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Ecological engineering in aquaculture: use of seaweeds for removing nutrients from intensive mariculture

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Abstract

Rapid scale growth of intensive mariculture systems can often lead to adverse impacts on the environment. Intensive fish and shrimp farming, being defined as throughput-based systems, have a continuous or pulse release of nutrients that adds to coastal eutrophication. As an alternative treatment solution, seaweeds can be used to clean the dissolved part of this effluent. Two examples of successfully using seaweeds as biofilters in intensive mariculture systems are discussed in this paper. The first example shows that *Gracilaria* co-cultivated with salmon in a tank system reached production rates as high as 48.9 kg m^{-2} a^{-1}, and could remove 50% of the dissolved ammonium released by the fish in winter, increasing to 90–95% in spring. In the second example, *Gracilaria* cultivated on ropes near a 22-t fish cage farm, had up to 40% higher growth rate (specific growth rate of 7% d^{-1}) compared to controls. Extrapolation of the results showed that a 1 ha *Gracilaria* culture gave an annual harvest of 34 t (d. wt), and assimilated 6.5% of the released dissolved nitrogen. This production and assimilation was more than twice that of a *Gracilaria* monoculture. By integrating seaweeds with fish farming the nutrient assimilating capacity of an area increases. With increased carrying capacity it will be possible to increase salmon cage densities before risking negative environmental effects like eutrophication and toxic algal blooms sometimes associated with the release of dissolved nutrients. The potential for using mangroves and/or seaweeds as filters for wastes from intensive shrimp pond farming is also discussed. It is concluded that such techniques, based on ecological engineering, seems promising for mitigating environmental impacts from intensive mariculture; however, continued research on this type of solution is required.

Introduction

Aquaculture, according to FAO statistics, is the fastest growing food production sector, with a yearly growth of about 4–11% (FAO, 1997; values for all aquatic products 1988–1995). Without doubt aquaculture will continue to play an important role in the global supply of fish and shellfish in the future. The present concern for continuing deterioration of coastal ecosystems and its subsequent impact on aquaculture and other uses, implies that a ‘precautionary principle’ be applied to any development activity that might be unsustainable. Aquaculture may contribute to the degradation of the environment, but paradoxically it is still dependent on the supply of clean waters, seed larvae supply and other ecosystem services (Rönnbäck, in press).

Traditional farming systems (e.g. extensive pond farming) dominate aquaculture production in many regions, but these are now slowly being replaced by intensive western oriented techniques (New & Wijkstrom, 1990; Ekins et al., 1994; Weber, 1996). This trend is disquieting, as it will often have negative implications for the environment. Intensive aquaculture systems have been described as ‘throughput-based systems’ (Daly & Cobb, 1989; Folke & Kautsky, 1992); they depend on large inputs of resources of which only a minor part is taken up by the cultured species, with the rest being released as wastes to the environment (Folke & Kautsky, 1989; Troell, 1996). Intensive farming of carnivorous fish species like yellowtail, seabream, seabass, trout and salmon in cages or tanks, and shrimp in ponds, are examples of such farming systems.

Existing solutions for aquaculture waste treatment have mainly focused on reducing particle load (discussed in Cripps, 1994), leaving the dissolved nutrient fraction untreated. However, the fact that treatment of effluents usually involves a higher degree of technology and thereby also higher costs, suggests that release of untreated water is the rule rather than the exception in intensive mariculture.

The rapid development of shrimp farming has had an adverse impact on the environment (Primavera, 1993), mainly through the conversion of large mangrove areas into shrimp ponds. Intensive shrimp farms have, compared to more extensive systems, much higher production per unit area. Thus, compared to extensive systems less mangrove forest is needed to reach a certain production level. However, outputs of wastes from intensive systems are much higher and the production depends to a larger extent upon external inputs of energy, feeds and chemicals to sustain yields.

Integration of seaweeds with fish and shrimps has been suggested as a means to counteract the release of dissolved nutrients, and at the same time convert it into a useful product (review in Brzeski & Newkirk, 1997; Kautsky et al., 1997a; Troell et al., 1999). The aim of this paper is to outline the possibilities and constraints in integrated systems where seaweeds function as biofilters in fish and shrimp mariculture. Since nitrogen is usually regarded as the limiting nutrient in coastal waters, the focus of this paper will be on nitrogen.

Characterisation of mariculture waste

The quality and quantity of wastes from aquaculture depends mainly on culture system characteristics and the choice of species, but also on feed quality and management (Iwama, 1991). The impacts on the environment will then depend on hydrodynamic conditions and the sensitivity of the receiving ecosystem. From intensive mariculture systems the principal wastes are uneaten feed and faeces, dissolved nutrients, dissolved organic compounds, chemicals and therapeutics (Beveridge et al., 1994). The release of bacteria, pathogens and farmed species escapees should also be included as waste components.

