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Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture

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Abstract

Rising global demand for seafood and declining catches have resulted in the volume of mariculture doubling each decade, a growth expected by the FAO to persist in the decades to come. This growth should use technologies with economical and environmental sustainability. Feed accounts for about half the cost in current high-volume fed mono-species aquaculture, mainly fish net pens or shrimp/fish ponds, yet most of this feed becomes waste. The resulting environmental impact and rising feed costs therefore hamper further growth of such farms. As in certain traditional polyculture schemes, plants can drastically reduce feed use and environmental impact of industrialized mariculture and at the same time add to its income. These nutrient-assimilating photoautotrophic plants use solar energy to turn nutrient-rich effluents into profitable resources. Plants counteract the environmental effects of the heterotrophic fed fish and shrimp and restore water

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quality. Today's integrated intensive aquaculture approaches, developed from traditional extensive polyculture, integrate the culture of fish or shrimp with vegetables, microalgae, shellfish and/or seaweeds. Integrated mariculture can take place in coastal waters or in ponds and can be highly intensified. Today's technologies are well studied and documented. They are generic, modular and adaptable for several culture combinations of fish, shrimp, shellfish, abalone, sea urchin and several species of commercially important seaweeds and vegetables. A 1-ha land-based integrated seabream–shellfish–seaweed farm can produce 25 tons of fish, 50 tons of bivalves and 30 tons fresh weight of seaweeds annually. Another farm model can produce in 1 ha 55 tons of seabream or 92 tons of salmon, with 385 or 500 fresh weight of seaweed, respectively, without pollution. Preliminary calculations show a potential for high profitability with large integrated farms. Several freshwater integrated fish–vegetable farms and a couple of modern fish–algae–shellfish/abalone integrated mariculture farms exist today, and several additional farms are planned. Three major international R&D projects promise to soon expand the horizons of the technology further. Therefore, modern integrated systems in general, and seaweed-based systems in particular, are bound to play a major role in the sustainable expansion of world aquaculture.

Keywords: Integrated aquaculture; Seaweed biofiltration; Modern mariculture

1. Introduction and rationale

While capture fisheries fall short of world demand, annual consumption of seafood has been rising, doubling in three decades (FAO, 2000). Obviously, just as we no longer depend on hunting, we can no longer depend solely on fishing. Even today, aquaculture provides over a quarter of the world's seafood supply, a figure the FAO expects will approach 50% by the year 2030 (Tidwell and Allen, 2001). With the diminishing availability of freshwater, most of this growth will take place in seawater.

Intensive fish mariculture today takes place largely in net pens while shrimp is farmed in coastal lagoons or ponds. The economic success of this approach has much to do with the fact that the nutrification of the environment involves little monetary cost to the growers, that is to say that mariculture does not yet have to internalize the cost of water treatment. However, this age is coming to a timely end in industrialized nations. Awareness by scientists, industry, the public and politicians is such that technologies with uncontrolled impact are no longer considered sustainable (Chamberlaine and Rosenthal, 1995; Costa-Pierce, 1996; Sorgeloos, 1999; Naylor et al., 2000; Chopin et al., 2001). Salmon farms in Norway are already legislated, regulated and licensed on siting, disease control, use of therapeutants, interaction with other species, waste discharges and feed quotas (Maroni, 2000). Moreover, growers themselves are coming to the realization that their own fish and shrimp live in these waters and are the first to suffer from nutrification consequences, such as harmful algal blooms, anoxia and parasites. This in itself is costly; however, growers will soon also have to pay for the remediation of the environmental impacts caused by their operations.

When synthesizing the treatment of modern aquaculture waters (freshwater and marine) and the mitigation of the environmental impacts of aquaculture (Lee and Jones, 1990; Wu, 1995; Krom et al., 2001), two main practical approaches are emerging: bacterial dissimilation into gases and plant assimilation into biomass.

Bacterial biofilters are dissimilative. Through a series of oxidation and reduction processes, they break the pollutants down into harmless gaseous N_2 and CO_2. Bacterial biofilters allow effective and significant aquaculture water recirculation (van Rijn, 1996); however, the technology is not simple (Losordo, 1998). A basic bacterial biofiltration system for fishpond water consists of devices for (i) oxygen supply, (ii) removal of particulate organic matter, (iii) oxidation (ozonation) of refractory dissolved organic matter, (iv) removal (nitrification) of ammonia, (v) alkalinity control, (vi) dissipation of excess CO_2, (vii) disinfection and last but not least, (viii) a lot of water pumping through the different devices. Such systems accumulate nitrate and sludge that need to be disposed of. In the best case, using the most advanced technology, the nitrate and organic sludge are treated by an additional anoxic denitrifying bacterial biofilter arrangement. Sadly, most current ‘‘water recirculating’’ farms discharge their nitrate and organic sludge to the environment (van Rijn, 1996). Furthermore, while bacterial biofilter technologies are suitable for relatively small intensive land-based cultures of lucrative organisms (Zucker and Anderson, 1999), there is no information available as to how such technologies can be integrated into large-scale low-cost fish net pens and semi-intensive shrimp ponds.

Biofiltration by plants, such as algae, is assimilative, and therefore adds to the assimilative capacity of the environment for nutrients (Krom, 1986). With solar energy and the excess nutrients (particularly C, N and P), plants photosynthesize new biomass. The operation recreates in the culture system a mini-ecosystem, wherein, if properly balanced, plant autotrophy counters fish (or shrimp) and microbial heterotrophy, not only with respect to nutrients but also with respect to oxygen, pH and CO_2 (Hirata et al., 1994; Rai et al., 2000). Plant biofilters can thus, in one step, greatly reduce the overall environmental impact of fish culture and stabilize the culture environment. Algae, and in particular seaweeds, are most suitable for biofiltration because they probably have the highest productivity of all plants and can be economically cultured (Gao and McKinley, 1994).

The complexity of any biofiltration comes at a significant financial cost. It is this added cost that has prevented bacterial-based intensive aquaculture technologies from producing large quantities of fish at competitive prices (Losordo and Westerman, 1994; Zucker and Anderson, 1999). To make environmentally friendly aquaculture competitive, it is necessary to raise its revenues. This can be achieved by increasing productivity per unit of feed, which, can account for about half of the production cost. The waste nutrients are considered in integrated aquaculture not a burden but a resource, for the auxiliary culture of plants (Chamberlaine and Rosenthal, 1995). The new plant biomass can nourish various shellfish, including bivalves, abalone, brine shrimp and sea urchins (Wikfors and Ohno, 2001). The additional shellfish culture is not essential, however, since algae (seaweeds, mainly) have a large market. About 8.6 million metric tons/year valued at US\$6.2 billion in 1998 (FAO, 2000) are sold for human consumption, phycocolloids, feed supplements, agrichemicals, nutraceuticals and pharmaceuticals. A culture system that diversifies its products by integrating the culture of fish/shrimp with an extractive algal culture, and with organisms that grow on these algae, therefore makes much sense, not only ecologically, but also economically (Anon., 2003).

The integrated culture of plants and herbivores side-by-side with fish and shrimp is a practical technology (Neori and Shpigel, 1999; Naylor et al., 2000). The environmental and economic consequences of this approach are better understood when the organisms are categorized into fed and extractive species (Chopin et al., 2001; Rawson et al., 2002). Fed organisms (mainly carnivorous fish and shrimp) are nourished by feed, be it commercial diets, "trash" fish, etc. Extractive organisms, as the name implies, extract their nourishment from the environment. The two economically important cultured groups that fall into this category are bivalve mollusks and seaweed. Bivalve mollusks (e.g., mussels, oysters and clams) build their own body while degrading suspended organic particles (uneaten feed, phytoplankton and bacteria) that they filter from the water. Algae use sunlight to build their biomass, while assimilating dissolved inorganic nutrients removed from the water. If properly cultured, the organisms of both extractive groups can turn pollutant nutrients into commercial crops and loaded effluents into clean water.

The present review describes the background, the evolution and the main current practices of plant-based integrated aquaculture from polyculture and freshwater integrated aquaculture, through fish–microalgae–shellfish integrated mariculture to those systems involving fish–seaweed (macroalgae) and macroalgivores in seawater, the basics of their operation, their functioning and their economics.

