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MINIREVIEW

INTEGRATING SEAWEEDS INTO MARINE AQUACULTURE SYSTEMS: A KEY TOWARD SUSTAINABILITY[1]

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The rapid development of intensive fed aquaculture (e.g. finfish and shrimp) throughout the world is associated with concerns about the environmental impacts of such often monospecific practices, especially where activities are highly geographically concentrated or located in suboptimal sites whose assimilative capacity is poorly understood and, consequently, prone to being exceeded. One of the main environmental issues is the direct discharge of significant nutrient loads into coastal waters from open-water systems and with the effluents from land-based systems. In its search for best management practices, the aquaculture industry should develop innovative and responsible practices that optimize its efficiency and create diversification, while ensuring the remediation of the consequences of its activities to maintain the health of coastal waters. To avoid pronounced shifts in coastal processes, conversion, not dilution, is a common-sense solution, used for centuries in Asian countries. By integrating fed aquaculture (finfish, shrimp) with inorganic and organic extractive aquaculture (seaweed and shellfish), the wastes of one resource user become a resource (fertilizer

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or food) for the others. Such a balanced ecosystem approach provides nutrient bioremediation capability, mutual benefits to the cocultured organisms, economic diversification by producing other value-added marine crops, and increased profitability per cultivation unit for the aquaculture industry. Moreover, as guidelines and regulations on aquaculture effluents are forthcoming in several countries, using appropriately selected seaweeds as renewable biological nutrient scrubbers represents a cost-effective means for reaching compliance by reducing the internalization of the total environmental costs. By adopting integrated polytrophic practices, the aquaculture industry should find increasing environmental, economic, and social acceptability and become a full and sustainable partner within the development of integrated coastal management frameworks.

Key index words: **assimilative capacity; bioremediation; coastal health; environmental impacts; integrated aquaculture; integrated coastal management; nutrification; salmon; seaweeds; sustainability**

According to Food and Agriculture Organization of the United Nations figures, the total world capture marine fisheries annual production has been nearly level since 1986 (Anonymous 2000). During the same period, global marine finfish and shellfish aquaculture production has increased by nearly 10% per year, making aquaculture the fastest growing global food production sector. In the past decade, the increase in global demand for seafood has been met by increased aquaculture, which provided 26.4% of the world fisheries production in 1998 (Anonymous 2000). As a result of this rapid production increase, it is not unreasonable to conceive that aquaculture activities might have affected the environment in a variety of ways, especially fish and shrimp aquaculture, which needs to be supplemented with an exogenous source of energy (food) (Beveridge 1996). Many authors have demonstrated that organic and inorganic inputs of food to fish culture have a substantial impact on organic matter and nutrient loading in coastal areas (Beveridge 1984, Brown et al. 1987, Gowen and Bradbury 1987, Rosenthal et al. 1988, López et al. 1988, Folke and Kautsky 1989, Handy and Poxton 1993, Chopin et al. 1999b), affecting the sediments beneath the culture installations and producing variations in the nutrient composition of the water column. This can lead, for example, to enhanced sediment metabolism, anoxia, sulfate reduction, and sulfide accumulation, high nitrogen and phosphorus flux, acidification, turbidity, and all other processes associated with eutrophication (Troell and Berg 1997). These environmental modifications can also affect the benthic fauna (Rodhouse et al. 1985, Hargrave et al. 1993, Nunes and Parsons 1998, Angel et al. 2000), fish abundance (Carss 1990), bird populations (Dankers and Zuidema 1995), macroalgal growth and diversity, epiphytic load and chemical composition (Ruokolahti 1988, Rönnberg et al. 1992, Chopin et al. 1999b, Bates et al. 2001), shifts in phytoplanktonic and zooplanktonic communities (Granéli et al. 1989, Carlsson et al. 1990, Capriulo et al. in press), and the composition and abundance of bacteria (Husevåg et al. 1991, Capriulo et al. in press).