Generally, less than 1/3 of the nutrients added through feed are removed by harvesting in intensive fish farming (Gowen et al., 1991; Holby & Hall, 1991; Hall et al., 1992). For intensive shrimp pond farming it is even less, ranging between 6 and 21% (Primavera, 1994; Briggs & Funge-Smith, 1994; Robertson & Phillips, 1995). Due to differences between systems and cultured species, wastes will be partitioned differently. The rapid water exchange often associated with coastal cage farming may quickly transport released dissolved nutrients away from the farming area, or if situated in turbulent water dilute them rapidly in a large water volume. Despite this, fish cage cultures have been shown to increase dissolved nutrient concentrations in surrounding marine waters (Weston, 1986; Black & Carswell, 1987; Persson, 1991 and references cited therein). Water from land-based fish farms (e.g. salmon cultured in tanks) is usually continuously replaced due to the fish being sensitive to low oxygen concentrations and build-up of metabolic wastes. In intensive fish cage farming about 50–60% of the supplied N is released to adjacent waters in dissolved form (mainly NH_4-N). In shrimp pond farming water column ammonia is usually rapidly taken up and incorporated in phytoplankton biomass, followed by subsequent accumulation in pond sediment. As little as 10% may leave the pond in dissolved form with effluent water (Briggs & Funge-Smith, 1994; Robertson & Phillips, 1995), depending on shrimp density and water management (Hopkins et al., 1995; Lorenzen et al., 1997). Shrimps are more tolerant and pond water replacement is therefore needed less frequently. In intensive shrimp cultures, with high rearing densities, water exchange can be as high as 30–50% per day depending on phase in the production cycle (Primavera, 1993; Flores-Nava, 1995; Thongrak et al., 1997). However, sometimes it may be kept lower due to infection risks from neighbouring cultures (Lin, 1995; Thongrak et al., 1997). Hopkins et al. (1993) and Lorenzen et al. (1997) found that particulate matter and dissolved nutrients in the outflow water increase considerably with higher water exchange rates. They concluded that assimilation by phytoplankton and nitrifying bacteria attached to detrital particles are the principal process of nitrogen removal from the water column. Water exchange rates higher than 0.3 d^{-1} resulted in mainly dissolved nitrogen being discharged (Lorenzen et al., 1997).

Depending on the fate of the solids accumulated in pond bottoms i.e. either being flushed out during pond cleaning, or being dumped on land or in the sea some distance from the farm, additional dissolved nutrients will, at a later stage, enter adjacent waterways after remineralisation.

Cause and effects from nutrient discharge

For nitrogen, which is the nutrient of major concern in marine environments, there is a consensus that at least 80% of the total losses (dissolved and organically bound) from fish farms are plant available and are potentially eutrophicating substances (Håkansson et al. 1988; Persson, 1988, 1991). Due to a more rapid remineralisation of aquaculture wastes in a tropical environment (Troell & Berg, 1997), this figure may be even higher for shrimp farming. Compared to the build-up of particulate organic matter on bottoms in the vicinity of intensive mariculture operations, environmental effects from the release of dissolved nutrients may not be so obvious. Although there is general concern that coastal environments are being subjected to hypernutrification and eutrophication from mariculture activities, very few cases of increased primary production in aquaculture have been documented. It has therefore been argued that nutrient release from fish farming is of minor importance (Gowen, 1994; Ackefors & Enell, 1994; Black et al., 1997). However, the lack of direct evidence of eutrophication may be due to the fact that water exchange rates are usually high. Phytoplankton, within this enriched water, having a cell doubling time counted in hours or days, may increase in number some distance from the farm area i.e. away from where impact studies usually are being performed. Also, natural variability is often so large that eutrophication effects, while existing, cannot be proved unless extensive monitoring programmes are started with the specific aim to detect such effects (Folke et al., 1997).

Apart from increased phytoplankton production, eutrophication can cause many other effects which may be more sensitive and relevant indicators e.g. changes in: energy and nutrient fluxes, pelagic and benthic biomass and community structure, fish stocks, sedimentation, nutrient cycling, oxygen depletion, and shifts between perennial and filamentous benthic algae (Folke et al., 1997). Due to time lags and the buffering capacity of ecosystems, the eutrophication process in an area may be slow, acting over time scales of several years (Wulff & Stigebrandt, 1989). Thus, when evaluating environmental effects from increased supply of matter, not only should local factors be considered but, because we are dealing with effects on complex natural systems, short-term and long-term ecological threshold effects, on both spatial and temporal scales, must also be considered (e.g. Costanza et al., 1993).

Few publications have directly linked the release of dissolved fish farm waste with hypernutrification or eutrophication in marine waters. Ruokolahti (1988) and Rönnberg et al. (1992) found increased growth of attached filamentous algae near fish cage farms in Baltic archipelagos. Gowen and Ezzi (1992) demonstrated that intensive cage culture can cause nutrient enrichment in tidally energetic, fjordic estuaries. The effluents from fish farming have very high N/P ratios (Folke et al., 1994), which are considered as a likely cause for the development of toxic and non-toxic algal blooms (Granéli et al., 1989; Carlsson et al., 1990; Edvardsen et al., 1990; Kaartvedt et al., 1991). Kaartvedt et al. (1991) linked the blooms of the toxic plankton alga *Prymnesium parvum*, which killed 750 t salmon and rainbow trout in fish farms in a Norwegian fjord, to nutrient loading from fish farms. The cause of recent outbreaks of fish kills in the U.S.A., e.g. in the estuaries of the Mid- and South-Atlantic states, as well as along the Texas coast, is suspected to be due to blooms of *Pfiesteria piscicida* and related dinoflagellates (Burkholder & Glasgow, 1997). Potential links to fish farming need to be investigated because it has been suggested that toxin production is stimulated by fish excreta-secreta, and also by inorganic and organic phosphate (Burkholder & Glasgow, 1997).

