease economic risks when price fluctuations occur, or if one of the crops is lost to disease or inclement weather. → *Form of 'natural' crop insurance.*

To help spread the word on the positive impacts of IMTA:

- Researchers should not only publish their work on IMTA in peer reviewed journals, but also in magazines geared toward the general public and industry professionals. It is very important to get the biological, economic and social results out as soon as possible as many institutions, agencies, industries and various organizations are taking a "wait and see" approach, which creates inertia for the development of IMTA systems.
- Government/industry/academia could launch public awareness campaigns (via media outlets, e.g. newspapers, TV and radio documentaries, pamphlets, websites; and information on IMTA seafood products available in the marketplace, through pamphlets, labels or stickers) to highlight the benefits of IMTA so that the general public could be reached and educated about this practice and the quality of its products.
- Academia/government/industry/general public should hold regular meetings to discuss progress, stumbling blocks, new directions, etc. so that the IMTA concept becomes better known, and progresses from better to best management practice (BMP).
- International exchanges between personnel working on IMTA could be established to exchange knowledge (e.g. conferences, workshops, student/researcher exchanges).
- A website database on IMTA could also be established to more easily share knowledge.

There is still a large amount of education and outreach required to bring society into the mindset of incorporating IMTA into their suite of social values. Some of the social surveys conducted in Canada (DFO, 2005; Barrington *et al.*, 2008) indicate that the general public is in favour of practices based on the "recycling concept". Whether this will translate into a greater appreciation of the sustainable ecological value of the concept, a willingness to support it tangibly with their shopping money, and demands to their elected representatives 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 determination to develop IMTA systems will, however, only come about if there are some visionary changes in political, social, and economic reasoning. This will be accomplished by seeking sustainability, long-term profitability and responsible management of coastal waters. It will also necessitate a change in the attitude of consumers towards eating products cultured in the marine environment in the same way that they accept eating products from recycling and organic production systems on land, for which they are willing to pay a higher price. IMTA systems, under their various forms, have existed for centuries in Asian countries, through trial and error and experimentation. Consequently, the Asian culture is accustomed to the concept of considering wastes from farming practices as resources for other crops rather than pollutants. However, this attitude still has a long way to progress in the western world where aquaculture is a more recent development. At the present time, several western organizations are trying to modify seafood consumption trends by incorporating such concepts into food safety, and environmental and social sustainability.

Governments have a role to play. One of the key roles for government agencies, from the municipal to the federal levels, is to understand the basic concept of IMTA and to evaluate their current and future policies. If they agree with the concept of IMTA, then they should try and promote protocols through their policies that will encourage the marine production sectors to follow those tenets. This could be done in the form of incentives or penalties similar to economic policies that are currently used to regulate environmental behaviour of people in land-based systems (i.e. fuel or cigarette taxes, better premiums for good behaviour on life insurance policies, incentives for identifying and recognizing the values of environmental services as in a few countries such as the Netherlands, Denmark and Sweden).

The aquaculture industry also has to play its role and be ready to help in the development of IMTA so that we take it along the continuum of R&D&C (C for commercialization). A closer association between natural, engineering and socio-economic scientists and industrial partners is necessary and, in fact, is very rewarding when it works. Scientists have to come down from their ivory tower and stop disparaging applied science, and industrial partners have to understand that answers do not always come from short-term projects and are not always black and white.

Academic institutions need to get involved. IMTA is truly interdisciplinary in nature. A lot of people talk about the interdisciplinary approach to problem solving, but very few practice interdisciplinarity and very few train students to be interdisciplinary minded. Academic institutions continue to teach along the classical disciplinary lines at both the undergraduate and graduate levels, which prevents cross-fertilization of minds and the development of appropriate minds for tackling interdisciplinary projects. Very few candidates for postdoctoral fellowships are presently ready for conducting interdisciplinary research. Academics need to develop curricula/programs to train the needed interdisciplinary scientists of tomorrow.

The international community of IMTA scientists and practitioners should coordinate its effort. It would be an understatement to say that gaining a working understanding of the essential functions of the ecosystem is a complex, but essential task. Reasonable estimates of the cause and effect relationships will have to be defined and this will take significant amounts of research time and funding. Although this knowledge will be needed for various ecological zones, these zones are often shared between various countries. For example, similar ecological processes are likely involved in temperate areas that are currently used to grow salmonids in sea pens in diverse countries such as Norway, Scotland, Chile, Canada and the United States of America. Therefore, it makes sense that these countries should collaborate in their efforts to understand how the ecological processes operate in their respective areas. Not only would a concerted effort allow for a sooner understanding of the principles involved so that all associated areas could benefit, it would also raise the public consciousness of the new paradigm on a global level.