Species that do not require exogenous feeding for their cultivation, like shellfish, can also affect the environment by changing local communities and food chain patterns, enhancing sedimentation, and altering water current direction and velocity (Kaspar et al. 1985, Tenore et al. 1985, Baudinet et al. 1990, Hatcher et al. 1994, Grant et al. 1995). Seaweed cultivation can modify the environment by changing sediment composition and dynamics, the meiobenthos, and by introducing exogenous materials (e.g. plastic), fertilizers, or pesticides (Olafsson et al. 1995, Buschmann et al. 1995, 1996a). Nevertheless, the effects of shellfish and seaweed cultivation are less dramatic than those associated with intensive fish and shrimp cultures because the latter result in a net addition of organic material and dissolved nutrients to the environment (Hopkins et al. 1995). The cultivation of shrimp and carnivorous fish species also appropriates very large ecosystem areas, that is, a large ecological footprint, to sustain their production (Kautsky et al. 1997b, Folke et al. 1998). This dependence on both local ecosystem support (e.g. clean water) and external ecosystem support (e.g. larvae and feed production) is not accounted for in the calculation of market prices and seldom included in models of fisheries and aquaculture management. Intensive aquaculture is, for this reason, not a substitute for fisheries because it largely depends on fisheries to harvest resources that are given to the cultured species in the form of feed pellets (Folke and Kautsky 1989, 1992). Feed companies are now developing new research and development structures to identify alternative sources of oil (especially of polyunsaturated fatty acids) and protein to counter diminishing supplies of raw material. Food supply stability, food safety, and traceability are becoming key worldwide issues. Notwithstanding the significant improvements in feed quality and the fact that land- and sea-vegetable substitutes have to some extent been obtained during recent years, it is still necessary to develop incentives and research programs to prevent the further misuse of marine ecosystems (Naylor et al. 1998, 2000).

In the above context, integrated aquaculture has been proposed as a means to develop environmentally sound aquaculture practices and resource management through a balanced ecosystem approach to avoid pronounced shifts in coastal processes. Fed aquaculture (e.g. finfish, shrimp) needs to be integrated with organic and inorganic extractive aquaculture (e.g. shellfish and seaweed). Conversion, not dilution, is the solution to pollution so that the wastes of one resource user become a resource (fertilizer or food) for the others. Integrated aquaculture provides nutrient bioremediation capability, mutual benefits to the cocultured organisms, economic diversification by producing other value-added marine crops, and increased profitability per cultivation unit for the aquaculture industry (Chopin et al. in press). Integrating seaweeds into fish/shrimp aquaculture not only counterbalances nutrient inputs but also other metabolic aspects, such as dissolved oxygen, acidity, and CO_2 levels, in one step. In contrast, nitrification filters compete with fish/shrimp for dissolved oxygen and alter alkalinity, thus requiring complex additional mechanical monitoring (electrodes) and control (aerators, pumps) devices.

The use of seaweeds integrated with fish cultures has been studied in open-water system conditions in Canada, Japan, Chile, and the United States (Petrell et al. 1993, Hirata and Kohirata 1993, Hirata et al. 1994, Petrell and Alie 1996, Troell et al. 1997, Chopin and Yarish 1998, Chopin et al. 1999b); in enclosed floating systems in Norway (Bodvin et al. 1996); and in land-based cultures in the United States (Ryther et al. 1975), Israel (Vandermeulen and Gordin 1990, Cohen and Neori 1991, Neori et al. 1991, 2000, Shpigel et al. 1993, Krom et al. 1995), Spain (Jimenez del Río et al. 1994, 1996), Sweden (Haglund and Pedersén 1993), and Chile (Buschmann 1996, Buschmann et al. 1994, 1996b). This review summarizes these results, provides a critical analysis, and determines a general conceptual framework. To achieve these goals, we analyze some key concepts, provide a summary of results obtained with marine open-water and land-based systems, introduce financial tools that permit internalization of environmental costs, and finally discuss their future applicability, especially for countries experiencing major finfish aquaculture development.

INTEGRATED AQUACULTURE IS NOT A NEW CONCEPT

Asian countries, which provide more than two thirds of the world's aquaculture production, have been practicing integrated aquaculture, through trial and error and experimentation, for centuries (Li 1987, Tian et al. 1987, Wei 1990, Liao 1992, Edwards 1992, 1993, Chan 1993, Chiang 1993, Qian et al. 1996). Interestingly, civilizations most successful at developing integrated aquaculture systems are the ones that treat wastes as valuable resources to be reused as they have understood the meaning of the word *recycling* for centuries. Integrated farming, especially in freshwater and brackish pond systems, is an ancient practice in China, which has become more refined as a consequence of the agricultural and rural development policies implemented since 1949. These policies were motivated by the need to maximize productivity per unit of land and water bodies and were based on diversified self-reliance in food and basic raw material production and the philosophy that the by-products (wastes) from one resource use must become an input into another use of resources (Ruddle and Zhong 1988). Western countries are regularly reinventing the wheel (Ryther et al. 1979, Indergaard and Jensen 1983, Kautsky et al. 1996, Chopin et al. 1999b). However, the determination to develop integrated aquaculture systems will only come about if there is a major change in the attitude of consumers toward eating products cultured on wastes and in political, social, and economic reasoning by seeking sustainability, long-term profitability, and responsible management of coastal waters.

