Beyond the Monospecific Approach to Animal Aquaculture—The Light of Integrated Multi-Trophic Aquaculture

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CHAPTER 25

BEYOND THE MONOSPECIFIC APPROACH TO ANIMAL AQUACULTURE — THE LIGHT OF INTEGRATED MULTI-TROPHIC AQUACULTURE

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Abstract: The focus of present-day aquaculture is typically monospecific animal culture. Even the development of "alternative" species for aquaculture usually refers to alternative species of fish or shellfish. However, although introducing another species of fish or shellfish may have short-term benefits, rarely does it balance energetically and ecologically in the long term. What is needed is appropriate proportions of different co-cultured organisms, performing different processes throughout the day and seasonally. Other than in Asia, the fundamental role and the contribution of seaweeds in coastal waters have frequently been either ignored or misunderstood. Seaweeds are rarely factored into modeling equations of coastal systems. At a time when nutrification of coastal waters is becoming a pressing issue worldwide and the contribution of the inorganic output of aquaculture to regional nutrient loading is becoming more widely recognized, integrating seaweeds, which act as biological nutrient scrubbers, into fish or shellfish aquaculture is a promising, balanced-ecosystem approach. Integrating seaweeds into aquaculture systems provides bioremediation capability, mutual benefits to the co-cultured organisms, and economic diversification of the industry by producing another value-added marine crop. We discuss these concepts and illustrate the benefits of integrated multi-trophic aquaculture (IMTA) using projects that we are conducting in New England, USA, in which the culture of the red alga *Porphyra* (nori) is integrated with salmonid culture, and in the Maritime Provinces, Canada, in which open-water aquaculture of *Chondrus crispus* (Irish moss) is conducted in proximity to mussel and oyster aquaculture operations. The aquaculture industry recognizes its

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need to practice responsible aquaculture by moving in new directions, such as IMTA. This will require wise investment in research and development.

Key words: aquaculture, Canada, environment, impacts, integrated multi-trophic aquaculture, seaweeds, *Chondrus crispus*, *Porphyra*, USA

1. INTRODUCTION

The fundamental role and the contribution of seaweeds in coastal waters have frequently been either ignored or misunderstood, especially in the Western World. Seaweeds are rarely factored into models of coastal systems. Usually, review papers on national aquaculture production either do not mention seaweed production numbers, or those numbers are not available for inclusion in such papers. In contrast, Asian countries generally have a long tradition of seaweed aquaculture. In 2000, for example, China produced 7.9 million metric tons (t) of algae—mainly the brown algae *Laminaria* and *Undaria* and the red algae *Porphyra*, *Gracilaria*, *Kappaphycus*, and *Betaphycus*. Cultivation of these genera represents 93% of the world seaweed aquaculture production (10.1 million tons, which itself represents 88% of the worldwide commercial harvest of seaweeds [FAO, 2000]). Such a tremendous biomass certainly provides significant "buffer capacity" in Chinese coastal waters, which are under considerable environmental pressure because of high human population density and related activities (e.g., reduced sewage treatment capacity [X.G. Fei, Institute of Oceanology, Qingdao, China, personal communication]).

Currently, development of the culture of "alternative" species is thought to reduce some aquaculture impacts. However, frequently those species are fish. Although introducing another species of fish into an aquaculture operation may generate short-term economic benefits, it rarely creates an energetically and ecologically balanced operation in the long term. Such aquaculture continues to be "fed" (finfish) aquaculture, in which a significant fraction of the additional food is not consumed and metabolic excretion is unidirectional (Ackefors and Enell, 1990).

Just as fish monoculture may not be environmentally sustainable, seaweed monoculture, too, has its limitations. Cultivated seaweed species are not immune to bacterial or fungal pathogenic infections, such as the "ice–ice" disease in *Kappaphycus* and *Eucheuma*, which spreads faster when plants are already stressed (Largo et al., 1999). In addition, intensive aquaculture of large macroalgae can impact current velocity, sedimentation rates, and, at night when these photosynthetic organisms also respire, oxygen consumption rates (J. Grant, Dalhousie University, Halifax, Canada, personal communication).

It is also thought that open-water aquaculture nutrification impacts will be reduced if aquaculture operations move onto land. This spatial shift should reduce the problem of concentrated nutrient loading in water bodies, which can become difficult to treat. However, concentrated effluents from on-land aquaculture operations would still need to be channeled through pipes and be appropriately treated before being re-used (close systems) or discharged (open systems).