Establishing the R&D&C continuum for IMTA

The maintenance of productive R&D programs is vital for any industry, particularly one as dynamic as today's aquaculture industry. As pointed out by Troell *et al.* (2003), several areas of R&D are especially important for IMTA:

- A thorough understanding of the biological, biochemical, hydrographic, oceanographic, seasonal and climatic processes, and their interactions, experienced at each IMTA site by the selected species/strains is crucial for management.
- To be useful, such R&D programs into these advanced aquaculture technologies should be conducted at scales relevant to commercial implementation or suitable for extrapolation, while still not being irreversible. They should address the biology, engineering, operational protocol and economics of these technologies.
- Models should be developed to estimate the appropriate biological and economic ratios between fed organisms, organic extractive organisms and inorganic extractive organisms at the aquaculture sites. If general models can be developed, they have to remain flexible and site manager friendly enough so that they can be tailored and adjusted to the specifics of a particular site.
- Adaptation and development of new technologies is very important to improve the efficiency of aquaculture operations. For example, what role does fallowing have in the functioning of an IMTA site? Is it necessary to fallow all organisms or just salmon?
- Engineers, statisticians, economists and marketing people play an important role in site design and operation, and in product distribution. Biologists, farm managers and stakeholders in general, should consult with these experts.
- The roles and functions of IMTA systems for improved environmental, economic and social acceptability should be analysed within the broader perspective of integrated coastal zone management and ecosystem carrying/assimilative capacity. The appropriate variables to measure, as proxies for describing the health of the system, often remain to be identified.
- Appropriate food safety regulatory and policy frameworks will have to be developed and harmonized among countries to enable the development of commercial scale IMTA operations in a more universal fashion.
- Educational, training and financial incentive approaches have to be developed to facilitate the outreach and transfer of these novel, and somewhat complex, IMTA technologies from the scientists to the industry, the different levels of government and the public at large.

As always, when large projects involve different parties, their timetables and objectives are not always aligned. The research is conducted under academic timelines in synchrony with grant schedules. Business runs on shorter timelines than science and has to be more flexible. Timelines for changing business plans only start once there are enough data to convince industry to start; but once they do, things will happen quickly. So, there is a need for harmonizing needs and deadlines by parties understanding that they operate under different constrains and objectives/goals.

The successful development of IMTA will require a clear commitment from the different players (the aquaculturists, the scientists, the government departments, the funding agencies, the ENGOs and the public at large), associated with a clear respect and appreciation of their respective contributions, while recognizing their specificities. The role and mission of R&D should be clearly understood. One has to realize that the order of the letters has its significance: it is R&D, not D&R (the horses before the carriage!). R&D should be conducted in a scientific manner to obtain and keep credibility and validity. If not properly carried out, it could lead to questionable data, unfounded speculations and biased conclusions. Consequently, one has to recognize that R&D is a full component of any economic development plan. One should also not forget that R&D is only justified if a "C" (commercialisation) comes next; unfortunately, there is frequently a major gap between R&D and C, often because the appropriate funding structures and incentives are not in place to take a R&D project to a C reality.

One must also understand that the performance evaluation of IMTA systems requires a different approach from the typical linear growth models used for monoculture over the last decades, without consideration of the environmental and social costs. Five-year profitability models, with the goal of reaching maximal performance for each cultured species in isolation, should be replaced by optimized, long-term and sustainable bio-economic models in which the yield per unit resource input is evaluated.

Finally, let us not forget that we are still in the infancy of modern intensive aquaculture and that some agricultural practices have taken centuries to develop into better, not yet best, management practices.

CONCLUSIONS AND RECOMMENDATIONS

The aquaculture ecological, engineering, economic and social challenges remaining to be solved are for some maybe daunting. However, the goal is to develop modern IMTA systems, which are bound to play a major role worldwide in sustainable expansions of the aquaculture operations of tomorrow, within a balanced ecosystem approach, to respond to a worldwide increasing seafood demand with a new paradigm in the design of the most efficient food production systems.

