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Integrated mariculture: asking the right questions

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Abstract

Reducing negative environmental impacts from aquaculture activities is a key issue for ensuring long-term sustainability of the industry. This study examines the major findings and methodology aspects from 28 peer-reviewed studies on marine aquaculture systems integrating fed and extractive organisms. All studies include seaweeds as extractive organisms. The main objective was to analyse the degree of relevance these findings have for large-scale implementation of integrated mariculture practices, and to identify necessary research areas for a future research agenda.

The following directions for future research were identified: (1) understand in detail the important biological/biochemical processes in closed recirculating and open seaweed culture systems; (2) conduct research into these advanced aquaculture technologies at scales relevant to commercial implementation or suitable for extrapolation; (3) broaden the focus to include factors affecting seaweed growth and uptake capacity; (4) improve experimental design for statistical calculations; (5) attain a detailed understanding of the temporal variability in seaweed-filtered mariculture systems; (6) define numerical design parameters critical for engineers in designing commercial recirculation systems with seaweed filters; (7) study the influences of location-specific parameters, such as latitude, climate and local seaweed strains/species, on seaweed filter performance; (8) include economic components, considering the added value of seaweeds, and

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feasibility aspects; (9) analyse the role and function of integrated aquaculture practices for improved environmental, economic, and social acceptability within the broader perspective of integrated coastal management initiatives; and (10) develop educational, training and financial incentive approaches to transfer these novel and somewhat complex technologies of integrated mariculture from the scientists to the industry.

Keywords: Mariculture; Land-based system; Open-water system

1. Introduction

Most of the world's fishing areas have reached their maximal potential for capture fisheries production, while demand for seafood worldwide is steadily increasing (FAO, 2001). The stagnation in fisheries of commercial species has also been accompanied by a gradual shift from large, valuable, carnivorous species to smaller, less valuable species (Pauly et al., 1998; Naylor et al., 2000; Caddy and Garibaldi, 2000).

On the other hand, global production from aquaculture has been increasing steadily, having more than doubled in the last decade; aquaculture now supplies one third of seafood consumed worldwide (FAO, 2001). To meet future demands for foodfish supplies, aquaculture production needs to increase by 50 million Mt by the year 2050 (Tacon and Forster, 2001). The FAO (2001) cautions that such an increase in aquaculture production will depend on new research and improved management practices. According to the FAO, major issues that need to be addressed are problems with access to proper technology and financial resources, together with environmental impacts and diseases.

Some argue that further increases in aquaculture production will come mainly from further investment in biotechnology (Hardy, 1999; Hew and Fletcher, 2001; Melamed et al., 2002), including technologies ranging from protein expression and DNA vaccines (and chips) to transgenic technologies. Large programs focusing on increasing aquaculture production through such means have been running in several countries for the past few decades and new ones are being launched (Myers et al., 2001). Increased knowledge and development of new methods within marine biotechnology have resulted in important breakthroughs for the aquaculture industry and further advances within this sector will continue to be important. However, without a clear recognition of the industry's large-scale dependency and impact on natural ecosystems and traditional societies, the aquaculture industry is unlikely to either develop to its full potential or continue to supplement ocean fisheries (Naylor et al., 2000; Chopin et al., 2001). Thus, to increase accessibility of seafood to economically depressed people, or even to maintain it at current levels, aquaculture development must be based on relevant species choices and sound technologies more relevant to developing countries (Naylor et al., 2000; Williams et al., 2000; Hambrey et al., 2001). Traditional and low technology farming approaches contain lessons learned over many generations, which should be regarded as valuable instructive bases for modern aquaculture development.