For a balanced-ecosystem approach, "extractive" (shellfish and seaweeds) aquaculture should be integrated with fed aquaculture as an innovative aquaculture development. Aquaculture operations that utilize a diversity of co-cultured organisms to perform different processes throughout the day and among seasons are needed; the biomasses of these organisms should be of such proportion that their productivity and metabolic processes counterbalance each other.

In both open-water and on-land aquaculture systems, seaweeds not only act as renewable biological nutrient scrubbers for water quality enhancement and coastal health improvement, but also represent marine crops of commercial value. In this chapter, the concepts of bioremediation, mutual benefits for the co-cultured organisms, and economic diversification of the aquaculture industry will be developed and illustrated by projects we are conducting in New England, USA, and the Maritime Provinces of Canada.

2. DEVELOPMENT OF *PORPHYRA*/FISH INTEGRATED MULTI-TROPHIC AQUACULTURE

A consequence of finfish aquaculture activities is significant loading of inorganic nutrients, especially nitrogen (N) and phosphorus (P), into coastal waters (Beveridge, 1987). Because of improvements in feed composition, digestibility, and feed conversion efficiency in recent years, the N and P discharge per ton of salmon (*Salmo salar*) per year is now estimated at 35.0 and 7.0 kg, respectively (Chopin et al., 2001; H. Ackefors, University of Stockholm, Stockholm, Sweden, personal communication).

In New Brunswick, Canada, salmon aquaculture production is concentrated in the Quoddy Region, where 96 salmon-farming sites are located within a rectangle of approximately 50 km by 40 km. In 2001, based on aquaculture production of 35,000 t, the exogenous N and P inputs into coastal waters through aquaculture operations were 1225 and 245 t, respectively. This significant nutrient loading does not rapidly disappear because of the exceptional tidal and flushing regime of the Bay of Fundy. The circulation in this bay is more likely that of a bathtub with tides going up and down on opposite sides than that of a bay with an open-ended mouth and a unidirectional flow. Considering only Passamaquoddy Bay (an embayment within the Bay of Fundy), Ketchum and Keen (1953) estimated a flushing time of about 15 days; the water residency time for the whole Bay of Fundy is probably around 76 days (F. Page, Department of Fisheries and Oceans, St. Andrews, Canada, personal communication). This clearly indicates that nutrient bioavailability, even at diluted levels, remains significant for a long period of time, which may put the nutrient carrying capacity of the Bay of Fundy at risk, especially when a nutrient-generating activity is geographically highly localized. Of course, the aquaculture industry is not the only source of nutrification and should not be the only one to be singled out. There are other point- and non-point-sources such as agricultural runoff, industrial runoff, urban and rural effluents, and sewage treatment facilities. However, as a precautionary measure, those in charge of aquaculture operations in the bay should develop practices that ensure remediation of the consequences of their activities.

This is precisely the type of situation in which seaweeds are important to coastal ecosystems. Seaweeds can be used in integrated multi-trophic aquaculture (IMTA) systems to bioremediate the coastal-water nutrification. Physiologically, seaweeds can be viewed as bioengineered systems that take up nutrients like sponges absorb water. However, similarly to a sponge, they can become nutrient-saturated. By periodically harvesting the saturated tissues, a significant quantity of nutrients can be removed from coastal waters and the regrowth of new tissue can continue the nutrient scrubbing process. Thus, these naturally appropriately engineered systems can compete with recent, human-engineered, proposed solutions, which need the test of time.

For rapid growth and appropriate marketable pigmentation, *Porphyra* (commonly known as nori) requires constant availability of nutrients, especially in the summer, when nutrients can become depleted (Chopin et al., 1999b). Cultivation of nori in proximity to salmon cages facilitates utilization of the nutrients loaded into the water by these fish farms; those nutrients then become valued resources (wastes become fertilizer) and can be managed. The desirable algal crops compete with undesirable algal nuisances for the nutrients. This reduces the likelihood of phenomena such as green tides in the vicinity of finfish aquaculture operations (Chopin et al., 1999b). This IMTA represents a clear case of mutual benefits for the co-cultured organisms. Seaweeds utilize the surplus nutrients for growth and fish health is enhanced because the water quality is improved.