The Western world tends to focus on high value and high production monoculture. Interestingly, this trend can now be observed among Asian newcomers to aquaculture as well, especially those involved with marine species, who are forgetting the good old principles of integrated aquaculture because of the temptation of short-term financial gain with only fish or shrimp aquaculture. Fortunately, nature does not take long to remind people of the common sense principles on which it functions (Rawson et al. in press). When an innovative aquaculture practice is successfully (i.e. economically profitable) developed by a few people, others follow in the same region, which often leads to geographically highly concentrated, high-density monoculture systems. This approach to aquaculture eventually leads to a deterioration of the quality of the environment, on which fish health is so dependent, because disease outbreaks are facilitated by the concentration of organisms and stressful environmental conditions. When aquaculture takes place in public waters (the Commons), to whom the primary responsibility falls for maintaining a balance between environment quality and aquaculture production very often becomes an unresolved issue, which is often handed, by default, to one or more government resource management agencies faced with a formidable task and often criticized by all sides.

One of the most difficult tasks of resource managers and policy advisors is understanding the assimilative capacity of coastal ecosystems under cumulative pressure as competing anthropogenic activities increase in the coastal zone (sewage effluents, urban/rural effluents, precipitation, agricultural/industrial runoffs, aquaculture, etc.). Most impact studies on aquaculture operations have typically focused on organic matter/sludge deposition because they are easily noticeable and measurable. Inorganic effluents, such as nitrogen and phosphorus, which are neither visible nor easily measured, have generally received much less attention because of the common human attitude of "out of sight, out of mind." Moreover, it is difficult to measure small long-term changes, and past studies, focusing on local measurements, have often failed to document dispersal patterns of dissolved nutrient fractions. The inorganic output of aquaculture is emerging as a pressing issue as nutrification of coastal waters is a worldwide phenomenon (Beveridge 1996, Kautsky et al. 1997a, Chopin et al. 1999b). As an example, a seaweed monitoring program in the Bay of Fundy, Canada, has demonstrated that seaweeds can be excellent bioindicators of nutrification/eutrophication and reveal that certain sites in the Bay of Fundy show symptoms of environmental stress (Bates et al. 2001).

Seaweeds can also be useful tools for measuring the zone of influence of an aquaculture site, because they are integrators of bioavailable nutrients over time (Troell et al. 1997, Chopin, unpublished data). The Atlantic salmon (*Salmo salar* Linnaeus) aquaculture industry in New Brunswick, Canada, is geographically highly concentrated in the Quoddy Region. Eighty-seven sites produced 20,230 tons in 1999 (Egan 2000) and 30,000 tons in 2000 (N. Halse, New Brunswick Salmon Growers Association, personal communication). With improvements in feed composition, digestibility, and conversion efficiency in recent years, the annual discharge per ton of salmon has been reduced: from 78 kg nitrogen and 9.5 kg phosphorus in the early 1990s (Ackefors and Enell 1994) to current estimates of 35.0 kg nitrogen and 7.0 kg phosphorus (ICES 1996, Department of Fisheries and Oceans Canada 1997, Chopin et al. 1999b, H. Ackefors, personal communication). Consequently, the exogenous nitrogen and phosphorus inputs into coastal waters through aquaculture operations in the region were 1,050 and 210 ton, respectively, in 2000. Contrary to common belief, even in regions of exceptional tidal and apparent flushing regimes like the Bay of Fundy, water mixing and transport may be limited and water residency time can be locally prolonged (Page 2001). Hence, nutrient bioavailability remains significant in some areas for a relatively long period of time in terms of assimilative processes. The finfish aquaculture industry should not be singled out because it is the “new kid on the coastal block.” However, as a relatively new contributor to the overall nutrification of coastal waters, it should not be exempt from developing innovative practices that ensure the remediation of the consequences of its activities.

This is precisely when one of the contributions of seaweeds to coastal ecosystems must be recognized and used. Unfortunately, it is striking to realize that—especially in the marine biology community in the Western world, historically dominated by zoologists who have been “kingdomly incorrect” for decades—the fundamental roles and contributions of seaweeds to coastal processes have frequently been either ignored or misunderstood and that seaweeds are rarely factored into modeling equations of coastal systems. Seaweeds are frequently cataloged as alternative or new species for aquaculture by many agencies. It is, however, worth noting that these biological systems have been withstanding the pressure and selection of evolution over a considerable period of time. For example, the genus *Porphyra*, a taxon selected for integrated aquaculture development (Chopin et al. 1999b), is considered one of the most ancient red algae, with fossils dating from 425 million years ago (Campbell 1980). The organismal morphological design of *Porphyra* has been well engineered in the evolutionary process for nutrient uptake and rapid growth. The mono- or distromatic thalli are typically 20–160 µm thick (Bird and McLachlan 1992, Chopin et al. 1999b), giving them a very high surface area to volume ratio (more membrane surface for uptake) and placing cells very close to pools of inorganic nutrients.