Shrimp farming and mangroves

The quality of discharged shrimp pond water in mangrove areas can be improved by using settling and treatment ponds (Lin, 1993; Hopkins et al., 1995). However, few farmers are willing to convert grow-out ponds for such purposes, due to the extra costs involved and the fact that farmers have to set aside ponds that otherwise could be stocked with shrimps (Thongrak et al., 1997). Laws forcing the farmers to treat their wastewater before releasing it to the environment are applied in some countries e.g. Thailand, but the law enforcement is still rather poor, resulting in low adherence (Flaherty & Choomjet, 1995; Dierberg & Kiattisimkul, 1996; Claridge, 1996).

Few studies have investigated eutrophication effects in mangrove environments caused by shrimp farming and the literature on long-term changes in habitat functions, species shifts or biodiversity loss due to shrimp farming activity are virtually non-existent. The impact of sewage on mangrove forests has been studied and since there are many similarities between urban and mariculture wastes with regard to their potential to cause eutrophication (Folke et al., 1997), these studies are also relevant from a shrimp farming perspective. Findings from these studies are somewhat contradictory. Thus, depending on waste load and characteristics of the mangrove system, the mangrove forest either functions as a nutrient sink, with no visible accumulation pattern (Tam & Wong, 1993), or a slow build-up of nutrients in sediment and biota (Boto & Wellington, 1983; Wong et al., 1995). It has been found that effluent discharged into a mangrove forest bypasses, to a large extent, the woody halophytes by eroding a direct path to the river systems or ocean (Temple-Banner, University of Victoria pers. com.). In addition, the water retention time can be increased by constructing effluent ponds, although this may prove fatal to mangrove species sensitive to long-term submersion.

Trott et al. (1996) studied how effluents from 5.3–11.4 ha shrimp pond farms influenced a surrounding mangrove ecosystem. Water quality, forest growth and litter fall, mangrove soil nutrient status and crab feeding activity were monitored over a two year period. Dissolved inorganic and organic nutrients, both in creek waters and in sediment porewater, together with litterfall from *Rhizophora* and *Ceriops* forests, were similar to undisturbed controls. However, during periods of shrimp farm discharge, chlorophyll a and BOD levels were significantly higher than during non-discharge periods and controls. The moderate effects on surrounding mangrove forest was explained by the fact that concentrations of suspended sediments, and dissolved organic and inorganic nutrients in the discharge waters were not significantly elevated compared to adjacent tidally flushed mangrove creeks.

In a recent study from South Australia the long-term discharge of sewage effluent into an *Avicennia* forest killed the offshore seagrasses, and as a consequence unconsolidated sediment from the seagrass beds washed into the mangroves and prevented new propagules from establishing (Peri Coleman, Delta Environmental Consulting, SA, Australia, pers. comm.). Furthermore, the deposition of sediments in the seaward fringe of trees created land accretion, which prevented drainage of landward trees facing stagnant pools at low tide. During summer these pools occasionally become fetid and anaerobic, with sulphur-reducing bacteria moving into the water column, resulting in mass mortality of trees overnight.

As discussed previously, it is necessary to increase our understanding of long term consequences on surrounding ecosystems from the nutrient discharge by mariculture systems. Thus, effects and carrying capacity must be defined on the basis of a holistic ecosystem perspective. This can be highlighted by the capacity of mangroves to assimilate nutrients from freshwater runoff, which is of importance to the stability of coastal water quality. This function of dampening nutrient fluctuations is critical, especially during wet seasons when significant amounts of runoff reaches the coast. Due to nutrient loading from shrimp farm wastes, it is possible that the capacity of mangroves in stabilising coastal water quality is lowered. This, in turn, might lead to threshold effects detrimental to other coastal ecosystem like e.g. coral reefs which require oligotrophic waters for vigorous growth.

Previous and present use of seaweeds as biofilters

Methods for treating effluents from enclosed mariculture systems with macroalgae were initiated in the mid 1970s (Haines, 1975; Ryther et al., 1975; Roels et al., 1976; Langton et al., 1977; Harlin et al., 1979). This approach has recently gained new interest (Vandermeulen & Gordin, 1990; Cohen & Neori, 1991; Neori et al., 1991; Haglund & Pedersén 1993; Buschmann et al., 1994, 1996; in press; Jiménez et al., 1994; Krom et al., 1995; Neori, 1996; Noeri et al., 1996), verifying that wastewater from intensive and semi-intensive mariculture is suitable as a nutrient source for seaweed production, and that integration with seaweeds significantly reduces the loading of dissolved nutrients to the environment. However, in open culture systems, like fish cage farming, the continuous exchange of water makes waste disposal difficult to control, and so far, few studies have investigated the possibilities of integrating seaweeds with such cultures (Hirata & Kohirata, 1993; Petrell et al., 1993; Hirata et al., 1994 a, b; Troell et al., 1997). There is also a serious dearth of literature focusing on the feasibility or application of integrated cultures of seaweeds and shrimps (He et al., 1990; Chandrkrachang et al., 1991; Lin et al., 1992, 1993; Primavera, 1993; Flores-Nava, 1995; Enander

& Hasselström, 1994; Phang et al., 1996), although this approach seems promising for shrimp farming (Primavera, 1993; Flores-Nava, 1995; Lin 1995).