We have investigated the relationship between N, P, and pigment (phycoerythrin and phycocyanin) contents of *Porphyra purpurea*, *P. yezoensis*, and *P. umbilicalis*, and N and P concentrations in seawater at sites remote from finfish aquaculture operations and at sites of experimental nori/salmon IMTA (Chopin et al., 1999b). Figure 1 exemplifies the differences in the quality of *P. purpurea* grown in these two environments at a time of the year when seawater nutrient availability is much reduced (averaging 2.98-μM N and 0.69-μM P). The pale, slow-growing nori, collected from a location remote from aquaculture operations, contains 24.7 ± 0.1 mg N/g dry weight (DW) and 2.0 ± 0.3 mg P/g DW. The healthy, fast-growing nori, collected from a location near a salmon aquaculture cage, contains 40.6 ± 0.1 mg N/g DW and 3.3 ± 0.1 mg P/g DW. *Porphyra purpurea* grown at this site has a constant and abundant supply of nutrients in the seawater (averaging 6.70-μM N and 0.87-μM P).

Based on the N and P numbers mentioned above, 22 and 27 standard nori nets would be necessary for the complete scrubbing of N and P, respectively,

Figure 1. Samples of *Porphyra purpurea* (nori) collected from a site remote from aquaculture operations (left) and from a site in proximity to salmon aquaculture (right)

per ton of salmon per year (Chopin et al., 1999b). These numbers are manageable over a year when one considers that nets can be stacked at certain periods in the cultivation process and that several harvests can be conducted over a growing season. However, rather than complete N and P scrubbing, the objective of cultivating desirable algal crops should be to reduce nutrient concentrations in seawater and, thereby, the probability of blooms of problem algal species that can trigger costly hypertrophic events such as eutrophication, diseases, harmful algal blooms, and green tides (Bruno et al., 1989; Folke and Kautsky, 1989; Merrill, 1996). Thus, fewer nets would be necessary.

We have also been working to estimate the *Porphyra* production required to remove N and P generated by a land-based fish farm (operated in tanks by Great Bay Aquafarms, Incorporated, New Hampshire, USA). The farm has an annual production of summer flounder (*Paralichthys dentatus*) fingerlings and adults of 8000 kg/yr and produces an effluent with average inorganic nutrient concentrations of 143-μM N and 10-μM P and a flow rate of 190 l/min. Thus, the farm discharges about 547.2 g of N and 82.1 g of P per day. We are presently developing a system for obtaining the best compromise between algal stocking density, growth rate, biomass yield, N and P uptake, and harvesting frequency for optimized bioremediation capacity (optimal nutrient removal with the smallest "footprint"). An accrued benefit to operators of this type of aquaculture is that discharged (unassimilated and/or excreted) N and P, which represent a loss of money, can be captured and converted into the production of salable nori and biochemicals, hence generating revenues that more than compensate for the expenses. Additionally, as legislative guidelines, standards, and controls on the discharge of inorganic nutrients from aquaculture operations into coastal waters become more stringent, bioremediation via the production of seaweeds could help the fish aquaculture industry avoid noncompliance problems.

3. DEVELOPMENT OF OPEN-WATER AQUACULTURE OF *CHONDRUS CRISPUS*

Raking, by hand or with a horse, of the carrageenophytic red alga *Chondrus crispus*, commonly known as Irish moss, for commercial gain was practiced as early as the mid-1920s in New Brunswick, Canada (Chopin, 1998); drag-raking of nearshore beds, from boats, started in the early 1950s in Prince Edward Island. Land-based aquaculture of *C. crispus* was initiated in the 1970s (Neish et al., 1977). After 15 years of research, some believed that *C. crispus* tank aquaculture in temperate regions could not compete in the carrageenan market with the harvest of natural populations or with tropical open-water aquaculture, mostly because operational and labor costs were high and solar and thermal conditions were inadequate (Bidwell et al., 1985). Others, such as Acadian Seaplants Ltd. personnel, persevered; they developed and adapted large-scale facilities to culture *C. crispus* for the production of an edible, high-added-valued product by manipulating the color and texture of selected isolates (Craigie et al., 1999).

Open-water aquaculture of carrageenophytes such as *Kappaphycus*, *Eucheuma*, and *Betaphycus* has been extremely successful in tropical regions (Doty, 1987), but has rarely been attempted in temperate regions (Chopin et al., 1999a). We decided to re-examine the potential of *C. crispus* for open-water aquaculture. We carefully selected strains and sites, and developed a new culture method using mussel "socks" (Figure 2) and an extended grow-out period. The population of origin, from a shallow inlet in northeastern Prince Edward Island (Basin Head), is unique in the Maritime Provinces of Canada. It is made of unattached, large, thick, mostly gametophytic fronds and reproduces almost entirely vegetatively through fragmentation. However, this morphotype presently cannot be discriminated from others by the molecular techniques used thus far (Chopin et al., 1996; Donaldson et al., 1998; Donaldson et al., 2000). Chopin et al. (1999a) demonstrated that Basin Head plants can be successfully transplanted to other sites with environmental conditions that yield comparable or even higher *C. crispus* productivity.