2. Seaweed as a monoculture

The culture of organisms that are low in the food chain and that extract their nourishment from the sea involves relatively low input. It is therefore no surprise that the two predominant cultures in world mariculture are extractive-seaweed and filter-feeding shellfish (FAO, 2000; Muller-Feuga, 2000; Troell et al., 2003). One seaweed, *Laminaria japonica,* cultured on long-line ropes in the coastal waters of China, constitutes over half of the world's aquatic plant production (Chiang, 1984; Fei et al., 1998, 2000; Tseng, 2001). Seaweeds and other aquatic plants constitute a natural resource, whose value to mankind has been extensively reviewed by Critchley and Ohno (1998). Seaweeds are eaten raw, cooked or processed. Many cosmetic and pharmaceutical products also contain seaweed polysaccharides—agars, carrageenans and alginates. The harvests of cultured seaweeds and shellfish from coastal waters also remove nearly a million tons of protein, with around 150,000 metric tons of nitrogen annually (Troell et al., 2003). The harvest of tens of thousands of metric tons of fresh seaweed and clams has economically mitigated eutrophication in the polluted Venice Lagoon (Cuomo et al., 1993).

Huguenin (1976) comprehensively reviewed the early developments and the basic engineering-economic considerations in modern land-based seaweed cultivation. The traditional and modern practices of seaweed culture have been reviewed recently in a series of 19 papers, emanating from a World Aquaculture Society (WAS) workshop on the subject, in three issues of World Aquaculture Magazine (Chopin et al., 1998; 1999a,b). Most open-water seaweed monoculture has taken place in Asia, South America, South Africa and East Africa. Nevertheless, *Porphyra* and *Laminaria* cultivations are thought to have a potential for generating a viable seaweed mariculture and integrated aquaculture industries in the USA and Canada (Chopin et al., 2001). In Atlantic Canada, successful research and development has led to the mass culture of the edible seaweed Irish Moss, *Chondrus crispus*, in land-based fertilized tanks and ponds (Craigie and Shacklock, 1995). In Chile, significant advances have been made towards the commercial production of *Chondracanthus chamissoii* and *Callophyllis variegata* as food products for the Japanese market (Buschmann et al., 2001a). Efficient large-scale and long-term tank cultivation of *Gracilaria* has been reported from Florida (Capo et al., 1999). In Israel, the various aspects involved with the commercial culture of the agarophyte *Gracilaria conferta* have been thoroughly developed since the 1980s (Friedlander et al., 1987, 1991).

3. The evolution from polyculture, through fish–phytoplankton–bivalve to modern seaweed-based integrated intensive mariculture

Thanks to their manageability, land-based aquaculture systems offer much promise for sustainability in tropical, subtropical and temperate mariculture. Issues such as solid waste management, nutrient recycling and feed conversion enhancement are more easily and profitably addressed on an industrial scale on land than in open-water fish farms. Pond mariculture also allows the farmer to confront and mitigate the difficult issues of ecosystem degradation, mangrove degradation, exotic species escapes, pathogen and gene transfer between cultured and wild species, harmful algal blooms (red tides), poaching, weather damage, waste and chemical discharge to the sea, and conflicts with other stakeholders of the sea. Various combinations of these benefits, intuitively sensed by aquaculturists and evidently proven profitable, have probably led to the independent development in different parts of the world of traditional aquatic polyculture, the forerunner of modern integrated mariculture. Aquatic polyculture is traditionally practiced in such parts of the world as the Pacific and Indian Ocean-bordering nations, particularly China. Rice/fish culture, popular in Europe in the 19th–early 20th centuries, has been practiced in China for millennia (Fernando, 2002). Earthen marine ponds, associated with natural or agriculture plants (such as mangroves and rice) are used on a wide scale for extensive shrimp farming in China, Indonesia, Ecuador, India, the Philippines, Taiwan, Thailand, Japan and more recently in Vietnam (Binh et al., 1997; Alongi et al., 2000). In Northern Europe, ducks, fish and crayfish have been raised together in freshwater ponds (Maki, 1982). The ducks eat the algae and small fish, and deposit manure, which promotes further growth of algae and other aquatic plants. Crayfish eat these plants, as do other herbivorous fish. In turn, predatory fish such as bass eat these. People then harvest the fish, ducks and crayfish. This type of polyculture is a managed imitation of a natural ecosystem. The culture of microalgae in wastewater from animal feedlots has also been researched and practiced in several countries for years, but will not be discussed further here. The use of seaweeds for such purposes has received only little attention (e.g., Asare, 1980; Edwards, 1998).

The cohabitation of very different crops in one polyculture pond requires compromises in the farm management, leading to overall reduced yields for each organism compared with monocultures. The integration of monocultures through water transfer between the organisms alleviates this deficiency of polyculture and allows intensification.

Edwards et al. (1988) crystallized the general definition of integrated farming as occurring when "an output from one subsystem in an integrated farming system, which otherwise may have been wasted, becomes an input to another subsystem resulting in a greater efficiency of output of desired products from the land/water area under a farmer's control." It is a prerequisite, however, that a successful sustainable integrated farming system mimics, as much as possible, the way the natural ecosystem functions (Folke and Kautsky, 1992). Kautsky and Folke (1991) introduced the concept of "integrated open sea aquaculture", in which coastal waters, made eutrophic by fish net pens, agricultural run-off and sewage, are used to supply cultured seaweed with dissolved nutrients and shellfish with plankton.

The concept of integrated aquaculture constitutes an essential element in Coastal Zone Management, aimed at reducing, in an economically and socially beneficial manner, the adverse environmental impacts of aquaculture (freshwater, saline or marine) on the coastal environment (Chow et al., 2001; Brzeski and Newkirk, 1997; McVey et al., 2002). One solution does not, however, fit all. Integrated farming, particularly aquaculture systems are dynamic, changing according to such variables as location, season, species and social environment (Edwards, 1998; Little and Muir, 1987).

Traditional integrated mariculture has been located principally in China, Japan and South Korea where farms of fish net pens, shellfish and seaweed have been placed next to each other in bays and lagoons. Through trial and error, optimal integration has been achieved, but the information for quantification and design has seldom been published (e.g., Fang et al., 1996; Sohn, 1996). Such mariculturists may not even be aware that what they do amounts to extensive integrated mariculture, and that to succeed, the fed and extractive components of their region's mariculture should work in harmony. Western countries have been latecomers to modern integrated aquaculture. Only toward the end of the 20th century, when the assimilative capacity of natural ecosystems was being overloaded by monocultures of shrimp and fish (Primavera, 1993; Rajendran and Kathiresan, 1997), did the interest in using algae as nutrient scrubbers in integrated aquaculture of finfish, shellfish and crustaceans become renewed (Gordin et al., 1981; Chopin and Yarish, 1998). It was then realized that the recycling of waste nutrients by algae and filter-feeding shellfish is the most likely way to economically improve world mariculture sustainability (e.g., Cuomo et al., 1997; Blancheton, 2000).

In modern coastal integrated mariculture, shellfish and seaweed are cultured in proximity to net pen fish culture (Troell et al., 1997; Troell and Norberg, 1998; Chopin and Bastarache, 2002). These studies have shown the potential of open-water integrated mariculture, once conditions are right (see in Troell et al., 2003). It should be noted, however, that the biofiltration of effluents by shellfish converts "nutrient packs," in the form of microorganisms, into dissolved nutrients, which, may negatively impact the environment (Kaiser et al., 1998; Troell and Norberg, 1998).

In land-based integrated culture (Neori et al., 1993; Shpigel et al., 1993b; Shpigel and Neori, 1996), the fed organisms, fish or shrimp, the extractive algae and the algivores are each cultured in their own pond or tank at medium to high levels of intensity. The water recycles between them. This allows taking care of the secondary mineralization of nutrients from the algae consumed "in farm." A Saudi Arabian shrimp farm on the coast of the Red

Sea, perhaps the largest and most innovative of its kind, passes the effluents from over a hundred 1-ha shrimp ponds into an additional area of 100 ha of treatment ponds/lagoons, rich with algae, bacteria and shellfish (New, 1999). According to this paper, the farm has greatly raised the assimilative capacity of the coastal desert oligotrophic ecosystem and has eliminated most of the environmental problems associated with the more traditional shrimp farms.