Case studies: Integrated fish farming and seaweeds

1. Land based fish tank cultivation

The agarophyte *Gracilaria chilensis* was used for removing dissolved nutrients from an outdoor intensive fish tank culture (see Buschmann et al., 1996 for details). The cultivation system consisted of eight circular 8 m^3 tanks for salmon culture (*Oncorhynchus kisutch* and *O. mykiss*), from which effluent water was channelled into decantation tanks for removal of suspended matter. The water was then lead by gravity to seaweed culture units. The water in the algal culture cells was replaced 10 times d^{-1}, had an algal inoculum maintained at 1.5 kg m^{-2} by harvesting at 15-d intervals and the algae were rotated by bubbling air. Fish production reached 30 kg m^{-3} during a 13 month production cycle, and food conversion could be maintained stable at 1.4 g food g $fish^{-1}$ production during the entire cultivation period. Ammonium was the nutrient that increased most in the fish effluents, reaching concentrations as high as 500 μg L^{-1} in spring and summer. *Gracilaria* production was 48.9 kg m^{-2} yr^{-1} and was able to remove 50% of the dissolved ammonium in winter, increasing to 90–95% in spring.

The production of *Gracilaria* increased total income by 18% (not including production costs). If costs for nutrient emission were to be paid for by the producer, i.e. practising the ‘polluter pay principle’, stipulated in the Rio declaration 1992, a further saving of 4% would be possible through the integration. The final conclusion from this study and a complementary economical study (Buschmann et al., in press) is that *Gracilaria* could be used for removing dissolved nutrients from fish tank effluents, generating economic benefits to the farmers as well as the society as a whole, and permitting a diversification of the production.

2. Open cage cultivation

Rope cultures of *Gracilaria chilensis* were co-cultivated with a coastal salmon cage farm (producing 230 t a^{-1}) in Chile (Troell et al., 1997). *Gracilaria* cultivated at 10 m from the salmon cages had up to 40% higher growth rates (specific growth rate of 7% d^{-1}) than at 150 m and 1 km distance. The nutrient content of algae was also higher close to the cages. Yield of agar per biomass ranged between 17–23% of dry weight, being somewhat lower closer to the farm but, due to higher growth rates, the accumulated agar production still peaked close to the fish cages. The degree of epiphytes and bryozoan coverage was low overall. An extrapolation of the results shows that 1 ha of *Gracilaria*, cultivated close to the fish cages, has the potential to remove at least 6.5% of dissolved nitrogen and 27% of dissolved phosphorus released from the fish farm. For nitrogen this may seem a minor reduction but, because the fish farm released nearly 16 tons of nitrogen annually, the volume assimilated by the algae is substantial. Although the size of *Gracilaria* culture used for the above calculation is small, it would give an annual harvest of 34 t (d. wt) of *Gracilaria*, valued at US$ 34,000. This Figure is twice that of a *Gracilaria* monoculture, not integrated with fish cage farming.

The conclusions from this study are that both economic and environmental advantages could be achieved by integrating algal cultivation with fish farming in open sea systems. A larger cultivation unit would increase nutrient removal efficiency and profits, but further studies focusing on full scale cultivation during different seasons are needed. The high water exchange rates that often characterise coastal fish farming will be of importance when integrating seaweeds with fish. Unlike particulate nutrients, the dissolved fraction will be transported over much greater distances. The proportion of integrated seaweeds benefiting from the surplus of dissolved nutrients will increase with the time that nutrient levels remain high in the water package passing the cages (Løland, 1993). There are two main factors that will determine the potential for seaweeds to remove nutrients: one is the capacity of the seaweeds to respond to an increased nutrient concentration, and the other is how precise the current pattern can be predicted, or how exposure to the nutrient rich water can be maximised (Troell & Norberg, 1998).

3. Footprints to visualise area required for nutrient absorption in integrated fish-seaweed farming

The spatial ecosystem area needed to take care of the released waste can be illustrated by calculating the farm’s ecological footprint (Robertson & Philipps, 1995; Berg et al., 1996; Kautsky et al., 1997b; Folke et al., 1998). The ecological footprint needed for assimilating nutrients released from aquaculture indicates how densely farms can be placed in an area without risking self-pollution, formation of algal blooms, etc.

Ecological footprint analysis of intensive tilapia cage farming showed that a pelagic system with an area 115 times larger than the area of the cages is needed to take care of the phosphate released. In a semi-intensive tilapia pond the nutrients could be assimilated within the pond area itself (Berg et al., 1996). Robertson and Phillips (1995) calculated that the nitrogen and phosphorus released from semi-intensive shrimp pond farming could be entirely assimilated by a mangrove forest, which was 2.4–2.8 times larger than the pond area itself. For intensive shrimp farming this area increased to 7.4–21.6 times the pond. If seaweeds are integrated in intensive aquaculture, the footprint for waste assimilation as well as the strain on the environment will be reduced. We can calculate this reduction for the above example of open cage salmon-*Gracilaria* culture in Chile. The salmon cage will release 5.52 kg N and 0.924 kg P m^2 a^{-1} (recalculated from Troell et al., 1997). Assuming an average pelagic primary production of 200 mg C m^2 d^{-1} for the area and an atomic ratio of 80 C:15 N:1 P (Redfield et al., 1963), it can be calculated that the footprints for nitrogen and phosphorus waste are 340 and 400 times larger than the cage area, respectively. When integrated with *Gracilaria,* the corresponding footprint is reduced to 150 and 25 times the cage area for nitrogen and phosphorus, respectively. This means that the carrying capacity of the area, in terms of nutrient absorption, is increased and that it should be possible to place salmon cages at somewhat higher densities before risking negative environmental effects from eutrophication.