Daily growth rates (DGRs), which ranged 3–4%/day (d) (some plants exceeded 6%/d), are lower than those recorded in tropical and subtropical farms of *Kappaphycus* and *Eucheuma*, the current main sources of carrageenans in the world (Chopin, 1998). These farms generally have DGRs that range

Figure 2. Mussel "socks" inoculated with the red alga *Chondrus crispus* (Irish moss)

3–5%/d (farms able to sustain a DGR of 7%/d are considered to be highly productive [Chopin et al., 1999a]). These relatively lower DGRs are, however, compensated for by the high carrageenan yields of this strain of *C. crispus* (58–74% DW in the summer) compared to *Kappaphycus* and *Eucheuma* (20–30% DW, or even down now to 11% DW [Chopin et al., 1999a]). The carrageenan yields of this *C. crispus* strain are also high compared to those generally reported for *C. crispus* harvested from natural beds (40–50% DW [Chopin, 1986]). This could be explained by strain selection and by nutrient levels in the algal tissues, which are correlated with ambient seawater nutrient levels at the sites (Chopin et al., 1999a). In Figure 3, we show that carrageenan contents follow the reverse trend of those of tissue P. A significant increase in carrageenan content occurred in June 1997 and corresponded to a drop in tissue total-P content; whereas, in 1998, the increase in carrageenan content and the concomitant decrease in tissue total-P content were much later. This is a clear illustration of what has been referred to as the "Chopin effect" (an inverse relationship between P and carrageenan contents [Chopin et al., 1990, 1995; Chopin and Wagey, 1999]), and is analogous to the "Neish effect" (Neish et al., 1977), which describes the impact of nitrogen nutrition on carrageenan content.

We are presently testing several sites in the proximity of mussel and oyster aquaculture operations to define the optimal physical (flushing rate, sediment, bottom vegetation), chemical (nutrient availability), and biological (biofouling) conditions for growth rates and carrageenan yields. Different sock handling