Future mariculture technologies could attain sustainability by integrating waste generating (fed) and cleaning (extractive) organisms in each farm (see review in

Buschmann et al., 2001; Chopin et al., 2001). Extractive species remove nutrients from the water. Many commercial shellfish are filter feeders that remove particulate organic nutrients; algae use sunlight to extract from the water dissolved inorganic nutrients. Thus, when integrated with fed aquaculture of, e.g. fish or shrimp, extractive organisms turn wastes into productive resources (Rawson et al., 2001, 2002; McVey et al., 2002). The new integrated aquaculture systems will use multiple species from different trophic levels for reducing wastes and costs (through recycling of wastes) while increasing total productivity (in weight and in value) with respect to feed input and pollution output. Polyculture has a long history in the freshwater environment, but not in marine and brackish waters. Although poorly studied in the past, a renewed interest in integrated techniques emerged in the early 1990s, and several different systems have since been proposed. These have attempted to: reduce the negative impacts of fed aquaculture on the aquatic environment; to productively remove and recycle toxic metabolites by using recirculating systems; to increase production of specific co-cultured extractive species (e.g. shellfish and seaweeds); and to increase overall productivity of the resources of feed, water and fossil energy (see Krom et al., 2001 for review; see also Section 3 for references).

On a global scale, mariculture of extractive organisms already removes a significant fraction of nutrients from the world oceans. Global aquafeed supplies for marine fish and crustaceans aquaculture for 2000 was estimated at 4.5 million Mt [FAO Review of The State of World Aquaculture data]. Up to 4% of that quantity, 180,000 Mt, is excreted to the sea as ammonia-N (using FCR of 2, feed N content of 6% and 2/3 of nitrogen excreted as ammonia-N (TAN)). Nominal nitrogen content in seaweed and in shellfish is approximately 0.5% and 1%, respectively. With present global yields of approximately 10 million Mt each [FAO Review of The State of World Aquaculture data], these harvests already extract roughly 150,000 Mt of nitrogen. However, it should be noted that extractive and fed aquaculture are very often geographically disjunctive because of the predominant monoculture approach and, consequently, rarely balance each other at the regional scale.

When new culture techniques/practices are being developed, there is a need for continuous evaluation of the achieved results. Research on integrated techniques in mariculture has now reached a stage where it has become necessary for such evaluation to be conducted. The benefits generated from such evaluation is that research efforts will be directed in the right direction by identifying issues being inadequately addressed, or by identifying new important research areas. Here we examine major findings and methodological aspects from 28 peer-reviewed studies on mariculture systems that integrate fed and extractive organisms, and that have been published during the last 30 years. What these studies have in common is that they all use seaweed as an extractive organism integrated with a fed culture system. Additional publications in the "grey literature" have been left aside. The present paper includes a general review of conducted research on integrated mariculture. The main focus is to provide an objective analysis of the degree of relevance findings may have for large-scale implementation of integrated mariculture practices. The potential of the seaweed-involved integrated mariculture approach, and the necessary areas for further research, are identified.

2. Importance and benefits from integrated mariculture

2.1. Integrated aquaculture—its role in aquaculture development

Traditional integrated freshwater systems primarily seek to satisfy a complex of environmental (e.g. maximizing resource use) and social aims rather than only being concerned with maximizing short-term profit (Ruddle and Zhong, 1988; Bailey, 1988; Primavera, 1991; Wilks, 1995). Although the focus of recent work on integrated techniques in modern mariculture has been on reduction of waste discharge by promoting biofiltration capacity and water recirculation, these new systems have the potential to increase overall profits through more efficient resource use (Krom et al., 2001).

Commercial modern marine and brackish water aquaculture is usually practiced as large monocultures. Like intensive feedlots, these systems have the potential to generate releases of waste material to the environment from uneaten feed and excreta. Even large-scale shellfish cultures can increase dissolved inorganic nutrient concentrations by increasing remineralisation of particulate organic material. This nutrification can result in various negative local environmental effects such as eutrophication, oxygen depletion, biodiversity modifications and pollution of the surrounding waters (Gowen and Bradbury, 1987; Braaten et al., 1988; Rönnberg et al., 1992; Beveridge et al., 1994; Richardson and Jørgensen, 1996; Bonsdorff et al., 1997; Mattila and Räisänen, 1998; Pitta et al., 1999; Hänninen et al., 2000; Naylor et al., 2000). Such effects are common features of all economic activities that concentrate resources collected over vast areas and use them in a linear fashion without managing the environmental consequences. The quality and quantity of wastes from aquaculture depend mainly on culture system characteristics and the choice of cultivated species, but also on feed quality and management (Iwama, 1991). Different species release wastes of different quality and quantity, but generally most of the nutrients added through feed are released to the environment (Fig. 1). The dominant fraction being released is generally in a dissolved form, particular for nitrogen (Gowen et al., 1991; Holby and Hall, 1991; Hall et al., 1992; MacIntosh and Phillips, 1992; Briggs