Moreover, seaweeds are definitely not new species to aquaculture. For example, the culture of *Porphyra* was established in Japan ca. 400 years ago (Ohno and Largo 1998). Considering the large quantity of seaweeds produced through aquaculture, many times surpassing in tonnage, and sometimes also in revenue, many animal aquaculture productions, seaweeds deserve more conspicuous exposure and recognition. In 1996, the brown alga *Laminaria japonica* Areschoug was the top species in terms of annual production of all types of aquaculture (fresh water, brackish water, and marine environments) and third in terms of annual economic value (Table 1). In 1998, of the 39.4 million ton of aquaculture production valued at US$53 billion, seaweeds contributed 8.6 million ton (21.7%) valued at US$5.9 billion (11.1%; Hanisak 1998, Anonymous 2000). In the marine environment, 44% of the 1998 annual production was provided by seaweeds (47% by mollusks, 8% by finfish, and 1% by crustaceans).

In 1995, China produced more than 4.8 million tons of cultivated seaweeds, mainly of the brown algae *Laminaria* and *Undaria* and of the red algae *Porphyra*, *Gracilaria*, *Kappaphycus*, and *Betaphycus*, which together represented 70.6% of the world’s seaweed aquaculture production (6.8 million tons, itself representing 87.1% of the worldwide commercial harvest of seaweeds, estimated at 7.8 million tons; Hanisak 1998, Fei et al. 1998). Such a tremendous biomass certainly provides a significant buffer capacity along the Chinese coast in terms of nutrient assimilation and conversion. Physiologically, seaweeds can be viewed as renewable biological nutrient scrubbers that take up nutrients very much like sponges absorb water. However, like any sponge, they can become saturated. This validates the sustainable harvesting of seaweeds and their cultivation integrated into fed-type operations (periodic removal of saturated tissues and therefore of significant amounts of nutrients to allow regrowth of new material to continue the scrubbing process). The target should be the development of enough competition for nutrients by cultivation of de-

TABLE 1. Worldwide annual production and economic value of top species in aquaculture in 1996 (Hanisak 1998, Anonymous 1999).

Species	Annual production		Annual value	
	Million tons	Rank	Billion US$	Rank
Laminaria japonica (kelp)	4.17	1	2.95	3
Crassostrea gigas (Pacific cupped oyster)	2.92	2	3.23	2
Hypophthalmichthys molitrix (silver carp)	2.88	3	2.79	4
Penaeus monodon (giant tiger prawn)	<0.60	>10	3.93	1
Salmo salar (Atlantic salmon)	<0.60	>10	1.87	7

sirable and profitable algal crops to reduce nutrient concentrations in seawater and the biomass of problem species below the threshold of devastating and costly hypertrophic events such as green tides (extensive blooms of macroalgae such as *Enteromorpha*, *Ulva*, and *Cladophora*), red or brown tides of harmful microalgal blooms, and blooms of short-lived filamentous algae such as *Ectocarpus* and *Pilayella* (Bruno et al. 1989, Merrill 1996, Schramm and Nienhuis 1996, Bates et al. 2001).

APPLICATION OF ALGAL NUTRIENT PHYSIOLOGY TO INTEGRATED AQUACULTURE

General concepts about nutrient uptake can be found in Lobban and Harrison (1994). Nutrient uptake kinetics, assimilation, storage, response to nutrient additions, response to different forms of nutrients (e.g. nitrogen as ammonium versus nitrate, nitrite or urea), nutrient ratios, critical tissue nutrient contents, and growth kinetics were discussed by Harrison and Hurd (2001) with respect to aquaculture. To optimize the seaweed component of an integrated aquaculture system, particular attention should be given not only to physical and chemical factors (such as light, temperature, effluent nutrient concentration and flux, water motion, etc.) but also to biological factors such as interplant variability (hence the need for selection), nutrient prehistory, type of tissue in culture, life history stages/age, control of parameters triggering reproduction stages, surface area to volume ratio of thalli, and morphological changes induced by cultivation techniques (e.g. ruffling, tendency to obtain sphere-shaped plants, production of hairs).

Seaweed cultivation in open and tank cultures have been extensively discussed (Hanisak 1987, Santelices and Doty 1989, McLachlan 1991, Craigie and Shacklock 1995, Friedlander and Levy 1995, Chopin and Yarish 1998, Craigie et al. 1999). However, it is important to note that from a bioremediation point of view, several concepts must be clearly defined, because they have different interpretations and meanings. The nutrient uptake efficiency is the average reduction (%) in nutrient concentration in water (also estimated by the nutrient accumulation in algal tissues). Nutrient uptake rate is the amount of nutrients removed per unit of time. A variant can be the nutrient area uptake rate, which is the amount of nutrients removed per unit of seaweed-covered area (such as a pond) per unit of time.