Sustainable shrimp farming

Many suggestions have been put forward for 'sustainable' shrimp farming. Of particular interest is the idea that future development should, as a means of minimising land use (i.e. clearing of mangroves), focus on intensive rather than extensive systems (Flores-Nava, 1995; Menasveta, 1997). Another suggestion, and something that is already taking place, is to locate intensive shrimp systems on higher elevations inland of the mangroves (Ythoff, 1996; Menasveta, 1997). However, even if situated outside the mangroves, wastewater will usually be released to adjacent mangrove systems or coastal waters and thereby still constitute a threat to these environments. Such cultures would therefore preferably consist of enclosed systems, where water is being filtered for particles and dissolved nutrients before being released to the environment. This could be accomplished in different ways, either using high-technology cleaning solutions, re-using the water in enclosed systems or treating the wastewater before release to the environment using integrated farming techniques i.e. using filter feeders and seaweeds as biofilters (Enander & Hasselström, 1994; Flores-Nava, 1995). Due to difficulties and high costs involved in re-circulating systems i.e. high-technology solutions (Hopkins et al., 1995), it may be unrealistic to believe that such a development will take place. Instead, intensive systems combined with secondary biological treatment units should be promoted. In a study of an integrated farming system, consisting of oysters and *Gracilaria* cultivated in tanks in the shrimp farm effluent water, total nitrogen and total phosphorus could be reduced by 41 and 52%, respectively (over 90% removal of ammonium, nitrate, nitrite and phosphate) (A. Jones, Dept Botany, Univ. Queensland, pers. comm.). Enander and Hasselström (1994) also demonstrated effective uptake of nutrients by mussels and seaweeds cultivated in ponds receiving shrimp effluent waters. They were able to remove 81% ammonium and 19% nitrate from the dissolved waste. The possibility for cultivating seaweeds in shrimp ponds in Malaysian mangroves was studied by Phang et al. (1996), who compared the growth of *Gracilaria* in a shrimp pond with plants in an irrigation canal and in a natural mangrove habitat. A threefold increase in growth was found in the irrigation canal compared to the shrimp pond and the natural mangrove, the latter two having similar growth. This was explained by larger secchi depth and more frequent water exchange in the canal. The plants cultivated inside the shrimp pond were also heavily epiphytised and grazed by fish. Phang et al. (1996) concluded that the difficulties encountered in the shrimp pond could be solved through better pond management; for instance, flow around the plants could have been increased if the plants had been placed further towards the edge of the pond.

To increase the sustainability of shrimp farming in mangrove environments the benefits from aquasilviculture systems integrated with seaweeds needs to be investigated.

Conclusions

The renewed interest in adopting new farming techniques e.g. methods built on the principles of ecological engineering, have the potential to find solutions that could mitigate negative environmental impacts from intensive mariculture. However, systems like fish tank farming, fish cage farming and shrimp pond farming have different characteristics regarding how waste is being emitted to the surrounding ecosystems. Thus, a solution applied in one type of culture may not be feasible in another. The development of techniques where seaweeds are used as biofilters is just in its infancy and continued research on ecologically sound production systems is needed.

References

Ackefors H, Enell M (1994). The release of nutrients and organic matter from aquaculture systems in Nordic countries. J. appl. Ichth. 10: 225–241.

Berg H, Michélsen P, Troell M, Folke C, Kautsky N (1996) Managing aquaculture for sustainability in tropical Lake Kariba, Zimbabwe. Ecol. Econ. 18: 141–159.

Beveridge MCM, Lindsay LG, Kelly AL (1994) Aquaculture and biodiversity. Ambio 23: 497–502.

Black E, Carswell B (1987) Sechelt Inlet, Spring 1986, Impact of salmon farming on marine water quality. British Columbia Ministry of Agriculture and Fisheries. Commercial Fisheries Branch. Victoria, British Columbia, 43 pp.

Black E, Gowen R, Rosenthal H, Roth E, Stechy D, Taylor FJR (1997) The cost of eutrophication from salmon farming: Implication for policy- a comment. J. environ. Manag. 50: 105–109.

Boto, KG, Wellington JT (1983) Nitrogen and phosphorus nutritional status of a northern Australian mangrove forest. Mar. Ecol. Progr. Ser. 11: 63–69.

Brzeski V, Newkirk G (1997) Integrated coastal food production systems – a review of current literature. Ocean coast. Manag. 34: 66–71.

Briggs MRP, Funge-Smith SJ (1994) A nutrient budget of some intensive marine shrimp ponds in Thailand. Aquacult. fish. Manag. 25: 789–811.

Burkholder JM, Glasgow Jr HB (1997) *Pfiesteria piscicida* and other *Pfiesteria*-like dinoflagellates: behavior, impacts and environmental controls. Limnol. Oceanogr. 42: 1052–1075.

Buschmann AH, Cavilan M, Troell M, Kautsky N, Medina A, Guzman O (in press) Integrated tank cultivation of salmonids and seaweeds: a technical and economical analysis. Ecol. Econ.:

Buschmann, AH, Mora OA, Gómez P, Böttger M, Buitano S, Retamales C, Vergara PA, Gutierrez A (1994) *Gracilaria* tank cultivation in Chile: use of land based salmon culture effluents. Aquacult. Engineering 13: 283–300.