The inception of modern integrated intensive mariculture on land has been the work of Ryther et al. (Goldman et al., 1974; Ryther et al., 1975) who approached, both scientifically and quantitatively, the integrated use of extractive organisms—shellfish, microalgae and seaweeds—in the treatment of household effluent. They described the concept and provided quantitative experimental results of integrated waste-recycling marine aquaculture systems. A domestic wastewater effluent, mixed with seawater, was the source of nutrients for phytoplankton culture, which in turn was fed to oysters and clams. Other organisms were cultured in a separate food chain, based on the organic sludge of the farm. Dissolved remnants of nutrients in the final effluent were filtered by seaweed (mainly *Gracilaria* and *Ulva*) biofilters. The weakness of this approach was the questionable value of organisms grown on human waste effluents. Adaptations of this principle to the treatment of intensive aquaculture effluents in both inland and coastal areas was proposed (Huguenin, 1976) and quickly followed by the integration to their system of carnivorous fish and of the macroalgivore abalone (e.g., Tenore, 1976).

The environmental and economic sense behind the integrated mariculture concept has instigated similar systems to independently be studied, or at least modeled, in Australia (Jones et al., 2001), Canada (Jones and Iwama, 1991), China (Shan and Wang, 1985; Lu et al., 1997; Qian et al., 1999b; Rawson et al., 2002), France (Hussenot et al., 1998; Lefebvre et al., 2000; Pagand et al., 2000), Japan (Inui et al., 1991), Thailand (Enander and Hasselstrom, 1994; Kwei Lin et al., 1993) and the USA (McDonald, 1987; Wang, 1990; Hopkins et al., 1993; Jacob et al., 1993; Sandifer and Hopkins, 1996; Kinne et al., 2001). Common to these approaches were dense phytoplankton populations, which were allowed to grow in fish/shrimp ponds or their effluents. The phytoplankton-laden water then passed over or through filter feeding shellfish, which harvested the phytoplankton. Most of these studies have, however, been either qualitative or at too small a scale to allow extrapolation for the industry.

Perhaps the first practical and quantitative integrated land-based cultures of marine fish and shellfish, with phytoplankton as the biofilter and shellfish food, were described by Hughes-Games (1977) and Gordin et al. (1981). A semi-intensive (1 kg fish m^{-3}) "green-water" seabream and grey mullet pond system on the coast of the Gulf of Aqaba (Eilat)–Red Sea, supported dense populations of diatoms, excellent for feeding oysters (Krom et al., 1989; Erez et al., 1990). Hundreds of kilograms of fish and oysters cultured in this experiment were actually sold. Neori et al. (1989) and Krom and Neori (1989) quantified the water quality parameters and the nutrient budgets in more intensive (5 kg fish m^{-3}) green water seabream ponds. For the most part, the phytoplankton in their ponds maintained a reasonable water quality and converted on average over half the waste nitrogen into algal biomass. The development of a practical intensive culture of bivalves in these phytoplankton-rich effluents, and the extremely fast bivalve growth rates achieved under these conditions, were described in a series of articles (Shpigel and

Fridman, 1990; Shpigel and Blaylock, 1991; Shpigel et al., 1993a,b, 2001a; Neori and Shpigel, 1999). This technology has formed the basis for a small farm (PGP 1994) in southern Israel.

Today, a significant amount of quantitative information has been gathered on the design, dimensions, performance, yields, pollution and even the expected income (as volatile as seafood prices can be) of the integrated mariculture of finfish–phytoplankton–shellfish. The conceptual understanding that has emerged from the data applies not only to Israel, but also with the necessary modifications to tropical, subtropical and temperate regions of the world. Similar systems are now studied in Southern (France, Spain and Portugal) and Northern (Scotland) Europe.

Shpigel et al. (1993b) presented the first quantitative performance assessment of a hypothetical family-scale fish/microalgae/bivalves/seaweed farm, based on actual pilot-scale culture data. They showed that at least 60% of the nutrient input to the farm could reach commercial products, nearly three times more than in modern fish net pen farms. Expected average annual yields of the system (recalculated for a hypothetical 1-ha farm) were 35 tons of seabream, 100 tons of bivalves and 125 tons of fresh seaweed. The most conservative figures for the yields of such a farm would be 25 tons of seabream, 50 tons of bivalves and 30 tons of fresh seaweed (Neori, unpublished). This would, of course, be a technically demanding farm, requiring experienced hands to control changes in water quality and in suitability for bivalve nutrition, related to the inherently unstable phytoplankton populations (Krom et al., 1985; Krom and Neori, 1989; Shpigel et al., 1993a). Seaweed-based integrated farms, described in the next section, alleviate the obstacles involved with microalgal-based biofiltration.

4. Seaweed-based integrated mariculture

A primary role of biofiltration in finfish/shrimp aquaculture is the treatment by uptake and conversion of toxic metabolites and pollutants. Bacterial biofilters oxidize ammonia to the much less toxic but equally polluting nitrate (e.g., Touchette and Burkholder, 2000), while microalgae photosynthetically convert the dissolved inorganic nutrients into particulate “nutrient packs” (Kaiser et al., 1998; Troell and Norberg, 1998) that are still suspended in the water. Macroalgae (seaweed), in contrast, sequester the nutrients out of the water. The clean and oxygen-rich effluent of a seaweed biofilter can therefore be readily recirculated back to the fishponds or discharged. Hirata et al. (1994; Hirata, personal communication) calculated that in addition to all other benefits, in a recirculation system, each kilogram of *Ulva* stock produces enough oxygen daily to supply the entire demand of 2 kg of fish stock. Nighttime oxygen consumption by seaweed is much lower than its daytime oxygen production. For example, gross photosynthetic O_2 production by *Porphyra amplissima* is up to 12 times higher than is its respiratory O_2 consumption (Kraemer et al., unpublished data). Integrated over a 12-h-light/12-h-dark day, a *Porphyra* culture could generate an O_2 surplus of 1.8 mmol O_2 g FW^{-1} day^{-1}. By feeding fish (and maximizing their respiration) in the day, the efficacy of algal produced O_2 for fish respiration can be maximized, (Schuenhoff et al., 2003).

Marketable biofilter organisms are essential to the commercial viability of integrated mariculture farms (Neori et al., 2001a,b). The seaweed genera most common in mariculture biofiltration (*Ulva* and *Gracilaria*) are safe and have been used for consumption by humans (B. Scharfstein, personal communication), by secondary cultured macroalgivores (such as abalone and sea urchins) and by other fish (Shpigel, Kissil and Neori, unpublished).

4.1. Coastal open-water-based systems

The water quality processes in open-water integrated mariculture are closest to the natural ones. To function well, seaweed culture and/or shellfish culture take place near the fish net pens and as much as possible in the same waters. Kelp (brown algae; Subandar et al., 1993; Ahn et al., 1998; Chopin, unpublished) and red algae (Buschmann et al., 1996; Chopin and Yarish, 1998) efficiently take up dissolved inorganic nitrogen present in fish net pen effluents (Troell et al., 1999), and seaweed production and quality are therefore often higher in areas surrounding fish net pens than elsewhere (Ruokolahti, 1988; Rönnberg et al., 1992; Troell et al., 1997; Chopin et al., 1999c; Fei, 2001; Fei et al., 2002; Chung et al., 2002; Chopin, unpublished). Seaweed growth on mariculture effluents has been also shown to be superior to that on fertilizer-enriched clean seawater (Harlin et al., 1978; Lewis et al., 1978; Vandermeulen and Gordin, 1990; Neori et al., 1991; Neori, unpublished; Shpigel and Scharfstein, personal communication). Agar yield and gel strength in the agarophytic red alga *Gracilaria* have been shown to improve when it is cultivated in salmon culture effluents (Martinez and Buschmann, 1996). The phycocolloid content of red algae usually drops under nutrient enrichment, but the increased seaweed yield more than compensates for it and results in higher total phycocolloid yield (Troell et al., 1997; Chopin and Yarish, 1998).

