Cah. Biol. Mar. (2001) 42 : 83-90

Integrated algal farming: a review

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Abstract: Integrated aquaculture has been proposed as an environmentally friendly way of recycling wastes, especially those produced through the cultivation of high trophic level species, which require the supply of exogenous energy (food). The cultivation of filter-feeders and seaweeds around fish culture cages has been tested for waste recycling. However, success has not been total, partly because the amount of filter-feeders and seaweed needed to remove a significant proportion of the wastes produced from intensive large scale cultivation systems is very large. Thus, semi-closed and land-based systems have been proposed as a technological alternative for integrated aquaculture. The latter type of systems are technically feasible, although, the high investments needed at present, prevent its more general use. In Chile, salmon cultivation is well established, and produces over 200,000 tons yr^{-1}. As a result of the rapid expansion of salmon farming, the concern regarding the environment is rising. Thus we have made experiments to integrate the cultivation of the agarophyte *Gracilaria*, with salmon farms. Our results indicate that this alga is capable of removing a significant proportion of the ammonium excreted by fish. Studies in land-based integrated culture systems indicate that fish production can reach over 30 kg m^{-3}, with an associated *Gracilaria* production of 49 kg (wet weight) m^{-2} y^{-1}. The environmental benefits associated with the development of integrated tank cultivation were assessed by analysing previously published and unpublished data. With these production results, a profitability analysis was made, internalizing the environmental benefits. As the waste discharge is highly reduced by integrating seaweed cultivation into a fish farm, the economic profitability of a commercial project is almost not affected by internalizing the environmental costs as compared to a situation without environmental requirements.

Résumé : L'aquaculture intégrée a été proposée comme un moyen d'épuration des effluents, en particulier ceux produits par l'élevage d'animaux de niveau trophique élevé qui nécessite un apport externe d'énergie (alimentation). L'élevage d'animaux filtreurs et d'algues marines à proximité de cages à poissons a ainsi été testé comme moyen d'épuration. Cependant, le succès de ces tentatives n'a pas été total en partie parce que les quantités de filtreurs et d'algues requises pour abaisser de manière significative les quantités d'effluents produits par des élevages intensifs sont démesurées. Aussi, des sytèmes semi-fermés ou basés à terre ont été proposés comme alternative technologique pour une aquaculture intégrée. Les sytèmes à terre sont techniquement réalisables bien qu'ils nécessitent aujourd'hui des investissements élevés, qui limitent leurs extensions. Au Chili, l'élevage du saumon est très développé et produit plus de 200.000 tonnes par an. Avec l'expansion rapide de l'élevage du saumon, les préoccupations concernant ses conséquences sur l'environnement se sont accrues. Nous avons donc réalisé des expériences pour intégrer la culture de l'algue rouge agarophyte *Gracilaria* aux fermes de saumon. Nos résultats indiquent que cette algue est capable de prélever des proportions significatives de l'ammoniaque excrétée par les poissons. Des études sur des systèmes de culture intégrée à terre indiquent que la production de poissons peut atteindre 30 kg m^{-3}, avec une production associée de *Gracilaria* de 49 kg (poids humide) m^{-2} an^{-1}. Le bénéfice pour l'environnement du développement de bassins de culture intégrée a été établi par l'analyse de données publiées ou non publiées. En tenant compte des résultats de production atteints, une analyse des profits a été réalisée en intégrant les bénéfices pour l'environnement. Comme les rejets d'effluents sont considérablement réduits lorsque l'on intègre la culture d'algues marines dans la ferme de poisson, les profits d'un projet commercial ne sont pas du tout affectés par la prise en compte des coûts environnementaux et restent comparables à ceux réalisés dans une situation où il n'y pas de contraintes environnementales.

Key words: Gracilaria, integrated aquaculture, nutrient recycling, seaweed cultivation

Introduction

Aquaculture actions have increased world-wide during the last years (Hempel, 1993), and in Chile there has also been a significant increment related to salmon production (Buschmann et al., 1996a). As a result of this rapid production increase, aquaculture activities might have affected the environment in a variety of ways, especially fish production which needs to be supplemented with an exogenous amount of energy (food) (Beveridge, 1996). It has been demonstrated by many authors that organic input of food to fish culture has a substantial impact on the nutrient loads in coastal areas (see reviews of Beveridge, 1984; Brown et al., 1987; Gowen & Bradbury, 1987; Rosenthal et al., 1988; Folke & Kautsky, 1989; López et al., 1988; Handy & Poxton, 1993), affecting the sediments beneath the culture installations and producing variations in the nutrient composition of the water column that can lead - for example- to enhanced sediment metabolism, sulphate reduction, high ammonium flux and sulphide accumulation. It have been demonstrated that these environmental modifications can imply changes in the benthic fauna (e.g. Rodhouse et al., 1985; Hargrave et al., 1993) fish abundance (e.g. Carss, 1990), bird populations (e.g. Dankers & Zuidema, 1995), macroalgal growth, epiphytes and chemical composition (e.g. Ruokolahti, 1988; Rönnberg et al., 1992), phytoplankton and zooplankton (e.g. Granéli et al., 1989; Carlsson et al., 1990) and the bacteriological flora (e.g. Husevåg et al., 1991).