Buschmann AH, M. Troell M, Kautsky N, Kautsky L (1996) Integrated tank cultivation of salmonids and *Gracilaria chilensis* (Gracilariales, Rhodophyta). Hydrobiologia 326/327: 75–82.

Carlsson P, Granéli E, Olsson P (1990) Grazer elimination through poisoning: one of the mechanisms behind*Chrysochromulina polylepis* bloom. In Granéli E, Sundström B, Edler E, Andersson D (eds) Toxic Marine Phytoplankton. Elsevier Science Publishing Co, New York: 116–122.

Chandrkrachang S, Chinadit U, Chandayot P, Supasiri T, (1991) Profitable spin-offs from shrimp-seaweed polyculture. INFOFISH Int. 6/91: 26–28.

Claridge G (1996) Legal approaches to controlling the impacts of intensive shrimp aquaculture: adverse factors in the Thai situation. Paper presented to the International Law Institute workshop on the legal and regulatory aspects of aquaculture in India and Southeast Asia, Bangkok, Thailand, 11–13 March, 1996.

Cohen I, Neori A (1991) *Ulva lactuca* biofilters for marine fish pond effluent. I. Ammonia uptake kinetics and nitrogen content. Bot. mar. 34: 475–482.

Cripps SJ (1994) Minimizing outputs: treatment. J. appl. Ichtyol. 10: 284–294.

Daly HE, Cobb JB (1989) For the Common Good: Redirecting the Economy Toward Community, the Environment and a Sustainable Future. Beacon Press, Boston, USA, 482 pp.

Dierberg FE, Kiattisimkul W (1996) Issues, impacts and implications of shrimp aquaculture in Thailand. J. environ. Manag. 20: 649–666.

Edvardsen B, Moy F., Paasche E, (1990) Hemolytic activity in extracts of *Chrysochromulina polylepis* grown at different levels of selenite and phosphate. In Granéli E, Sundström B, Edler E, Andersson D (eds) Toxic Marine Phytoplankton. Elsevier Science Publishing Co, New York: 284–289.

Ekins P, Hillman M, Hutchison R (1994) The Gaia Atlas of Green Economics. Anchor Books, Doubleday, New York, 191 pp.

Enander M, Hasselström M (1994) An experimental wastewater treatment system for a shrimp farm. INFOFISH Int. 4/94: 56–61.

Flaherty M, Choomjet K (1995) Marine shrimp aquaculture and natural resource degradation in Thailand. J. environ. Manage. 19: 27–37.

Flores-Nava A (1995) Some considerations on sustainable shrimp mariculture. Jaina 6: 8.

FAO (1997) Aquaculture production statistics 1985–1995. FAO Fisheries Circular No. 815, Revision 9, FAO Rome.

Folke C, Kautsky N (1992) Aquaculture with its environment: prospects for sustainability. Ocean coast. Manag. 17: 5–24.

Folke C, Kautsky N, Troell M (1994) The costs of eutrophication from salmon farming: Implications for policy. J. environ. Manage. 40: 173–182.

Folke C, Kautsky N, Troell M, (1997) Salmon farming in context: response to Black et al. J. environ. Manage. 50: 95–103.

Gowen RJ, Weston DP, Ervik A (1991) Aquaculture and the benthic environment. In Cowey CB, Cho CY (eds), Nutritional Strategies and Aquaculture Waste, Proceedings of the first international symposium on nutritional strategies in management of aquaculture waste (NSMAW). Department of Nutritional Science, Univ. of Guelph, Guelph, Ontario, 1991: 187–205.

Gowen, RJ (1994) Managing eutrophication associated with aquaculture development. J. appl. Ichthyol. 10: 242–257.

Gowen RJ, Ezzi IA (1992) Assessment and prediction of the potential for hyper-nutrification and eutrophication associated with cage culture of salmonids in Scottish coastal waters. Dunstaffnage Marine Laboratory, Oban, Scotland, 136 pp.

Granéli E, Carlsson P, Olsson P, Sundström B, Granéli W, Lindahl O (1989) From anoxia to fish poisoning: The last ten years of phytoplankton blooms in Swedish marine waters. In Cosper EM, Bricelj VM, Carpenter EJ (eds) Novel Phytoplankton Blooms - Causes and Impacts of Recurrent Brown Tides and Other Unusual Blooms. Coast. estuar. Stud. 35: 407–428.

Haglund K, Pedersén M (1993) Outdoor pond cultivation of the subtropical marine red alga *Gracilaria tenuistipitata* in brackish water in Sweden. Growth, nutrient uptake, co-cultivation with rainbow trout and epiphyte control. J. appl. Phycol. 5: 271–284.

Haines KC (1975) Growth of the carrageenan-producing tropical red seaweed *Hypnea musciformis* in surface water, 870 m deep water effluent from a clam mariculture system, and in deep water enriched with artificial fertilizers or domestic sewage. In Persson G, Jaspers E (eds), Proc. 10th Eur. Symp. Mar. Biol., Ostend, Belgium, Sep. 17–23, 1975. Universa Press, Wetteren. Vol. 1: 207–220.

Hall, POJ, Holby O, Kollberg S, Samuelsson M-O, (1992) Chemical fluxes and mass balance in a marine fish cage farm. IV. Nitrogen. Mar. Ecol. Progr. Ser. 89: 81–91.