It was also demonstrated that the abundance of phytoplankton and organic particles and the growth of filter feeders often increase in waters that surround fish net pens (Buschmann et al., 2001b; Robinson, MacDonald and Chopin, personal communication). All these observations combine to make open-water fish–seaweed–shellfish integrated mariculture an attractive approach (Rawson et al., 2002). Integration with seaweeds and/or filter feeders is often the only economically feasible alternative for waste treatment in open-water systems (Troell et al., 2003). Indeed, a hybrid open-water/onshore integrated mariculture of seaweed, fish and shellfish has formed an integral part of the mariculture operations planned for the nutrient-rich upwelled water for generation of electricity by OTEC (Ocean Thermal Energy Conversion) in Hawaii (Mencher et al., 1983; OTEC web site http://www.nrel.gov/otec/what.html and references therein). More recent work in China by Fei et al. (2000, 2002) reported the rope culture of the economically important agarophyte, *Gracilaria lemaneiformis* near fish net pens. Growing over 5 km of culture ropes on rafts in Guangdong Province, the seaweed increased in density from 11.16 to 2025 g m^{-1} in a 3-month growing period. After these initial studies, they enlarged the culture area over the following 4 months to 80 km of rope. They reported that there was an increase in culture density on the culture ropes to 4250 g m^{-1}. They estimated an increase in the biomass of *Gracilaria* (in the culture area) to 340 metric tons fresh weight due to its culture in close proximity to fish net pens. Different work along similar principles has taken place elsewhere (Hirata and Kohirata, 1993; Matsuda et al., 1996; Yamasaki et al., 1997; Yamauchi et al., 1994). Several groups have developed, particularly, the integrated cultivation of salmonids with kelps (Fujita et al., 1989; Subandar et al., 1993; Chopin et al., 2001) or with red algae (Buschmann, 1996; Buschmann et al., 1994, 1995, 1996, 2001b; Troell et al., 1997; Chopin et al., 1999c). Another interesting complementary integrated approach for the reduction of the environmental impact on the sea bottom by the net pen sludge has been the culture underneath them of scavengers (gray mullets—Katz et al., 1996; sea cucumbers—Ahlgren, 1998), or worms in the pond sludge (Honda and Kikuchi, 2002) as secondary crops.

In open mariculture systems, nutrient uptake efficiency by seaweeds has been low in some systems due to the 3-D hydrographic nature of the water flow (Petrell et al., 1993; Troell et al., 1997; Troell et al., 2003); this technology therefore requires further R&D and modeling (such as on the potential of several harvests of several crops; Chopin, unpublished). Furthermore, studies investigating the open-water integrated mariculture approach have been hampered by the difficulties involved with experimentation and data collection at sea (Petrell et al., 1993; Petrell and Alie, 1996; Troell et al., 1997, Chopin et al., 1999c, 2001). The approach may generate a heightened commercial interest once high value seaweeds such as *Porphyra*, *Laminaria* or *Macrocystis* can be cultured as biofilters that produce novel human food products (Fei, 2001; Gutierrez et al., in press).

It seems that coastal open-water integrated mariculture farms have not yet spread through the salmonid culture industry, not so much because of technical or biological obstacles, but rather due to ignorance and disbelief (Chopin, unpublished; Yarish, unpublished). A recent interdisciplinary project supported by AquaNet, the Network of Centres of Excellence for Aquaculture in Canada, is intended to set up several preindustrial-scale demonstrations of integrated farms, to help the net pen farm owners become familiar with the approach of integrated salmon, mussels and kelp (*Laminaria*) culture (Chopin and Bastarache, 2002).

4.2. Land-based integrated aquaculture

Integrated aquaculture takes place in water of all salinities. A major evolution is taking place in freshwater integrated aquaculture. Lewis et al. (1978), Culley et al. (1981), Corpron and Armstrong (1983), Schwartz and Boyd (1995), Brown and Glenn (1999), and Brown et al. (1999) described the use of wetlands and floating plants in the treatment of freshwater and saline aquaculture effluents. While most wetland plants have little commercial value, the integration of fish culture with vegetable cultivation, referred to by some as “aquaculture hydroponics” (Seawright et al., 1998), “aquaponics” (Rakocy, 1999) and “partitioned aquaculture” (Turker et al., 2003) makes good economic sense. Effluents from an Arizona (USA) semi-intensive, low-salinity shrimp farm have recently been shown as a good nutrient source even for cereals and olive trees, with obvious economic advantages for both shrimp and crop farms (McIntosh and Fitzsimmons, 2003). The freshwater approach has culminated in the US Virgin Islands, where lettuce is cultured in the effluents of a tilapia farm in a two-crop recirculating production system (Rakocy, 1997, 1999). Future Aqua Farms, near Halifax, Nova Scotia, Canada, is also operating a hydroponics system with tilapia and spinach, lettuce, arugula, basil and watercress

(Lockett, 2003). In the USA, tilapia is cultured with phytoplankton (Turker et al., 2003). Bringing this approach back to seawater, a large shrimp-*Salicornia* farm has been operating in Eritrea for several years (web site http://www.cnn.com/2000/WORLD/africa/12/25/eritrea.sea.farm/). Apparently, the farm cultures marine shrimp, whose excretions nourish microbial/phytoplankton-fed tilapia. From there, the water flows to *Salicornia* basins and finally to a mangrove plantation (http://www.shaebia.org/artman/publish/article_251.html).

Interesting studies on seaweed-based integrated mariculture, starting on a laboratory scale and slowly expanding to outdoors pilot scale, began appearing in the 1970s. In the earliest quantitative studies, Haines (1976), followed by Langton et al. (1977), reported on an excellent red seaweed yield when cultured in a shellfish culture effluent. Harlin et al. (1978) then reported on the integrated culture of fish and seaweed (*Hypnea musciformis*). The theoretical and practical principles of intensive large-scale land-based seaweed culture were studied and developed first at Woods Hole Oceanographic Institution in Massachusetts and later at Harbor Branch Oceanographic Institution in Florida, USA, by Ryther et al. (Huguenin, 1976; Lapointe and Ryther, 1978; DeBusk et al., 1986; Hanisak, 1987; Bird, 1989) and in Halifax, Nova Scotia, Canada (Bidwell et al., 1985; Craigie and Shacklock, 1995; Craigie, 1998; Craigie et al., 1999). Seaweed-based integrated systems have since gained recognition as a most promising form of sustainable mariculture (Naylor et al., 2000), once their practicality, the quantitative aspects of their functioning and their economics are demonstrated (Vandermeulen and Gordin, 1990; Cohen and Neori, 1991; Neori et al., 1991, 1993; Shpigel et al., 1993b; Troell et al., 2003).

Further developments in mariculture seaweed biofilter R&D, and the integration of fish or shrimp with seaweed culture, have taken place on land, or with results that are applicable to land-based farms, in Chile (Buschmann et al., 2001b, *Gracilaria*; Chow et al., 2001, *Gracilaria*), China (Chang and Wang, 1985; Qian et al., 1999a,b, *Ulva*), Israel (Neori and Shpigel, 1999, *Ulva* and *Gracilaria*), South Korea (Chung et al., 2002), the Philippines (Hurtado-Ponce, 1993, *Gracilariopsis*; Alcantara et al., 1999, *Gracilariopsis*), Spain (Grand Canaria—Jimenez del Río et al., 1994, 1996, *Ulva*) and Sweden (Haglund and Pedersen, 1993, *Gracilaria*). Systems that integrate shrimp and red seaweed have been studied, the largest being in Hawaii (Nelson et al., 2001, *Gracilaria*), and small-scale efforts have been reported by Phang et al. (1996, *Gracilaria*) from Malaysia, Kinne et al. (2001, various algae) from the USA and Chang and Wang (1985), Yin (1987), Wei (1990) and Liu et al. (1997) from China, all of them with *Gracilaria*. Ali et al. (1994) reported on a laboratory-scale integrated culture of shrimp and green seaweed (*Ulva*) in Japan. There are also similar studies in the Asia Institute of Technology in Thailand (Yi et al., 2001; Kwei Lin, personal communication).

Quantitative nutrient budgets and performance data from sub-commercial-scale integrated systems of fish and seaweed in warm- and cold-water regions, respectively, have been published from Israel (Krom et al., 1995; Neori et al., 1996) and Chile (Buschmann et al., 1996). In both climates, the fish assimilated only a quarter of the nitrogen in the feed, and the associated seaweed could remove most of the remaining unassimilated nitrogen. The excess nitrogen from the culture of 1 kg of fish could nourish the culture of over 5 kg of seaweed. Excess phosphorus was removed in much smaller proportions than nitrogen.