Species that do not require exogenous feeding for their cultivation, like mussels, also affect the environment by enhancing sedimentation (Kaspar et al., 1985; Baudinet et al., 1990; Hatcher et al., 1994; Grant et al., 1995). Seaweed cultivation can also modify the environment by changing sediment composition, introducing exogenous materials (e.g. plastic), fertilizers or pesticides (Buschmann et al., 1995; Buschmann et al., 1996a). Nevertheless, the effects of mussel and seaweed cultivation are less dramatic than those associated with intensive fish and shrimp cultures as the latter results in a net addition of organic material and dissolved nutrients to the environment. The cultivation of shrimp and carnivorous fish species also appropriate very large ecosystem areas, i.e. the ecological footprint, to sustain their production (Folke et al., 1997). 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 market prices and seldom included in models of fisheries and aquaculture management. Intensive aquaculture is for this reason not a substitute for fisheries as it largely depends on fisheries to harvest resources that are given to the cultured species in the form of feed pellets (Folke & Kautsky, 1989; 1992). It must be indicated that notwithstanding the significant improvements in feed quality and vegetable substitutes obtained during recent years, it still seems necessary to develop incentives and research programs to prevent the further misuse of marine ecosystems (Naylor et al., 1998).

In the above context, integrated aquaculture has been proposed as an environmentally friendly way of recycling wastes produced through the cultivation of high trophic level species requiring supply of exogenous energy (e.g. Shpigel et al., 1993; Buschmann, 1996). The use of seaweed integrated with fish cultures has been studied in open system conditions in the Pacific coast of Canada and Chile (Petrell et al., 1993; Petrell & Alie, 1996; Troell et al., 1997), enclosed floating systems in Norway (Bodvin et al., 1996), and land-based cultures in Israel (Vandermuelen & Gordin, 1990; Cohen & Neori, 1991; Neori et al., 1991), Spain (Jimenez del Río et al., 1994; 1996), Sweden (Haglund & Pedersen, 1993) and Chile (Buschmann et al., 1994; Buschmann et al., 1996b). This review summarizes these results, provides a critical analysis and determines a general conceptual framework. To achieve these goals, we first analyse concepts, provide a summary of open system and land based studies results, then we introduce financial tools that permits internalization of environmental costs and finally we discuss their future applicability, especially for developing countries, like Chile.

General concepts

General concepts about nutrient uptake and their conceptual basis can be obtained from Lobban & Harrison (1995). Also, seaweed cultivation in open and tank cultures, together with general principles that are required to produce the algae have been extensively discussed (Hanisak, 1987; Santelices & Doty, 1989; McLachlan, 1991; Friedlander & Levy, 1995) and are for this reason not presented here. However, it is important to indicate that from a bio-filtering point of view, several concepts must be clear, because they have different interpretations and meanings. The nutrient uptake efficiency is defined as the average reduction (%) in the nutrient concentration. On the other hand, another important concept is the nutrient uptake rate which is the amount of nutrients removed per unit of time. Both concepts vary depending on the environmental conditions that the culture presents during the specific period, but also from some culture conditions like the tank depth, stocking density and the water turnover rate. For example, Jimenez del Río et al. (1994) found that the dissolved nitrogen uptake efficiency was inversely related to water exchange and directly related with the stocking density of *Ulva* in tank cultures using fish effluents, and the nitrogen uptake rate was directly related to both, flow rate and stocking density. 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 & Varas, 1998). The importance of distinguishing the different implications is related to the objective of the study. If the aim is to have "clean" discharges, uptake efficiency is a good indicator, but if the aim is to increase biomass production, resulting in smaller reduction of nutrients in the water being discharged, the nutrient uptake concept will sustain better the points to achieve this goal.