Harlin MM, Thorne-Miller B, Thursby GH (1979) Ammonium uptake by *Gracilaria* sp. (Florideophyceae) and *Ulva lactuca* (Chlorophyceae) in closed system fish culture. Proc. int. Seaweed Symp. 9: 258–292.

He X, Peng T, Liu S, Huang J, He Z, Xu Q, Huang L (1990) Studies on the elimination of stress factors in *Peneaus* diseases. Trop. Oceanol./Redai Haiyang 9: 61–67 (in Chinese with English Abstract).

Hirata H, Kohirata E (1993) Culture of sterile *Ulva* sp. in a marine fish farm. The Israeli J. Aquacult.- Bamidgeh 45: 164–168.

Hirata, H, Kohirata E, Guo F, Danakusumah E, Xu BT (1994a) Cage culture of the sterile *Ulva* sp. in a coastal fish farm. In Chou LM, Munro AD, Lam TJ, Chen TW, Cheong LKK, Ding JK, Hooi KK, Khoo HW, Phang VPE, Shim KF, Tan CH (eds) The Third Asian Fisheries Forum. Asian Fisheries Society, Manila, Philippines: 124–127.

Hirata H, Yamasaki S, Maenosono H, Nakazono T, Yamauchi T, Matsuda m (1994b) Relative budgets of $p\,O_2$ and $p\,CO_2$ in cage polycultured Red Sea bream, *Pagrus major* and sterile *Ulva* sp. Suisanzoshoku 42: 377–381.

Holby O, Hall POJ (1991) Chemical fluxes and mass balance in a marine fish cage farm. II. Phosphorus. Mar. Ecol. Progr. Ser. 70: 263–272.

Hopkins JS, Browdy CL, Hamilton II RD, Heffernan III JA (1995) The effect of low-rate sand filtration and modified feed management on effluent quality, pond water quality and production of intensive shrimp ponds. Estuaries 18: 116–123.

Håkansson L, Ervik A, Mäkinen T, Möller B (1988) Basic concepts concerning assessments of environmental effects of marine fish farms. Nordic council of ministers, Nord 1988, No. 90, 103 pp.

Iwama GK (1991) Interactions between aquaculture and the environment. Crit. Rev. envir. Contr. 21: 177–216.

Jiménez del Rio M, Ramazanov Z, García-Reina G (1994) Optimization of yield and biofiltering efficiencies of *Ulva rigida* C. Ag. cultivated with *Sparus aurata* L. waste waters. Sci. Mar. 58: 329–335.

Kaartvedt S, Johnsen TM, Aksnes DL, Lie U, Svendsen H (1991) Occurrence of the toxic phytoflagellate *Prymnesium parvum* and associated fish mortality in a Norwegian fjord system. Can. J. Fish. aquat. Sci. 48: 2316–2323.

Kautsky N, Folke C, Berg H, Jansson Å, Troell M (1997b) The ecological footprint concept for sustainable seafood production: a review. Ecol. Apps. 8: S63–S71.

Kautsky N, Troell M, Folke C (1997a) Ecological engineering for increased production and environmental improvement in open sea aquaculture. In Etnier C, Guterstam B (eds), Ecological engineering for wastewater treatment. Lewis Publisher, Chelsea, Michigan, 496 pp.

Krom MD, Ellner S, van Rijn J, Neori A (1995) Nitrogen and phosphorus cycling and transformations in a prototype ‘non-polluting’ integrated mariculture system, Eilat, Israel. Mar. Ecol. Prog. Ser. 118: 25–36.

Langton RW, Haines KC, Lyon RE (1977) Ammonia-nitrogen production by the bivalve mollusc *Tapes japonica* and its recovery by the red seaweed *Hypnea musciformis* in a tropical mariculture system. Helgoländer wiss. Meeresunters. 30: 217–229.

Lin KC, Raumthaveesub P, Wanuchsoontorn P (1993) Culture of the green mussel (P*erna viridis*) in waste water from an intensive shrimp pond: concept and practice. World Aquaculture 24: 68–73.

Lin CK (1995) Progression of intensive marine shrimp culture in Thailand. In Browdy CL, Hopkins SJ (eds), Swimming Through Troubled Water. Proceedings of the special session on shrimp farming, Aquaculture ’95. World Aquaculture Society, Baton Rouge, Louisiana, USA: 13–23.

Lin CK, Ruamthaveesub P, Wanuchsoontorn P, Pokaphand C (1992) Integrated culture of green mussel (*Perna viridis*) and marine shrimps (*Penaeus monodon*). Book of abstracts and schedule, Aquaculture ’92, Orlando, FL, 21–25 May.

Løland G (1993) Current forces on, and water flow through and around, floating fish farms. Aquacult. Int. 1: 72–89.

Menatsveta P (1997) Intensive and efficient shrimp culture system, the Thai way, can save mangroves. Aquacult. Asia 2: 38–44.

Neori A, Cohen I, Gordin H (1991) *Ulva lactuca* biofilters for marine fishpond effluent. II. Growth rate, yield and C:N ratio. Bot. mar. 34: 483–489.

Neori A, Krom MD, Ellner SP, Boyd CE, Popper D, Rabinovitch R, Davison PJ, Dvir O, Zuber D, Ucko M, Angel D, Gordin H (1996) Seaweed biofilters as regulators of water quality in integrated fish-seaweed culture units. Aquaculture 141: 183–199.