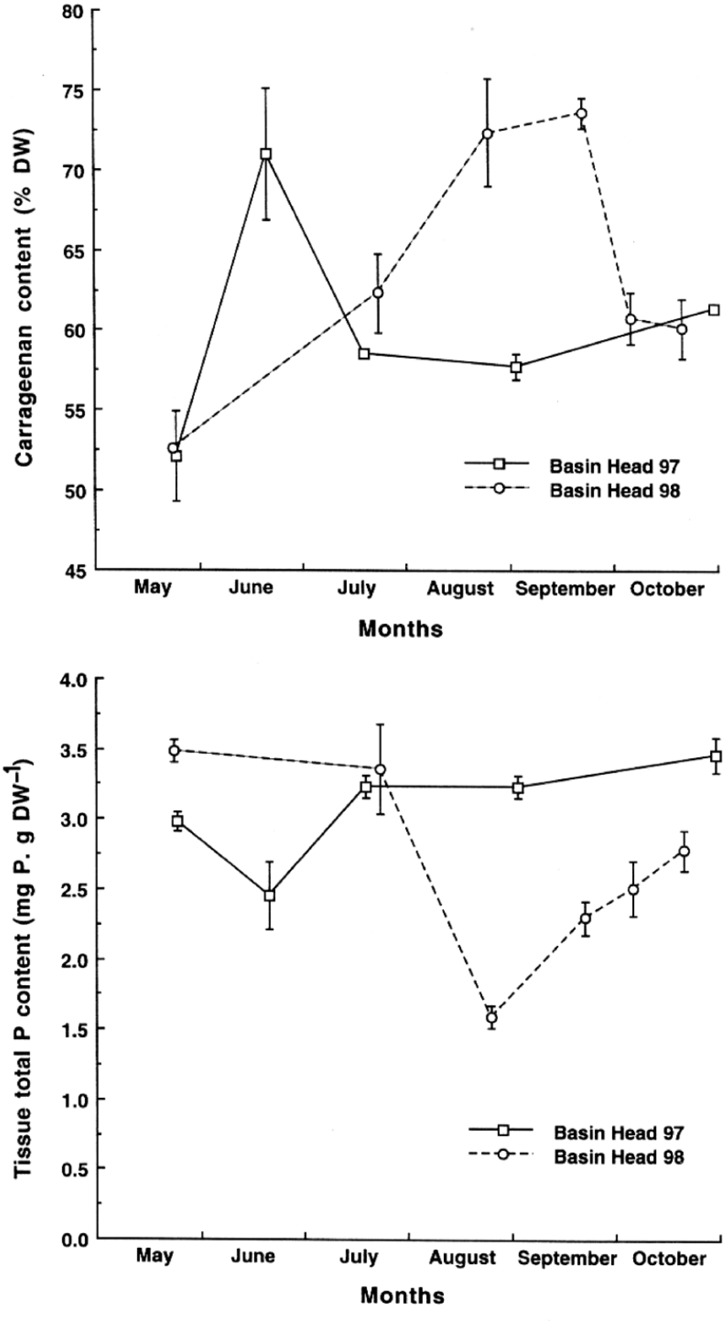

Figure 3. Variations in carrageenan content (% dry weight [DW]; top) and in tissue total phosphorus content (mg P/g DW; bottom) in *Chondrus crispus* at Basin Head, Prince Edward Island, Canada, May–October 1997 and 1998. Values represent means ($n = 3$) ± SD

methods, grow-out techniques (hanging or bottom culture, socking density, size of frond fragments) and timing strategies of inoculation and harvesting are also tested to develop the most efficient and commercially viable techniques. If DGRs could be improved and with carrageenan contents two to three times those of *Kappaphycus* and *Eucheuma*, this approach could become economically competitive with mechanization. Moreover, because the phycocolloid industry presently wants to diversify its sources of raw material, there is a renewed interest in cold-water species of carrageenophytes. *Chondrus crispus* culture could also serve as any of the following:

1. an alternative source of Irish moss that would complement the declining harvest of wild C. *crispus* (Chopin, 1998);
2. a source of high-quality carrageenans in the κ-family (instead of the κ-/λ-mixture from harvested natural beds);
3. a component of the economic diversification of the shellfish and finfish aquaculture industry, which could integrate it as a complementary activity that would provide additional income and serve as a natural scrubbing system for disposal of excess N and P.

4. CONCLUSIONS

Nutrification of coastal waters as a result of anthropogenic activities is a worldwide phenomenon increasingly recognized as a pressing issue. Finfish aquaculture can be, at a regional level, one of the contributors to this significant nutrient loading (Beveridge, 1987; Kautsky et al., 1997). This often monospecific and animal "fed" type of aquaculture is presently at a crossroad; as its economic and environmental limitations are realized, its sustainability is questioned (Naylor et al., 2000). To avoid pronounced shifts in coastal processes when the carrying capacity of the environment is exceeded, fed finfish aquaculture should be integrated with inorganic extractive seaweed aquaculture and organic extractive shellfish aquaculture to reduce nutrient loading (especially of N and P) and organic deposition. There is no doubt that the aquaculture industry is here to stay in the "coastal scape." However, it has to develop, in a timely manner, sustainable aquaculture practices. Responsible aquaculture now needs to be supported and implemented, rather than simply described in codes of good or best practices.

Considering economically important seaweeds as renewable biological nutrient scrubbers demonstrates an understanding of one of their fundamental roles in coastal ecosystems and validates their use in integrated aquaculture systems. Seaweed aquaculture is an excellent choice for eutrophication abatement (bioremediation), and also provides another value-added marine crop for diversification of the aquaculture industry (Mumford and Miura, 1988; Petrell et al., 1993; Chopin et al., 1999b).

To work, integrated aquaculture still requires fine-tuning. It is highly site-specific (e.g., what flow rates and nutrient concentrations are available?) and species-specific (which species to integrate, and in which proportions?). Thus, research and development (R&D) is still needed to arrive at the optimal system for each particular bay. Rapid overgeneralization of techniques and protocols would not take into consideration the particularities of each specific bay. If the species of seaweeds selected for cultivation are efficient biological nutrient removal systems, the productivity and carrying capacity of particular sites could be improved. Consequently, the number of fish cages or tanks could be increased and even more revenues could be generated by the aquaculture industry, which seeks sustainability, long-term profitability, and responsible management.

To successfully develop integrated aquaculture systems, much R&D remains to be undertaken, particularly in the following areas:

1. transfer and modification of cultivation technologies for use in local environments and to fit local socioeconomic situations;
2. development of cultivation techniques for marketable, fast-growing, native species that will be available for harvest at different times of the year and in diverse habitats;
3. development of site-specific modeling capabilities to define the appropriate proportions of the different co-cultured organisms.

Pivotal for its success in the future, the aquaculture industry will have to wisely invest in R&D to move in new directions, through the development of innovative bioengineering concepts and practices that will optimize its efficiency and the diversification of marine crops, while ensuring that the health of coastal waters is maintained.

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