The quantitative production estimates that exist from both warm- and cold-water regions agree with each other. Recalculated from the data in Shpigel and Neori (1996) and conservatively revised, a 1-ha seabream–*Ulva* farm is expected to produce 55 tons of fish and 385 tons fresh weight of seaweed annually. Calculations for a commercial-scale integrated tank system of salmonids and red seaweed (Buschmann et al., 1996) show that a 1-ha farm is expected to produce 92 tons of fish and 500 tons fresh weight of seaweed annually.

The functioning and management of a co-culture of several organisms, each with its own requirements and influence on water, can get rather complicated. Harvesting strategy and marketing policy can add to the confusion. Mathematical and design models have therefore been instrumental and should be even more so in the future, in the development of modern integrated aquaculture (Huguenin, 1976; Fralick, 1979; Indergaard and Jensen, 1983; McDonald, 1987; Petrell et al., 1993; Dalsgaard et al., 1995; Ellner et al., 1996; Chung et al., 2002).

5. Principles of seaweed biofilter design and operation

Ammonia is toxic to most commercial fish at concentrations above 100 μM (1.5 mg NH_3–N l^{-1}) (Wajsbrot et al., 1991; Hagopian and Riley, 1998). To avoid toxicity, the capacity of any useful fishpond biofilter to remove TAN (total ammonia N, NH_3+NH_4) should therefore match the rate of TAN production. In seaweed-based integrated mariculture systems, TAN and the other excess nutrients from the fed finfish/shrimp culture are taken up by seaweed. Most systems studied used *Ulva* spp. and *Gracilaria* spp., whose industrial culture technologies are known and whose nutrient uptake capacities are among the highest known (e.g., Martinez-Aragon et al., 2002). The use, as biofilters, of species from the economically important seaweed genus *Porphyra* (nori in Japanese) is currently under study in the USA and Canada (Yarish et al., 1999, 2001).

The choice of seaweed species for inclusion in an integrated aquaculture system must first depend upon meeting a number of basic criteria: high growth rate and tissue nitrogen concentration; ease of cultivation and control of life cycle; resistance to epiphytes and disease-causing organisms; and a match between the ecophysiological characteristics and the growth environment. In addition, given the ecological damage that may result from the introduction of nonnative organisms, the seaweed should be a local species. Beyond these basic criteria, the choice of seaweed will be influenced by the intended application. If, the focus is placed on the value of the biomass produced, then subsequent decisions will be based on the quality of the tissue and added value secondary compounds (e.g., *r*-phycoerythrin). If the principal focus is the process of bioremediation, then nutrient uptake and storage and growth are the primary determinants. The optimal system would include a seaweed species that incorporates both value and bioremediation.

Growth rate is defined, to a large extent, by morphology (Littler and Littler, 1980); generally speaking, the higher the ratio of surface area to volume (SA/Vol), the faster the specific growth rate. Phytoplankton have higher SA/Vol than seaweeds, with correspondingly higher growth rates (Table 1). Similarly, the thin sheet morphology has a higher growth rate than does the fleshy one.

It is more difficult to generalize on nutrient sequestration. A biofilter seaweed species must grow very well in high nutrient concentrations, especially ammonium. Seaweed that does not show this capacity, such as *Chondrus* (that prefers nitrate over ammonium) has only a limited use. To take up nitrogen at a high rate, fast-growing seaweed should be able to build up a large biomass N content. The common biofilter seaweeds, when grown in eutrophic waters, accumulate a high total internal N content. When expressed on a percent dry weight basis, maximal values for *Ulva*, *Gracilaria* and *Porphyra* grown in the eutrophic conditions characteristic of fish farm effluent range between 5–7% as N in dw or 30–45% as protein in dw (Neori et al., 2000; Carmona et al., 2001; Schuenhoff et al., 2003). In addition to the requisites described above, the ideal choice for the seaweed biofilter also has a market value (Sahoo et al., 2002). This encompasses the sale of seaweed products for a range of markets, including human consumption as food or therapeutants (Critchley and Ohno, 1998), specialty biochemicals, or simply as feed for the algivore component of the integrated system (Neori et al., 1998, 2000).

To date, only a handful of seaweeds have been thoroughly investigated for their aquaculture and/or bioremediation potential. Perhaps the most complete body of research has encompassed the genus *Ulva*. These flat sheet morphotypes have correspondingly high growth rates as well as high nitrogen contents, making them very good candidates for remediation (Cohen and Neori, 1991; Neori et al., 1991). Their life cycle and its controls are generally well known, and *Ulva* has been successfully integrated into mid- to large-scale animal mariculture systems (Hirata and Kohirata, 1993; Jimenez del Río et al., 1996; Neori et al., 2001b; Schuenhoff et al., 2003). Possibly the only drawback is the limited after-market for harvested biomass. *Porphyra* not only has many of the same characteristics (e.g., maximal growth rates >25% day^{-1}) but also produces biomass with high market value, including the tissue itself (for use as nori) and specialty biochemicals. On the other hand, the life cycle of *Porphyra*, is not understood well enough, yet, to maintain year-round growth of a purely vegetative culture. *Gracilaria*

Table 1
Examples of the influence of morphology on growth rate of potential biofilter seaweeds

Morphology	Dimensions	SA/Vol	Example	Representative specific growth rate (% day^{-1})
Small sphere (phytoplankton)	10 μm diameter	150,000	*Tetraselmis suecia*	51[a]
Thin sheet	2×5 cm×80 μm thick	25,000	*Porphyra amplissima*, *Ulva* spp.	25[b]
Fleshy	2×5 cm×500 μm thick	4100	*Gracilaria parvispora*	10[c]

[a] Gonzalez Chabarri et al. (1992).

[b] Kraemer et al. (unpublished).

[c] Nelson et al. (2001).

and *C. crispus* (Irish moss) have a history of mariculture study. Nutrient removal during growth and extraction of agar or carrageenans from the harvest are important, though maximal growth rates of these fleshy morphotypes are typically less (ca. 10% day^{-1}) than the flat sheets (Marinho-Soriano et al., 2002; Nagler et al., 2003). Kelps (*Laminaria* and *Macrocystis*) are candidates presently being investigated in Canada (Chopin and Bastarache, 2002) and Chile (Gutierrez et al., in press).

Resistance to epiphytes (as well as to small herbivorous animals) is a biological requisite of a biofilter seaweed species. Epiphytes are pest seaweeds and microalgae that use the cultured seaweed or the walls of the pond as substrates and compete for nutrients and light. Once the epiphyte population becomes significant, the seaweed culture is no longer a monoculture. Epiphyte growth on the cultured seaweed itself and on the pond's walls can be prevented, their growth rate can be slowed down or they can sometimes be selectively killed off. Fast growing opportunistic seaweeds, such as *Ulva*, suffer from epiphytes only when they get stressed and do not grow at their usual fast rate. The fact that it is often the main epiphyte in monocultures of other seaweed makes *Ulva* the preferred biofilter seaweed genus ('if you can't beat them—use them'). However, once a different kind of seaweed (perhaps more marketable like the rhodophytes *Gracilaria*, *Phorphyra* or *Kappaphycus*) is selected as the biofilter, proper management of the cultures can lessen the epiphyte problem. Prior studies are already providing promising directions for preventing, and effectively combating, epiphytes. Filtered and even UV-treated inflow water can greatly reduce the potential for epiphyte contamination of a system. Grazing invertebrates have been tested with limited success, but are probably not a solution for commercial-scale operations (Craigie and Shacklock, 1995). The control over environmental conditions allowed by tank mariculture systems may be used strategically to influence competition between maricultured seaweeds and epiphytes. The main management tools are proper harvesting frequency and water flow (Buschmann et al., 1994), changes in water level (Neori, Shpigel, Scharfstein and Ben Ezra, unpublished), pulse feeding and a high stocking density (Friedlander et al., 1987, 1991). Less opportunistic seaweed, such as *Gracilaria*, can be effectively maintained "clean" by a judicious use of pulse nutrient supply and control of light levels through stocking density. Pulse nutrition promotes the growth of fleshier *Gracilaria*, which can store nutrients over a longer period than can the thin bladed epiphytes, *Ulva* and *Enteromorpha*. Likewise, overstocking slower growing low-light seaweed allows it to compete for the light and nutrients with the fast-growing high-light epiphyte (Craigie and Shacklock, 1995). Over stocking and frequent slight changes in water level are particularly effective in combating epiphyte growth on the pond's walls. Since epiphytes are generally small, they are rapidly affected by environmental stresses, a strategy that Asian mariculture operations take advantage of by periodically raising *Porphyra* nets out of the water and allowing the biomass to partially dry. This kills much of the epiphyte biomass without significantly harming the macrophytes. Fleshy seaweeds are more tolerant of chemicals such as chlorine than thin seaweeds, a fact that can ultimately be of use in the eradication of a severe thin-epiphyte problem. An acute epiphyte infestation may eventually require replacement of the entire stock, cleaning of the pond and restocking with clean seaweed stock from 'clean' restocking ponds. These ideas offer starting points but, clearly, additional research is needed to define the best solutions (Troell et al., 2003).