These variables depend on the environmental conditions experienced by the culture during a specific period of time and on culture parameters such as the nutrient prehistory of the plants, growth rate and stocking density, tank depth, water turnover rate, and biomass harvesting frequency. For example, Vandermeulen and Gordin (1990), Cohen and Neori (1991), Neori et al. (1991), and Jimenez del Río et al. (1994) found that increasing ammonium loading rates per unit area of *Ulva* tank cultures fed with fish effluents led to decreased dissolved nitrogen uptake efficiency but increased nitrogen area uptake rate. *Ulva* yield and protein content also increased with increasing rates of ammonium supply per unit area. Studies carried out in Chile came to the same conclusion, as ammonium uptake efficiency decreased with the water turnover rate, but the uptake per gram of *Gracilaria* per time increased (Muñoz and Varas 1998). Both *Ulva* and *Porphyra* perform better as nitrogen scrubbers with ammonium than with nitrate, which is excellent in the context of intensive fish aquaculture, where most of the nitrogen is released as ammonium (Neori 1996, Carmona et al. 2001).

The relative importance of nutrient uptake efficiency and rate depends on the purpose of the cultivation system. If the aim is to have clean effluent discharges, nutrient uptake efficiency is important. If the aim is to increase biomass production, resulting in a comparatively smaller reduction of nutrients in the water being discharged, then nutrient uptake rate should be monitored. Neori et al. (1996) showed, however, that by recycling the water of a fish pond through a seaweed pond, it was possible to simultaneously achieve high nutrient uptake efficiency and rate. This requires adjusting the seaweed pond area, with its known average daily uptake rate (in the case of *Ulva*, over 40 kg ammonium-N per hectare per day) to the expected rate of fish nutrient production (about 45 kg ammonium-N per 100 tons of sea bream per day). Recycling the water between the two ponds, at the proper rate, exerts high nutrient loading rates on the seaweed biofilter and results in both high nutrient removal efficiency and rate. The addition of one or several seaweed ponds, in series of decreasing size, at the outflow of the culture system as a final polishing step can increase the overall efficiency of ammonium removal even further.

REVIEW OF RESULTS OBTAINED WITH MARINE OPEN-WATER AND LAND-BASED SYSTEMS

Systems using seaweeds for the removal or conversion of wastes fall into two groups: open-water or land-based cultivation systems. In open-water systems, waste disposal and removal are difficult to monitor and control. Despite the fact that such systems have been operating in an empirical manner for centuries in Asia, our understanding is limited by the restricted number of scientific studies on such integrated systems, because of the complex multidisciplinary approach they require, rendered even more complex by often unpropitious commercial and regulatory settings (Petrell et al. 1993, Newkirk 1996, Petrell and Alie 1996, Troell et al. 1997, 1999b, Chopin et al. 1999a,b). Chopin et al. (1999b) developed an aquaculture project integrating *Porphyra* (nori) and salmon. For rapid growth and appropriate marketable pigmentation, *Porphyra* requires constant availability of nutrients, especially in the summer when temperate waters are generally nutrient depleted. Cultivation of nori in the proximity of salmon alleviates this nutrient depletion by using the constant nutrient supply of the fish farm, which is then valued and managed. This represents a clear case of mutual benefits for the co-cultured organisms when meaningful developments in integrated coastal zone management are sought: seaweeds use the nutrients required for their growth, while contributing to water quality improvement around fish for their health enhancement. Chopin et al. (1999b) calculated that 27 and 22 nori nets (18 m × 1.8 m) would be necessary for the complete removal of phosphorus and nitrogen released per ton of fish per year, respectively. However, the ultimate goal should be to reduce nutrient concentrations in seawater below the threshold triggering hypertrophic events, thus requiring fewer nets. Unfortunately, such triggering levels are often unknown, highly site specific, and many other environmental factors may be involved in the development of hypertrophic conditions. Some brown algae (Subandar et al. 1993, Ahn et al. 1998) and red algae (Buschmann et al. 1996b, Troell et al. 1997, Chopin et al. 1999b) show a high capacity for removing nutrients from fish effluents, and seaweed production is higher in areas surrounding fish cages than in areas remote from aquaculture operations (Troell et al. 1997). Nonetheless, modeling research still needs to be conducted to define the nutrient uptake efficiency and assimilative capacity of these systems. By using the red alga *Gracilaria chilensis* Bird, McLachlan *et* Oliveira, Troell et al. (1997) concluded that a suspended culture of 1 ha, at a stocking density of 1 kg $\mathrm{WW \cdot m^{-2}}$ (0.5 kg WW at the two depths, -1 m and -3 m), removes 5% of the dissolved inorganic nitrogen and 27% of the dissolved inorganic phosphorus released from a 227-ton mixed fish farm (coho salmon, *Oncorrhynchus kisutch* Walbaum, and rainbow trout, *O. mykiss* Walbaum), equivalent to a reduction of 1,020 kg and 375 kg, respectively. One thing to keep in mind is that fish culture is three dimensional (sea cages), whereas seaweed culture is almost bidimensional (surface nets or shallow rope cultures) because it is dependent on the solar radiation reaching the first few meters underwater. Because fish are cultivated in a relatively small surface area, achieving a significant removal of fish dissolved wastes requires that seaweed cultivation is carried out at high densities and increasing depths, which may be advantageous in the summer to avoid pigment photodestruction and can facilitate the operation of vessels for the fish-related activities of a farm. Nevertheless, from an economic point of view, suspended seaweed farming appears to be commercially interesting (Petrell et al. 1993, Troell et al. 1997, Chopin et al. 1999b). The agarophytic alga *G.* chilensis showed higher agar yields and increased gel strength when cultivated near salmon cages (Weidner and Bello 1996). *Porphyra purpurea* (Roth) C. Agardh and *Porphyra umbilicalis* (Linnaeus) J. Agardh had higher phycoerythrin and phycocyanin contents when cultivated in the proximity of salmon cages (Chopin et al. 1999b).