Summary of previous results

In general, studies related to the use of seaweed for the removal of wastes can be classified into those developed for open systems, and recycling wastewaters in land-based culture systems. In open culture systems, waste disposal is difficult to control and a reduced number of integrated studies investigating this exist (Petrell et al., 1993, 1996, Troell et al., 1997). If nitrogen is a limiting factor, the nitrogen produced by the fishes in cultivation can result in increased productivity of the seaweed, and permits the removal of nutrients.

Notwithstanding that some brown algae (Subandar et al., 1993; Ahn et al., 1998) and red algae (Buschmann et al., 1996b) show a high capacity to remove dissolved inorganic nitrogen present in fish effluents, and that seaweed production is higher in areas surrounding fish cages than in isolated conditions (Troell et al., 1997), nutrient removal does not seem to be highly significant (Petrell et al., 1993). By using the red alga *Gracilaria*, Troell et al. (1997) concluded that a suspended culture of 1 ha will remove 5% of the dissolved inorganic nitrogen released from the fish farm and 27% of the released dissolved phosphorus. This contradiction appears because fish culture is three dimensional (sea cages) and seaweed culture is bi-dimensional depending on the solar radiation that reach the sea surface. For this reason, as fish are cultivated in a small surface, it is required that seaweed cultivation can be carried out at higher densities and increasing depths, to achieve a significant removal of fish dissolved wastes. Nevertheless, from an economic point of view, suspended seaweed farming appears to be of commercial interest (Petrell et al., 1993; Troell et al., 1997). It has been proved that the agarophytic alga *Gracilaria* can show higher agar yields and with an increased gel strength when it is cultivated near salmon cages (Weidner & Bello, 1996).

Fish effluents produce by land-based systems are easier to treat than open systems (Seymour & Bergheim, 1991) and studies that began in the mid 70's (Haines, 1975; Ryther et al., 1975; Langton et al., 1977; Fralick, 1979; Harlin et al., 1979), have recently gained new interest (Vandermeulen & Gordin, 1990; Cohen & Neori, 1991; Neori et al., 1991; Haglund & Pedersen, 1993; Buschmann et al., 1994; 1996b; Krom et al., 1995; Martínez & Buschmann, 1996; Neori et al., 1996). In general, this literature indicates that seaweed can reduce as much as 90% of the ammonium produced by fish (e.g. Cohen & Neori, 1991; Jimenez del Río, et al., 1994; Buschmann et al., 1996b). Nevertheless, the main problem in this type of system is related to their optimal functioning. In general, as the different physiological processes of the seaweeds respond differently (Lobban & Harrison, 1995), the optimization of a culture with a different objective (e.g. biomass production versus bio-filtering efficiencies) are complex. For example, growth, nitrogen uptake, agar production and quality respond differentially to nitrogen addition (Fig. 1). This means that the culture conditions will be different if the objective is to produce biomass for the production of phycocolloids, or if the intention is the use the seaweed as a biofilter.

In tank culture it is possible to manage nutrient availability by changing the water flow. By increasing the water flow, nutrient flux increases that determines that the seaweeds will not be nutrient limited, permitting a higher biomass production, and in this condition, the nutrient uptake efficiency will be lower (Fig. 2). On the other hand, if the flow rate is low, nutrients will become limiting, biomass production will decrease, but the nutrient uptake efficiency will be higher (Fig. 2). For this reason it is of primary importance to establish the main target of the culture to intend to optimize its functioning. This also has implications with the species selection. If the seaweed will only be used as a bio-filter, low commercial value species like *Ulva* can be used to depurate fish effluents (Cohen & Neori, 1991; Jimenez del Río et al., 1994). However, species like *Gracilaria* offer both alternative, high bio-filtering efficiency (Haglund & Pedersen, 1993) and an interesting commercial value which can significantly increase the incomes (Buschmann et al., 1996b).