Water is the medium that transports the pollutants from the fish culture to the biofilter. In typical modern land-based integrated systems, water from fishponds recirculates through seaweed biofilter ponds, where waste organic matter is broken down and dissolved nutrients are taken up. Recirculation between the fish and the seaweed improves the performance of the integrated system, since it reduces pumping in of clean water and discharging of effluents, while at the same time maintaining in the fishpond safe ammonia and dissolved oxygen levels. Treatment of the fish culture effluents on their way to be discharged without water recirculation wastes many advantages of seaweed biofilters and cuts significantly the intensification of the fish culture unit.

The rate of areal TAN uptake (grams N taken up per square meter per day) is an economically critical feature in seaweed biofilters. For a given fish culture capacity, a higher areal ammonia uptake rate is inversely proportional to the size and the cost of the biofilter systems. Another critical feature of a seaweed biofilter is the N uptake efficiency, the fraction of TAN concentration in the raw effluents removed as they pass through the biofilter. Higher ammonia uptake efficiencies reduce the rate at which the fish/shrimp pond water has to be recirculated.

The dependence of TAN uptake rate and of uptake efficiency on TAN load are inversely proportional to each other. A seaweed biofilter has to be N starved to remove TAN with a high efficiency. Unfortunately, N-starved seaweed biofilters perform poorly with respect to the other three important biofiltration parameters—areal TAN uptake rate, yield and protein content. Hence, it is not possible to achieve in one-stage seaweed biofilters that are high in both TAN uptake rates and TAN uptake efficiencies (Cohen and Neori, 1991; Chopin et al., 2001; Troell et al., 2003). A novel three-stage seaweed design has solved this conflict (Schuenhoff et al., 2003; Neori et al., 2003). *Ulva* cultured in this biofilter design has taken up TAN at high uptake rates (3–5 g N m^{-2} day^{-1}) and at the same time also with high TAN uptake efficiencies (approaching 90%). With this performance and with 1000 metric tons fish releasing about 500 kg TAN day^{-1}, a seabream farm requires between 10 and 16 ha of *Ulva* sp. biofilters for each 1000 tons of fish standing stock.

Ammonia (and ammonium), a chemically reduced compound, is assimilated as much as two to three times faster than the oxidized nitrate by many types of seaweed (Lobban et al., 1985; Neori, 1996; Ahn et al., 1998). The microbial oxidation of ammonia (nitrification) therefore diminishes the performance of the integrated system (Krom et al., 1995; Schuenhoff et al., 2003) and should be avoided. Maintaining the cleanliness of all wet surfaces, including those of pipes, helps prevent the development of nitrifying bacteria (Dvir et al., 1999). Piping between the fishponds and the biofilters should have the smallest possible SA/Vol ratio (i.e., wide and short), and anaerobic conditions inside them should be prevented. The performance of a seaweed biofilter of good design, construction and operation, depends on the areal TAN loading rate (concentration times the water exchange rate) by a saturation curve that approaches an asymptote at about 8 g TAN m^{-2} day^{-1}. The maximal biofiltration of any nutrient occurs, of course, in daytime, yet some TAN is also taken up at night, particularly when the TAN load to the algae is low (Cohen and Neori, 1991; Schuenhoff et al., 2003).

Water recirculation between the fishponds and the seaweed ponds, or passing the effluent through a series of seaweed biofilters, can raise TAN uptake efficiency by the seaweed biofilters while maintaining high areal uptake rates, seaweed yield and protein content (Schuenhoff et al., 2003; Neori et al., 2003). Areal yield (kg m^{-2} day^{-1}) is the product of seaweed areal density (kg m^{-2}) and growth rate (kg produced kg^{-1} day^{-1}). Optimal seaweed density maximizes yield by absorbing 99% of the incoming sunlight. For maximal yield, seaweed density is maintained at its optimum by the harvest of the biomass once it doubles, as frequently as every 2–3 days in summer.

Land-based culture of seaweed in tanks, ponds and ditches has been developed in most places following the bottom-aerated pond approach developed by the group led by Ryther in the 1970s and concisely described by Huguenin (1976), Bidwell et al. (1985), DeBusk et al. (1986), Bird (1989) and Craigie and Shacklock (1995) . The basic principle of this successful technology has been the vertical movement, by bottom aeration, of seaweed suspensions in tanks and ponds, and the passage of nutrient-laden water through them. The vertical movement of an optimally stocked seaweed pond allows each algal frond to be exposed to an optimal light dose. The water turbulence generated by the aeration thins the hydro-boundary layer around the frond surface, speeding the inflow to the fronds of nutrients and outflow from the frond of excess oxygen, a feature that has been shown to minimize photorespiratory losses of production in a culture of the red alga *Porphyra yezoensis* (Gao et al., 1992). An alternative approach in seaweed pond and ditch culture, using stakes and ropes, has emerged from the technologies used for large-scale coastal seaweed farming of Southeast Asia, such as in Malaysia (Phang et al., 1996). This approach, however, has not provided the nutrient removal rates and the areal yields necessary for intensive mariculture, for reasons probably related to insufficient water turbulence, high turbidity and low nutrient concentrations.

The by-production of high-quality seaweed in the biofilters calls for the co-culture of marine macroalgivores. Already in the 1970s, Tenore (1976) published his pioneer study on the integrated culture of seaweed and abalone. This was followed by the integrated abalone–*Ulva* and *Gracilaria* system of Neori et al. (1998) in Israel, of abalone and green algae in Japan (Sakai and Hirata, 2000), and of *Palmaria*–abalone in the USA (Evans and Langdon, 2000).

The quantitative aspects of the three-stage integrated cultivation of fish, seaweed and abalone were assessed by Shpigel et al. (1996) and Shpigel and Neori (1996). A fish–seaweed–abalone farm has since been built and operated based on this assessment (see below). Data from a commercial pilot study and from the commercial farm conservatively suggest that for a 1-ha farm, the annual production of 50 tons of seabream, 33 tons of abalone and 333 tons fresh weight of seaweed, all of which is eaten by the abalone. Buschmann et al. (1996) and Chopin et al. (2001) described detailed economic income calculations for a fish–seaweed farm. They showed seaweed sales would profitably cover the extra cost associated with the biofilters. Internalizing the environmental benefits of nutrient removal by the seaweed (the cost a responsible society is ready to pay for the treatment of that amount of nutrients by standard technologies) can be calculated as an additional significant monetary advantage, inherent to the seaweed “self-cleaning” technology in comparison with fed monocultures (Chopin et al., 2001), as detailed below.

6. SeaOr Marine Enterprises—a modern seaweed-based integrated farm

SeaOr Marine Enterprises, on the Israeli Mediterranean coast, 35 km north of Tel Aviv, is a modern intensive integrated mariculture farm. It is the culmination of much of the knowledge reviewed in the present article. The farm cultures marine fish (gilthead seabream), seaweed (*Ulva* and *Gracilaria*) and Japanese abalone (Fig. 1).