A common misconception is that all present aquaculture nutrification impacts will disappear when operations move on land, a solution presented by some as the way of the future for the aquaculture industry. It will certainly alleviate the problem of dilution of the nutrient loading in bodies of water that becomes very difficult to monitor and treat. Concentrated effluents from on-land aquaculture operations will remain, however, to be channeled through pipes and to be appropriately and profitably treated—mechanically, chemically, and, most economically, by biological means—before being reused (closed systems) or discharged (open systems). Fish effluents produced by land-based systems are comparatively easier to treat than those from open systems (Seymour and Bergheim 1991, Troell et al. 1999a). Experimental projects began in the 1970s (Haines 1975, Ryther et al. 1975, Tenore 1976, Langton et al. 1977, Fralick 1979, Harlin et al. 1979). During the last decade, renewed interest in incorporating macroalgae as the biofilter link in integrated carnivore–herbivore polyculture systems has produced new approaches and practical technologies (Vandermeulen and Gordin 1990, Cohen and Neori 1991, Neori et al. 1991, 1996, 1998, 2000, Haglund and Pedersén 1993, Buschmann et al. 1994, 1996b, Krom et al. 1995, Martínez and Buschmann 1996, Shpigel and Neori 1996, Neori and Shpigel 1999, Nelson et al. 2001). These studies indicate that seaweeds can assimilate as much as 90% of the ammonium produced by intensive fish culture (Cohen and Neori 1991, Neori et al. 1991, 1996, Jimenez del Río et al. 1994, Buschmann et al. 1996b, Neori and Shpigel 1999). Enander and Hasselström (1994) integrated the culture of prawn (*Penaeus monodon*), mussel (*Mytilus edulis*), and the red alga *Gracilaria* sp.; they recorded a reduction in the effluent of 81% for ammonium, 19% for nitrate, 72% for total nitrogen, 83% for phosphate, and 61% for total phosphorus.

The main issue in the effective implementation of these systems is their optimal functioning, which requires an in-depth understanding of the physiology and nutrition of the selected species. With seaweeds, like with many organisms, the different physiological processes taking place have different requirements and optima (Lobban and Harrison 1994, Harrison and Hurd 2001). Consequently, the optimization of the overall efficiency of a cultivation system can be complex because it will require finding of a compromise between apparently conflicting objectives (e.g. biomass or particular compound production versus bioremediation efficiency; Chopin and Yarish 1998). For example, growth, nutrient (nitrogen and phosphorus) uptake, carrageenan or agar production, and phycocolloid quality respond differentially to nutrient enrichment (Neish et al. 1977, Chopin et al. 1990, 1995, Chopin and Wagey 1999, Buschmann et al. 2001).