New MB, Wijkstrom UN (1990) Feed for thought: some observations on aquaculture feed production in Asia. World Aquaculture 21: 17–23.

Persson G (1988) Relationships between feed, productivity and pollution in the farming of large rainbow trout (*Salmo gairdneri*). Swedish Environmental Protection Agency, Stockholm, PM 3534, 48 pp.

Persson G (1991) Eutrophication resulting from salmonid fish culture in fresh and salt waters: Scandinavian experiences. In Cowey CB, Cho CY (eds), Nutritional Strategies and Aquaculture Waste: 163–185.

Petrell RJ, Mazhari Tabrizi K, Harrison PJ, Druehl LD (1993) Mathematical model of *Laminaria* production near a British Columbian salmon sea cage farm. J. appl. Phycol. 5: 1–14.

Phang S-M, Shaharuddin S, Noraishah H, Sasekumar A, (1996) Studies on *Gracilaria changii* (Gracilariales, Rhodophyta) from Malaysian mangroves. Hydrobiologia 326/327: 347–352.

Primavera JH (1993) A critical review of shrimp pond culture in the Philippines. Rev. fish. Sci. 1: 151–201.

Primavera JH (1994) Environmental and socioeconomic effects of shrimp farming: the Philippine experience. INFOFISH Int. 1/94: 44–49.

Robertson AI, Phillips MJ (1995) Mangroves as filters of shrimp pond effluents: predictions and biogeochemical research needs. Hydrobiologia 295: 311–321.

Roels OA, Haines KC, Sunderlin JB (1976) The potential yield of artificial upwelling mariculture. In Persson G, Jaspers E (eds), Proc. 10th Eur. Symp. Mar. Biol., Ostend, Belgium, Sept. 17–23, 1975. Universa Press, Wetteren. Vol. 1: 358–394.

Rönnberg O, Ådjers K, Roukolahti C, Bondestam M (1992) Effects of fish farming on growth, epiphytes and nutrient content of *Fucus vesiculosus* L. in the Åland archipelago, northern Baltic Sea. Aquat. Bot. 42: 109–120.

Rönnbäck P (in press) The ecological basis for economic value of Seafood production supported by mangrove ecosystems. Ecol. Econ.

Ruokolahti C (1988) Effects of fish farming on growth and chlorophyll *a* content of *Cladophora*. Mar. Poll. Bull. 19: 166–169.

Ryther JH, Goldman JC, Gifford JE, Huguenin JE, Wing AS, Clarner JP, Williams LD, Lapointe BE (1975) Physical models of integrated waste recycling-marine polyculture systems. Aquaculture 5: 163–177.

Tam NFY, Wong YS (1993) Retention of nutrients and metals in mangrove sediment receiving wastewater of different strengths. Envir. Technol. 14: 719–729.

Thongrak S, Prato T, Chiayvareesajja S, Kurtz W (1997) Economic and water quality evaluation of intensive shrimp production systems in Thailand. Agricultural Systems 53: 121–141.

Troell M (1996) Intensive fish cage farming: impacts, resource demands and increased sustainability through integration. PhD-thesis, Stockholm University, Stockholm, pp. 148.

Troell M, Berg H 1997. Cage farming in the tropical Lake Kariba, Zimbabwe: impact and biogeochemical changes in sediment. Aquaculture Res. 28: 527–544.

Troell M, Halling C, Nilsson A, Buschmann AH, Kautsky N, Kautsky L (1997) Integrated open sea cultivation of *Gracilaria chilensis* (Gracilariales, Rhodophyta) and salmonids for reduced environmental impact and increased economic output. Aquaculture 156: 45–61.

Troell M, Kautsky N, Folke C 1999 Comment: Applicability of integrated coastal aquaculture systems. Ocean coast. Manage. 42: 63–69.

Troell M, Norberg J (1998) Modelling output and retention of suspended solids in an integrated salmon- mussel culture. Ecological Modelling 110: 65–77.

Trott LA, Alongi DM, Olsen D (1996) Results from the monitoring program in mangrove creek ecosystems near Sea Ranch Pty Ltd. The Australian Prawn Farmers' Association 1996 Workshop and Annual General Meeting, 26–28 July, 1996, Cairns, Australia.

Uthoff D (1996) From traditional use to total destruction-forms and extent of economic utilization in the Southeast Asian mangroves. Natural resources and development, vol 43/44, Institute for Scientific Co-operation, Tübingen, Federal Republic of Germany: 58–94.

Vandermeulen H, Gordin H (1990) Ammonium uptake using *Ulva* (Clorophyceae) in intensive fishpond systems: mass culture and treatment of effluent. J. appl. Phycol. 2: 263–374.

Weber M (1996) So you say you want a blue revolution? The Amicus Journal, Fall 1996: 39–42.

Weston DP (1986) The environmental effects of floating cage mariculture in Puget Sound. School of Oceanography, College of Oceans and Fisheries Sci., University of Washington, Seattle, USA, 148 pp.

Wong YS, Lan CY, Chen GZ, Li SH, Chen XR, Liu ZP, Tam NFY (1995) Effects of wastewater discharge on nutrient contamination of mangrove soils and plants. Hydrobiologia 295: 243–254.

Wulff F, Stigebrandt A (1989) A time dependent budget model for nutrients in the Baltic Sea. Global biogeochem. Cycles 3: 63–78.