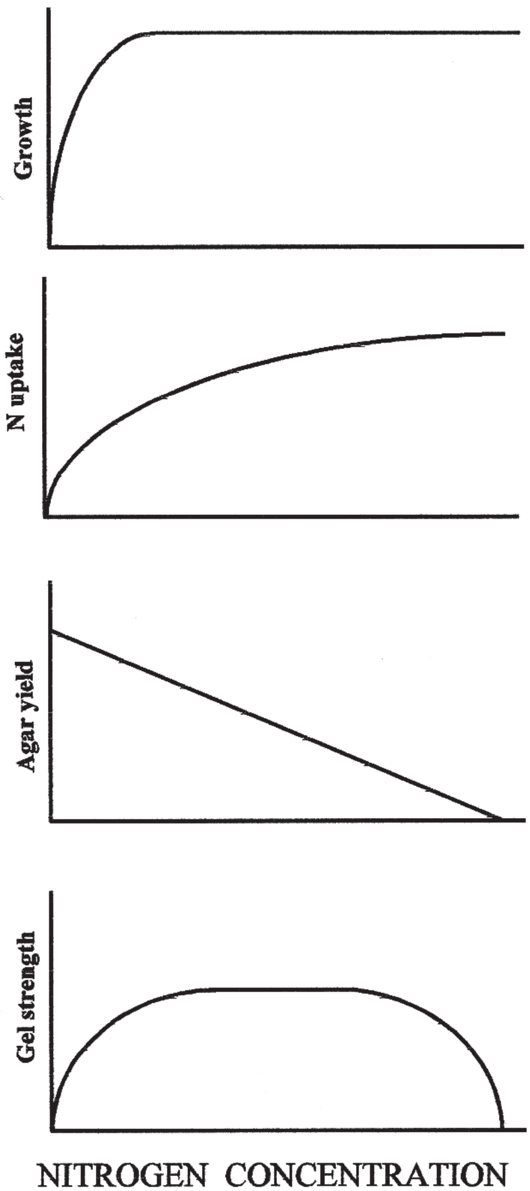

Figure 1. General model showing the variation of seaweed growth, nitrogen uptake rate, agar yield and gel strength as a function of the changes in the dissolved nitrogen in the seawater.

Figure 1. Modèle général présentant les variations de croissance des algues, de leurs taux d'absorption d'azote, de rendement en agar et en force de gel en fonction de la charge en azote dissous dans l'eau de mer.

Internalizing environmental costs

A cost analysis of an installation for 100 t of salmon production and seaweeds in a land-based system was presented by Alvarado (1996). The cost of producing salmon depends largely on the stocking density achieved in the fish culture. For example, the investments for 200 t of fish production increase from US$ 250,000 to US$ 6,500,000 when the stocking density declines from 60 to 15 kg m^{-3}. The operational cost also increases with increasing culture size, but decreases with the stocking density because of the water requirements, which gives different costs for each fish culture density. With an average salmon price of US$ 4.8 kg^{-1}, the incomes for 600 t of net production are US$ 2,880,000 (Alvarado, 1996). Considering the water flow requirements for 200 and 600 net t of salmon, the production of seaweed increases from 500 to 1,700 wet t (Buschmann et al., 1996b). Assuming a conservative price for *Gracilaria* of US$ 1.00 kg (dry) the additional income in a 600 t salmon culture unit can reach US$ 550,000.

Considering the production of solid and dissolved wastes based on the amount of N and P kg^{-1} incorporated to the system given by Buschmann et al. (1996b) and applying a cost for nutrient released to the environment (based on calculations from Folke et al., 1994; US$ 6.4 to 12.8 kg^{-1} for N and US$ 2.6 to 3.8 kg^{-1} for P) it is possible to internalize the total environmental cost for a 250 t of fish gross production which is US$ 201,411. However, by internalizing the environmental cost, but now considering the savings produced by minimizing the disposal of N and P to the environment, this reaches only US$ 64,000, which reduces the environmental cost by at least 80 %. The internalization of the environmental cost can mean a significant reduction of the profitability of a project (Table 1). The considerable reduction of the N and P loads achieved by removing the solids and by using *Gracilaria* as a bio-filter proves that the project recovers high profit (Table 1).

Conclusions

The data available on the environmental consequences of intensive aquaculture activities in the marine coastal areas of Chile, indicate that their effect appears not to be important at this time, as the coastal areas used for farming purposes has, in general, high current speeds (Buschmann et al., 1996a). Nevertheless, it would appear that the Chilean salmon industry would only be able to cover the costs involved in the treatment of wastewaters if ecological foods are administered and proper management of the feeding process is ensured (Buschmann et al., 1996a). This situation is more favourable than that of farmers in some developed countries, where they are not in a position to finance the waste treatment required to minimize the environmental costs of these aquaculture practices (Folke et al., 1994). The use of an integrated culture system can further enhance the sustainability of these intensive aquaculture practices (Folke