In tank culture, nutrient availability can be controlled by changing the water flow. By increasing the water flow nutrient flux increases, which allows a high biomass production of nutrient-sufficient seaweeds;

however, the nutrient uptake efficiency is low and nutrient concentrations remain high in the effluents. On the other hand, if the water flow is low, nutrients become limiting and macroalgal biomass production decreases, but the nutrient uptake efficiency is higher and the nutrient concentrations in the effluents can be lower. Of course, this is within the physiological assimilative capabilities of the cultivated organisms. This emphasizes that to optimize a system not only should its main target(s) be clearly established, but the appropriate species should be selected based on a thorough understanding of the organism (Hanisak 1998). If a seaweed is only used as a biofilter, previously identified low commercial value species like *Ulva* can be used to depurate fish effluents (Cohen and Neori 1991, Hirata and Kohirata 1993, Jimenez del Río et al. 1994). However, this apparent bioremediation merely shifts the problem of waste disposal as the algal scrubber will in turn need to be disposed of or treated. On the other hand, species like *Gracilaria, Porphyra, Palmaria, Chondrus,* or *Laminaria* offer both high bioremediation efficiency and commercial value in established markets (phycocolloids, human consumption, etc.) or developing ones (diets for other high-valued aquaculture organisms [herbivorous fish, abalone, sea urchin] and other niche markets; Haglund and Pedersén 1993, Buschmann et al. 1996b, Hanisak 1998, Yarish et al. 1998, Chopin et al. 1999a). Recently, Neori and Shpigel (1999) demonstrated that *Ulva lactuca* Linnaeus, rendered protein-rich through its use as fish pond biofilter, acquires nutritional value that increases the overall profitability of an aquaculture operation per cultivation unit as well as per resource unit (water, food, energy, and labor). The recycling *Sparus aurata* (gilthead sea bream)/*Ulva lactuca* (sea lettuce) system developed by Neori et al. (2000) allows for the reduction of seawater consumption and energy by 75%, while also producing 7 kg of *Ulva lactuca* per kg of fish, which are then converted into 0.5 kg of the lucrative macroalgivore abalone (a similar approach can be used with sea urchin).

When the value added for the service of improving water quality and coastal health is finally recognized, quantified and combined with that of the principal crop (the traditional finfish or shrimp aquaculture), the seaweed component of an integrated aquaculture system will be understood to significantly improve the success of a diversified operation. An accrued benefit to operators of this type of aquaculture is the fact that the currently discharged (unassimilated and/or excreted) phosphorus and nitrogen, which represent a loss of money in real terms, will be captured and converted into the production of salable biomass and biochemicals, hence generating revenues that may more than compensate for the expenses. Additionally, as legislative guidelines, standards, and controls regarding the discharge of inorganic nutrients into coastal waters become more stringent in many countries, bioremediation via the production of seaweeds will help the fish aquaculture industry avoid noncompliance.

INTERNALIZING ENVIRONMENTAL COSTS

The technical and economic cost–benefit analysis of a land-based center for the production of salmon and seaweeds in Chile was conducted by Alvarado (1996). The cost of producing salmon depends largely on the stocking density achieved in the fish culture. For example, the investment for 200 tons of fish production increases from US$250,000 to US$6,500,000 when the stocking density declines from 60 to 15 $\mathrm{kg \cdot m^{-3}}$. The operational cost also increases with increasing culture size but decreases with the stocking density because of the water requirements, which leads to different costs for each fish culture density. With an average price of US4.8\cdot \mathrm{kg^{-1}}$ for salmon, the income for 600 tons of net production is US$2,880,000. Considering the water flow requirements for 200 and 600 net tons of salmon, the production of seaweed increases from 500 to 1,700 wet tons (Buschmann et al. 1996b). Assuming a conservative price of US1.00\cdot \mathrm{kg^{-1}}$ (dry) for *Gracilaria*, the additional income in a 600-ton salmon culture unit can reach US$550,000.

Considering the production of solid and dissolved wastes based on the amount of nitrogen and phosphorus incorporated to the system given by Buschmann et al. (1996b) and applying a cost to nutrients released to the environment based on calculations from Folke et al. (1994; US$6.4 to 12.8$\cdot \mathrm{kg^{-1}}$ for nitrogen and US$2.6 to 3.8$\cdot \mathrm{kg^{-1}}$ for phosphorus, based on treatment costs in Swedish sewage treatment plants), it is possible to internalize the total environmental cost for 250 tons of gross fish production at US$201,411. However, when considering the savings realized by integrating the culture of *Gracilaria* to minimize the disposal of nitrogen and phosphorus to the environment, the total environment cost is only US$64,000, which represents a reduction of 68.2%. Table 2 shows the different levels of profitability that can be reached, with farms of different net productions and different stocking densities, when environmental costs are not internalized (present situation

TABLE 2. Profitability analysis using the net present value (NPV in US$) and internal rate of return (IRR in %) of a culture system simulating three different net salmon productions (200, 400, and 600 tons) and four different fish stock densities (15, 30, 45, and 60 $\mathrm{kg \cdot m^{-3}}$) without internalizing the total environmental costs.