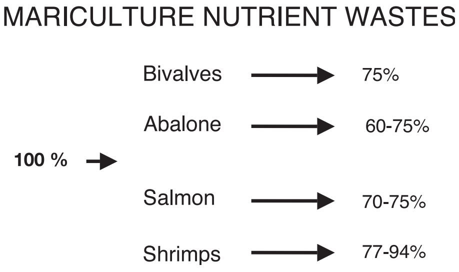

Fig. 1. Range of nutrient discharge (total) from some aquaculture species. For salmon and shrimps, the percentages are for both nitrogen and phosphorus; for bivalves and abalone, the percentages are only for nitrogen. One hundred percent is the total amount of nutrients in feed (cf. Gowen et al., 1991; Holby and Hall, 1991; Hall et al., 1992; MacIntosh and Phillips, 1992; Briggs and Funge-Smith, 1994; Robertson and Phillips, 1995; Bergheim and Åsgård, 1996; Neori et al., 2000).

and Funge-Smith, 1994; Robertson and Phillips, 1995; Bergheim and Åsgård, 1996; Neori et al., 2000).

The local impact on the environment then ultimately depends on local/regional hydrodynamic conditions, the physical, chemical and biological characteristics of the receiving ecosystem (expressed in the region's biological assimilative capacity) and on additional release of waste products from other sources (e.g. urban and rural human settlements and sewage effluents, agricultural/industrial runoffs, precipitations, etc.).

The rapid scale increase now seen in human activities in coastal areas puts further pressure on already impoverished functions of coastal ecosystems. Therefore, legislative guidelines, standards and controls regarding the discharge of nutrients from various sources (including aquaculture operations) are starting to become more stringent in many countries. Development of integrated mariculture, i.e. bioremediation via integrated concepts with a capacity to restore the quality of the discharged water to its natural state, may help the aquaculture industry avoid noncompliance, and gain both direct and indirect benefits from improving water quality and coastal ecosystem health.

The aquaculture industry has, over the last decades, managed to substantially reduce its emission of wastes by intense research into feed development, better conversion efficiency and improved management (Bergheim and Åsgård, 1996; Hardy, 1999; Chopin et al., 2001, Hardy and Tacon, 2002). Until now, this has been the only effective approach for reducing discharge of dissolved nutrients from open systems (i.e. cages). Land-based systems have some alternatives for reduction in dissolved nutrients but these have limitations (discussed below). Integration with seaweed introduces a practical and viable solution (Chopin et al., 2001). Additional arguments for integrated mariculture include possible increased income, social benefits and diversified production (Buschmann et al., 1996; Troell et al., 1997; Chopin et al., 1999b, 2001).

2.2. Existing alternative measures for waste treatment

Release of untreated water from intensive mariculture systems is more often the rule rather than the exception. Practice of "dilution–the solution" dominates. Adding to the mariculture cost, profit cutting approaches like water treatment are resisted by the industry, and are adopted by it only under pressure from regulating agencies or from nature itself (e.g. red tides, infectious diseases, etc.). Today, dissolved nutrients can be removed effectively from some mariculture effluents by biological and chemical filters. Biological filters are often based on bacterial oxidation of ammonia to the less toxic form of nitrogen, nitrate, by nitrification. The method, however, does not remove nutrients. Under anaerobic conditions and with the presence of proper organic matter, other bacteria can further transform nitrate waste into N_2 gas that then can be removed from the system. These systems are, however, both complex and costly. Genetic engineering and selection of nitrifying and denitrifying bacteria is suggested as contributing significantly to enclosed, recirculating marine culture systems in the future (Lyndon, 1999). Different species of microalgae are also used as biological filters in outdoor tank/pond systems or in indoor tubular photo-bioreactors. Microalgae can advantageously be grown in the same pond as fish, and then be filtered out by an integrated culture of shellfish. However, microalgal populations are difficult to control (bloom and crash cycles) in open ponds, and limit water exchange. Too much water exchange may simply wash them out.