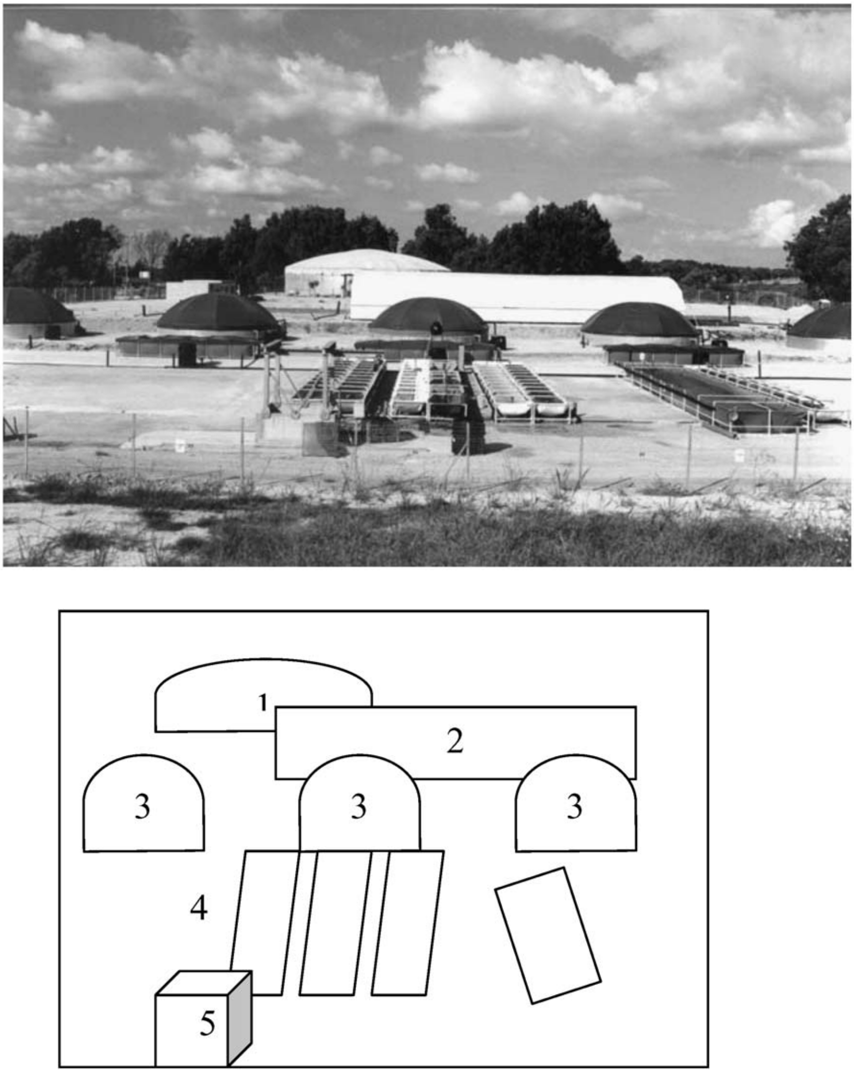

Fig. 1. The SeaOr Marine Enterprises integrated mariculture farm in Mikhmoret, on the Mediterranean coast of Israel. From back to front (numbers in line diagram): (1) water reservoir, (2) abalone culture facility, (3) fishponds, (4) seaweed ponds and (5) effluent sump and seaweed harvesting facility.

This farm best utilizes the local advantages in climate and recycles the fish-excreted nutrients into seaweed biomass, which is fed on site to the abalone. The process of nutrient recapture in the mariculture system is at the same time also an effective water purification process that allows the water to be recycled to the fishponds or to meet point-source effluent environmental regulations. The farm has received permits and support from the agencies concerned with environmental protection in Israel.

7. Economics

In the cost sheet of a modern intensive fish culture farm, the cost of fish feed proteins constitutes the largest item. However, three quarters of the proteins fed to the fish are excreted and eventually end up as dissolved ammonia. Algae recapture from the water and recycle ammonia, carbon dioxide, orthophosphate and micronutrients back into useful, protein-rich (>35% of dw) biomass (Neori et al., 1991, 1996). As predicted by Ryther et al. in the 1970s (Huguenin, 1976), seaweed farms on land can be profitable, as proven by the farm of Acadian Seaplants Limited in Nova Scotia, Canada (http://www.acadianseaplants.com/edibleseavegetables.html) which has been operating for years. It is only logical to conclude that synergism can make an integrated farm, composed of two independently profitable farms (fish or shrimp and seaweed) even more profitable particularly with the savings on seaweed fertilization and on wastewater treatment.

An efficient algal-based integrated mariculture farm maintains optimal standing stocks of all the cultured organisms, considering the respective requirements of each for water and nutrients and the respective rates of excretion and uptake of the important solutes by each of them. This allows the profitable use of each of the culture modules with minimum waste.

Table 2
Integrated mariculture—seabream–*Ulva*: expected performance from the use of 500 metric tons feed year^{-1a}

Organism	Pond dimensions (ha)	Yield (metric tons year^{-1})	Revenues ($\times$1000 Euro year^{-1})
Seabream	1	265	1050
Ulva	3.5	2215	885–1770
Total	4.5	2500	1935–2820

[a] The numbers in Tables 2–6 are rounded and are based on pre-commercial pilots (each about 200 m^2) operated in Southern Israel. The following values have been used (results from commercial farms are not very different, but are protected from publication by proprietary rights): Seabream: Food Conversion Ratio (FCR) = 1.9; feed protein content = 49%; average fish stocking density = 200 metric tons ha^{-1}; average annual fish yield = 300 metric tons ha^{-1}; seabream farm gate price = 4 Euro kg^{-1}; Seaweed: ammonia uptake rate = 4 g m^{-2} day^{-1}; ammonia uptake efficiency = 85%; average annual *Ulva* yield = 600 metric tons ha^{-1}; DW in *Ulva* = 15%; protein content in *Ulva* = 40% in dw; seaweed farm gate price=0.4–0.8 Euro (fresh weight kg)$^{-1}$; Abalone: FCR = 12 metric tons *Ulva* 1 metric ton of production; average stocking density = 25 kg m^{-2}; average annual yield = 10 kg m^{-2}; farm gate price = 35 Euro kg^{-1}; added cost of production of a kilogram abalone to a seabream and *Ulva* farm = 16 Euro kg^{-1}; Sea urchin: FCR = 8 metric tons *Ulva* 1 metric ton of production; average stocking density = 20 kg m^{-2}; average annual yield = 10 kg m^{-2}; farm gate price = 20 Euro kg^{-1}; added cost of production of a kilogram sea urchins to a seabream and *Ulva* farm = about the same as for abalone, but data are less solid.

Table 3
Integrated mariculture—seabream–*Ulva*–abalone/sea urchin: expected performance from the use of 500 metric tons feed year^{-1a}

Organism	Pond dimensions (ha)	Yield (metric tons year^{-1})	Revenues (×1000 Euro year^{-1})
Seabream	1	265	1050
Ulva[b]	3.5	2215	0
Abalone[c]	1.85	185	6500
Sea urchins[c]	2.75	275	5500
Sums	6.35–7.25	450–550	6550–7550

[a] See footnote a in Table 2.

[b] Used for algivore culture and neglecting nitrogen recycling.

[c] Both herbivores can be cultured interchangeably.

Of course, sunlight is a necessary prerequisite in algal systems. The following additional factors all need to be considered in the assessment of the economic viability of a seaweed-based integrated mariculture system: cost of land, energy and labor; access to clean seawater, supplies, marketing, shipping and other services; availability of educated and/or technically oriented people; access to large markets; political, business and financial infrastructures that can support or at least understand a hi-tech agricultural project. It is therefore difficult to compare the situation in different countries. The data from Israel, presented below, may only assist readers to estimate the financial plan of hypothetical farms in other countries. Labor cost can be critical. A seabream–*Ulva* farm of the scale described next needs 10–12 employees (including management and marketing). In Israel, with an average salary of about 27,000 Euro a year, labor costs cut profits by approximately 40%.

The pilot farms operated at the Israeli National Center for Mariculture (Neori et al., 1996; Neori and Shpigel, 1999) have generated preliminary real estimates, somewhat less conservative than our earlier estimates, of the financial costs and revenues expected from this technological approach (Tables 2–6). A seabream (*Sparus aurata*)–seaweed (*Ulva lactuca*) farm that annually uses 500 metric tons of seabream feed is expected to market 265 metric tons of fish and over 2000 metric tons of algae (Table 2). It will occupy about 4.5 ha of ponds and will generate farm gate revenue of 2–3 million Euro annually for the sale of the fish and the seaweed, according to present price ranges. A more advanced farm, based on the model implemented in Israel by SeaOr Marine Enterprises, can expect to

Table 4
Cost information for an integrated mariculture farm that uses 500 metric tons feed year^{-1} (7–8-ha pond area) at current Israeli prices in 1000 Euro year^{-1a}

Integrated system	Initial investment (×1000 Euros)	Salaries	Operation[b]	Total annual cost for the farm
Seabream–*Ulva*	1300	230	1650	1870
Seabream–*Ulva*–abalone	**	**	**	4810

**Proprietary data.

[a] See footnote a in Table 2.