		Profitability indicators	
Fish net production	Stocking density	NPV	IRR
200	15	n.p.	n.p.
	30	n.p.	n.p.
	45	455,692	24.1
	60	685,939	30.0
400	15	n.p.	n.p.
	30	814,882	21.9
	45	1,965,197	34.3
	60	2,498,356	42.2
600	15	n.p.	n.p.
	30	2,065,330	26.2
	45	3,743,201	40.0
	60	4,569,269	47.8

n.p., no profit.

TABLE 3. Profitability analysis using the net present value (NPV in US$) and internal rate of return (IRR in %) of a culture system simulating three different net salmon productions (200, 400, and 600 tons) and four different fish stock densities (15, 30, 45, and 60 kg·m^{-3}), considering the internalization of the total environmental costs.

		Profitability indicators	
Fish net production	Stocking density	NPV	IRR
200	15	n.p.	n.p.
	30	n.p.	n.p.
	45	n.p.	n.p.
	60	n.p	n.p.
400	15	n.p.	n.p.
	30	n.p.	n.p.
	45	n.p.	n.p.
	60	339,186	19.2
600	15	n.p.	n.p.
	30	n.p.	n.p.
	45	505,167	18.6
	60	1,330,517	25.4

n.p., no profit.

throughout the world). If laws or regulations were implemented to have aquaculture operations responsibly internalize their environmental costs, a significant reduction of their profitability would occur (Table 3). By integrating the culture of the nutrient scrubber *Gracilaria*, environmental costs of waste discharges are significantly reduced and profitability is significantly increased (Table 4). Even if it does not reach the profitability of the first case scenario 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).

CONCLUSIONS

The accelerated development of intensive fed aquaculture throughout the world is not without regionalized impacts, especially when the activities are highly concentrated or located in suboptimal sites. Unfortunately, impacts are often realized after environmental stresses become obvious because of our general lack of understanding of the assimilative capacity of coastal waters and its predictive modeling (Rawson et al. in press). Responsible aquaculture practices should be based on a balanced ecosystem management approach, the basic premise of which is to incorporate the biological and environmental functions of a diverse group of organisms into a unified system that maintains the natural interactions of species and allows an ecosystem to function sustainably.

TABLE 4. Profitability analysis using the net present value (NPV in US$) and internal rate of return (IRR in %) of an integrated culture system simulating three different net salmon productions (200, 400, and 600 tons) and four different fish stock densities (15, 30, 45, and 60 kg·m^{-3}), 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.

		Profitability indicators	
Fish net production	Stocking density	NPV	IRR
200	15	n.p.	n.p.
	30	n.p.	n.p.
	45	39,982	15.8
	60	270,230	20.8
400	15	n.p.	n.p.
	30	n.p.	n.p.
	45	1,133,772	25.7
	60	1,666,931	32.2
600	15	n.p.	n.p.
	30	818,195	19.4
	45	2,496,785	30.3
	60	3,322,135	37.5

n.p., no profit.

One common sense solution is the development of integrated systems by combining fed and extractive aquaculture at several trophic levels. By significantly reducing the total environmental costs of aquaculture operations, this approach should find increasing environmental, economic, and social acceptability, especially if the "user pays" concept gains momentum as a tool in integrated coastal management (Soley et al. 1994, Buschmann et al. 1996a, Coastal Zone Canada Association 2001). The development of such practices would certainly be less expensive and less labor intensive than implementing and respecting regulations or laws on conventional waste treatment enacted by state or governing agencies (Folke et al. 1994).

To successfully develop integrated aquaculture systems, much research and development remains to be undertaken, particularly in the following areas:

- Transfer and modification of cultivation technologies to local environments and socioeconomics;
- Development of the cultivation of native species of marketable value that will be fast growing at different times of the year and in diverse habitats;
- Site-specific biological, chemical, physical, and socioeconomic modeling to define the appropriate proportions between the different cocultured organisms;
- Development of a regulatory and legislative management framework with enough flexibility to allow experimental and innovative practices at a meaningful preindustrial scale.

Pivotal for the success of the aquaculture industry in the future will be the wise investment in research and development (not development and research, as is seen too often) and the implementation of current novel technologies and concept, to move in new directions to optimize its efficiency through diversification, while maintaining the health of coastal waters. The aquaculture industry is here to stay in our "coastalscape": it has its place in the global seafood supply and demand and in the economy of coastal communities. To help ensure its sustainability, however, it needs to responsibly change its too often monotrophic practices by adopting polytrophic ones to become better integrated into a broader coastal management framework.

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