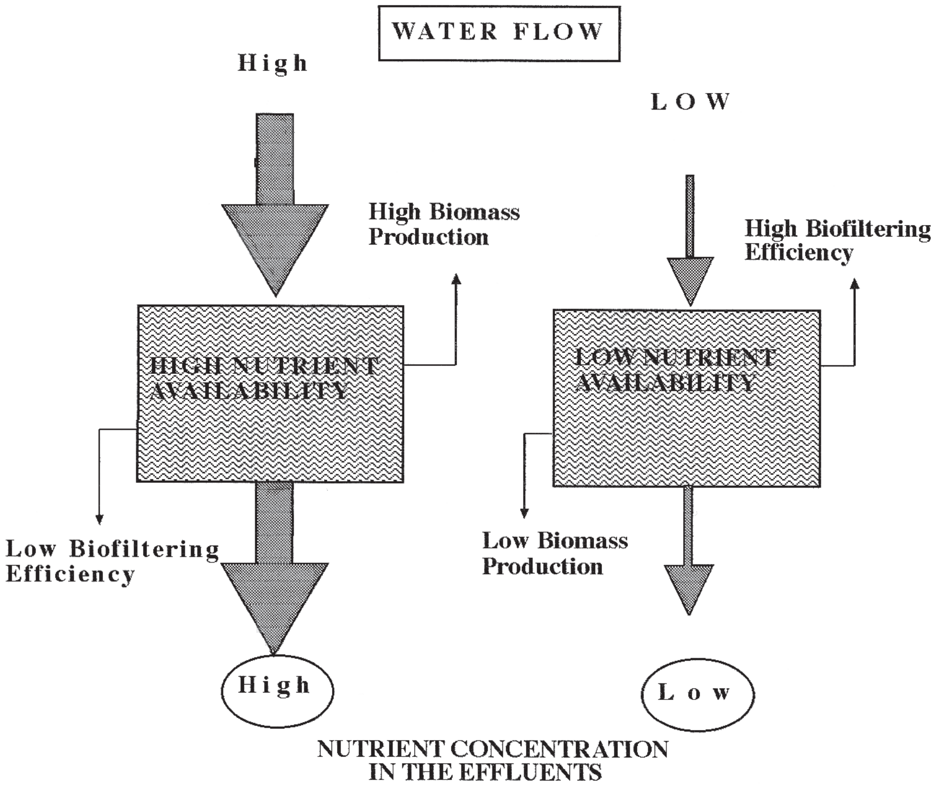

Figure 2. General model showing the effect of the water turnover rate on growth and biofiltering efficiency. A high water turnover determines a high biomass production capacity, as nutrients are not a limiting factor, however the biofiltering efficiency will decrease. On the other hand if the water turnover rate is reduced, nutrient will begin limited, that implying a lower capacity for the algae to grow, but an increase of the biofiltering efficiency.

Figure 2. Modèle général présentant l'effet du renouvellement en eau sur l'efficacité de biofiltration. Un renouvellement important détermine une capacité élevée d'accroissement de biomasse, cependant l'efficacité de biofiltration décroit. Par contre, un renouvellement réduit rend les éléments nutritifs limitants pour les algues qui ont alors une croissance réduite, mais l'efficacité de biofiltration est accrue.

Table 1. Profitability analysis using the net present value (NPV in US$) and internal rate of return (IRR in %) of the integrated culture system simulating three different net salmon production of 600 gross t and for a fish stock of 30 kg m^{-3}. A) Without considering the environmental costs: B) considering the total environmental costs and C) considering the environmental costs with the reduction of the wastes discharges by recycling nutrients.

Tableau 1. Analyse des profits d'un système d'aquaculture intégrée (valeur nette présente, NPV en US$ et taux interne de retour, IRR en %). La simulation inclut trois productions de saumon de 600 t pour une densité de poisson de 30 kg m^{-3}. A) Sans prise en compte des coûts environnementaux. B) En considérant le coût total environnemental. C) En considérant les coûts environnementaux après la réduction des effluents par recyclage des éléments nutritifs.

	Profitability Indicators	
	NPV	IRR
A)	2065330	26.2
B)	n.p.	n.p.
C)	8181915	19.4

n.p.= no profit

& Kautsky, 1992), which constitute an important source of income for developing countries. However, research in order to enhance the waste removal is still needed. The technical and economic feasibility of intensive fish-seaweed tank cultivation systems can be an important point if the environmental cost are internalized (Soley et al., 1994; Buschmann et al., 1996a). Without the removal of waste by seaweeds production units seems not to be profitable. This point is important, as economic stability and production diversification with less environmental impact are needed to encourage the further development of the activity. On the other hand, the practice of these economical environmental regulations is less expensive and has lower labour requirements than the traditional control practices by state officials.

Acknowledgements

This work was supported by FONDECYT 1940816 and this review was prepared with the help of FONDAP O&MB assigned to AHB. Several students and research assistants participated: for all of them our acknowledgements. Moreover, the first author wish to indicate his gratitude to M.C. Hernández-González, L. Vidal, G. Aroca and G. Furci for their help during the preparation of this manuscript.

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