Most of the countries with coastlines in temperate regions of the globe have some level of aquaculture ongoing, although very few, with the exception of Canada, Chile, South Africa, the United Kingdom, Ireland, the United States of America and China, have ongoing IMTA systems near or at commercial scale. IMTA has enormous potential for growth in all the countries discussed. Several countries have active research programs gaining knowledge about their regions potential for development of IMTA, while other countries have made no direct groundwork toward the development of IMTA.

Genera of particular interest and those with high potential for development in IMTA systems in marine temperate waters include:

- *Laminaria, Saccharina, Sacchoriza, Undaria, Alaria, Ecklonia, Lessonia, Durvillaea, Macrocystis, Gigartina, Sarcothalia, Chondracanthus, Callophyllis, Gracilaria, Gracilariopsis, Porphyra, Chondrus, Palmaria, Asparagopsis* and *Ulva* (seaweeds),
- *Haliotis, Crassostrea, Pecten, Argopecten, Placopecten, Mytilus, Choromytilus* and *Tapes* (molluscs),
- *Strongylocentrotus, Paracentrotus, Psammechinus, Loxechinus, Cucumaria, Holothuria, Stichopus, Parastichopus, Apostichopus* and *Athyonidium* (echinoderms),
- *Nereis, Arenicola, Glycera* and *Sabella* (polychaetes),
- *Penaeus* and *Homarus* (crustaceans), and
- *Salmo, Oncorhynchus, Scophthalmus, Dicentrarchus, Gadus, Anoplopoma, Hippoglossus, Melanogrammus, Paralichthys, Pseudopleuronectes* and *Mugil* (fish).

This is based on established husbandry practices, habitat appropriateness, biomitigation ability and the economic value of these species.

In order to ensure the expansion of IMTA in these regions several steps should be taken where appropriate. These include:

1) Establishing the economic and environmental value of IMTA systems and their co-products – seaweeds and invertebrates can be very profitable cultured species, not only for their services as effluent biomitigators, but also as differentiated premium cash crops diversifying the aquaculture sector and reducing risks.

2) Selecting species appropriate to the habitat and available technologies – native species should be used, to avoid problems with invasive, and potentially harmful, species.
3) Selecting species according to the environmental and oceanographic conditions of the sites proposed for IMTA development, and also according to their complementary ecosystem functions.
4) Selecting species that are capable of growing to a significant biomass in order to capture many of the excess nutrients and remove them efficiently at harvesting time.
5) Selecting species that have an established or perceived market value and for which the commercialization will not generate insurmountable regulatory hurdles.
6) Promoting effective government legislation/regulations and incentives to facilitate the development of IMTA practices and the commercialization of IMTA products.
7) Educating government/industry/academia and the general public about the benefits of IMTA. This can be done by disseminating knowledge through diverse media supports targeting diverse audiences.
8) Establishing the R&D&C continuum to ensure success in the long term for IMTA to become a widespread reality.

Taking all these factors into account, IMTA can be used as a valuable tool towards the establishment of a more sustainable aquaculture sector. IMTA systems can be environmentally responsible, profitable and sources of employment in coastal regions for any country that develops them properly, especially when government, industry, academia, communities and ENGOs work in consultation with each other. It is highly recommended that IMTA systems be utilized wherever possible, and ultimately replace monoculture operations in regions where they can be developed.

The reasons for this aquaculture system replacement have been made clear in this report. IMTA is the best option for a sustainable aquaculture industry. It is environmentally responsible, economically profitable and more socially acceptable. The IMTA project established in the Bay of Fundy, Canada, has provided solid examples concerning all these issues (environmental, economical and social) and can be referred to as a base model for temperate water IMTA. Indeed, several other countries in temperate waters have begun to establish their own IMTA systems, although much more R&D&C is needed.

Overall, the keystone of IMTA is integration. As pointed out during a workshop on IMTA in Saint John, New Brunswick, Canada, in March 2004 (Robinson and Chopin, 2004), a successful IMTA operation must integrate all stakeholders into its development plan. Government, industry, academia, the general public and ENGOs must work together. The role of IMTA in an integrated coastal zone management plan must be clearly defined. Beyond selecting the appropriate species for growth at a particular site, economics and social acceptability must also play a key role. Once these are established, a focused R&D&C programme will ensure efficiency and long-term sustainability for the aquaculture sector.

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