[b] The initial investment is broken up and included in the operating costs over the years.

Table 5
Investment breakdown for a seabream–*Ulva*–abalone farm[a]

Component	%
Fish culture facilities	34
Seaweed culture facilities	24
Abalone culture facilities	25
Other costs	17

[a] See footnote a in Table 2.

convert the biofilter seaweed to 185 metric tons of the Japanese abalone (*Haliotis discus hannai*) or 275 metric tons of the purple sea urchin *Paracentrotus lividus* (Table 3). This sophisticated farm will occupy up to 7.25 ha of ponds and will generate 6.5–7.5 million Euro annually, but its expenditures will also be high. The expected investment for the two-species farm is 1.3 million Euro in Israel (Table 4); detailed figure estimates for a three-species farm of this size have not been disclosed by the company. However, an estimate for a small seabream and abalone farm, with an annual production of 20 and 11 metric tons, respectively, is an initial investment of 730,000 Euro and annual operating costs of 525,000 Euro, including the payback of the initial investment (Neori et al., 2001a,b). Based on these numbers, the estimated breakdown of investment between the species (Table 5) and our results from smaller pilots (Shpigel, Scharfstein and Neori, unpublished), the overall annual operating costs for the farm described in Table 3 will be slightly less than 5 million Euro (Table 4).

When comparing these figures with those of a flowthrough pond farm with untreated effluents, or with the figures of a net pen farm, one has to consider that in the not too distant future the cost of the water treatment, on the basis of the ‘‘polluter pays’’ principle, will be added to the costs of those monoculture farms. The internalization of the waste treatment value of 12 Euro per kilogram of nitrogen waste and 2 Euro per kilogram of phosphorus waste (based on wastewater treatment cost in Sweden) (Chopin et al., 2001) can reduce the annual revenues (1,050,000 Euro, Tables 2 and 3) of net pen seabream farms (but not integrated farms) of the same fish production (265 metric tons) as described here by 225,000 Euro, or nearly a quarter. As has already been calculated for a land-based salmon and *Gracilaria* farm in Chile, this internalization will probably erase much of the profit of a conventional fish (or shrimp) monoculture farm in today’s highly competitive seafood markets. The overall estimated profits of the two integrated seabream farms in this admittedly simplistic calculation (Table 6) suggest a good potential for profitability. The economic data provided here should serve to illustrate that intensive seaweed-based

Table 6
Approximate profits assessed for two types of seaweed-based integrated mariculture farms that would each use 500 metric tons feed $year^{-1}$, in Israel, in thousands of Euros $year^{-1}$[a]

Integrated system	Revenues (Tables 2 and 3)	Total annual cost for the farm (Table 4)	Profits
Seabream–*Ulva*	1935–2820	1880	55–940
Seabream–*Ulva*–abalone/sea urchins	6550–7550	4810	1740–2740

[a] See footnote a in Table 2.

integrated mariculture has good potential for being highly profitable, even before and, certainly, after the "polluter pays" principle is implemented in mariculture.

8. Conclusions

A large body of good-quality research has been made worldwide, on different integrated aquaculture systems that use plants to take up waste nutrient and at the same time add to the income of the farms. Today's integrated sustainable mariculture technologies have developed from the traditional "all in one pond" polyculture and allow much higher intensification. R&D over three decades has brought the integrated land-based technology to a commercial reality. Through plant biofilters, integrated aquaculture recycles nutrients into profitable products, while restoring water quality. Fish–phytoplankton–shellfish systems convert the fish waste into bivalves, which have a large global market. Fish–seaweed–macroalgivore (such as abalone and sea urchin) systems have a choice of marketing either the seaweed or the macroalgivore, while they use less land than the fish–phytoplankton–shellfish systems and maintain a more stable water quality. Integrated aquaculture, in both freshwater and seawater, can be profitable, thanks to the sales of the biofilter organisms—vegetables, shellfish and seaweed. The results are higher yields and income per ton of feed and per ton of water. Furthermore, the integrated culture system fulfills, at no extra effort, practically all the requirements of organic aquaculture (Naturland®, 2002), a feature that opens up to the aquaculturist new lucrative markets. The technologies are generic and modular, adaptable for fish/shrimp culture at any level of intensification. Several commercial freshwater farms already cultivate fish with vegetables. Two or three integrated marine farms culture fish, shrimp, seaweed, oysters, clams, abalone and sea urchins, and the interest in this approach is growing. The use of a similar approach in open-water fish culture farms has not yet reached commercial reality in the western world, even though several studies have proven its practicality and even tough it is done traditionally in coastal mariculture particularly in Southeast Asia. What slows the commercial implementation of integrated technologies is not related, in our opinion, to careful commercial considerations or to the technological/scientific unknowns delineated in Troell et al. (2003). Rather, it is related to a resistance to change and to the slow implementation of the "polluter pays' principle.

Of course, further R&D will better define the processes and interactions that operate between the cultured organisms, improve the performance of each module and of the integrated farm, improve management protocols and adapt the concept to different locations and to different organisms. Three large programmes are attempting to address this today.

(A) Supported by AquaNet, the Network of Centres of Excellence for Aquaculture, an interdisciplinary project, involving the University of New Brunswick, the Canada Department of Fisheries and Oceans, the Canadian Food Inspection Agency and several industrial partners, is developing an open-water integrated mariculture system in the Bay of Fundy, Canada. Salmon (*Salmo salar*), mussel (*Mytilus edulis*) and kelp (*Laminaria saccharina*) are being grown together at several industrial pilot-scale sites to develop an integrated aquaculture model and to train students and professionals in this innovative approach to aquaculture. The productivity and role of each component (fish, shellfish and seaweed) is being analyzed so that the appropriate proportions of each of them can be defined. The data are expected to help develop a sustainable system in which metabolic processes counterbalance each other within acceptable operational limits and according to food safety guidelines and regulations. The ultimate goal of this project is to transfer this model, of environmentally and economically balanced diversification and social responsibility, to other sites and make it a concept transferable to other aquaculture systems.

(B) Funded by the European Commission's "Quality of Life" programme and coordinated by the Wadden Sea Station Sylt (AWI), the SEAPURA (species diversification and improvement of aquatic production in seaweeds purifying effluents from integrated fish farms) project intends to develop and test cultivation of high-value seaweed species not used before in poly-aquaculture with fish farms in Spain and Portugal, with accompanying research conducted in Germany and Northern Ireland. The research tackles issues such as unwanted seaweed sporulation and seasonality. The cultivated seaweed biomass will be used for the human food market mainly in France, for extraction of pharmaceutical substances, or for fish feed additives, with possible antibiotic effects of the cultivated seaweed.

(C) Funded by the European Commission's "Innovation" programme and coordinated by Israel Oceanographic and Limnological Research, National Center for Mariculture, Eilat, the GENESIS programme is a collaboration between Israeli, French and Scottish scientists and companies. It develops the evaluation and transfer of the generic integrated environmentally friendly mariculture approach from Eilat, Israel, to the European mariculture industry. Three prototype integrated systems for warm (Israel), temperate (Southern France) and cold (Scotland) water conditions, with a variety of valuable marine products including fish, crustaceans, mollusks and aquatic plants, are evaluated for their performances with respect to water, nutrients and waste management. Intensification and the use of nutrients, water and energy are optimized. The project also develops suitable products and services for the commercialization of the technology and establishes the financial viability and consumer acceptance of its products.

It is anticipated that the results of these projects, which utilize information reviewed in the present paper, will establish the generic characteristics of the integrated aquaculture concept. They should greatly enhance the understanding and acceptance of the approach, leading to the development of integrated mariculture farms throughout Europe and the Mediterranean countries, North and South America and the Indo-Pacific regions.

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