Two main types of chemical filters are used—activated carbon filters and ion-exchange filters. Carbon filters remove dissolved nutrients by having an active carbon substance to facilitate adsorption of inorganic molecules. Carbon filters are mainly used for targeting organic molecules. Ion-exchange filters are based on ion-charged material that gets quickly inactivated in ion-rich seawater. Both these filters also get quickly biofouled. With respect to phosphorus removal, it should be possible to use chemical precipitation in a similar way as used in sewage treatment facilities. Biological phosphorus removal, by either oxic or anoxic bacteria, is also an option, but the phosphorus-saturated bacterial biomass has to be removed and disposed of to complete the process.

The above discussion only applies to land-based systems; for open-water systems, no similar applicable methods for removing dissolved nutrients have been suggested in the literature. Techniques similar to those used on land could, possibly, be adapted to open systems if these farming systems are made more “closed” and if flow and retention time could be controlled (Bodvin et al., 1996). To our knowledge, no such integrated system exists today at any commercial scale.

In summary of this issue, most biofiltration techniques in land-based systems only partially or unconsistently transform nutrients into other forms, thus not really reducing the environmental load. They also have limited abilities to function in environments with high nutrient concentrations. It can be concluded that integration with seaweed offers perhaps the most viable and attractive option to the profitable extraction of nutrients discharged from mariculture into valuable products.

3. Research on integrated mariculture

Advances in contemporary society with integrated cultivation techniques in marine and brackish environments originate from the development of intensive methods using seaweeds (macroalgae) and bivalves for treating sewage outlets (Ryther et al., 1972, 1975; Goldman et al., 1974). Methods using seaweeds for treating effluents from enclosed land-based mariculture systems were initiated in the mid-1970s (Haines, 1975; Ryther et al., 1975; Langton et al., 1977; Harlin et al., 1978). The rapid expansion of intensive mariculture systems (i.e. fish farming and shrimp cultivation) and the concern for negative effects on the environment from such practices, have, during the 1990s, renewed and increased research into the development of seaweed-based integrated techniques (Vandermeulen and Gordin, 1990; Cohen and Neori, 1991; Neori et al., 1991, 1996; Haglund and Pedersén, 1993; Buschmann et al., 1994, 1996, 2001; Jiménez del Rio et al., 1996; Krom et al., 1995; Neori, 1996; Troell et al., 1997; Neori and Shpigel, 1999; Chopin et al., 1999a,b). All these studies have demonstrated that wastewater from intensive and semi-intensive mariculture is a suitable nutrient source for the intensive production of seaweed, thereby reducing the discharge of dissolved nutrients to the environment.

Integrated land-based cultures have, in some cases, also developed to include additional combinations of species from different trophic levels. Examples of such systems are: integrated bivalve-shrimp cultivations (Wang and Jacob, 1991; Jacob et al., 1993; Hopkins et al., 1993; Lin et al., 1993; Osorio et al., 1993), integrated bivalve-fish cultivations (Shpigel and Blaylock, 1991; Shpigel et al., 1993b) and integrated cultivations consisting of both algae and molluscs cultivated in effluents from fish or shrimps (Shpigel et al., 1991, 1993a; Enander and Hasselström, 1994; Neori et al., 1996, 1998, 2000; Neori and Shpigel, 1999).

In open-culture systems, such as fish cage farming, only a few studies have investigated the possibilities of integrated farming. Among these some have focused on using seaweeds as biofilters (Hirata and Kohirata, 1993; Hirata et al., 1994; Troell et al., 1997; Chopin et al., 1999a), and some on the possibilities of using bivalves (Jones and Iwama, 1991; Taylor et al., 1992; Stirling and Okumus, 1995; Troell and Norberg, 1998; Buschmann et al., 2000; Mazzola and Sarà, 2001; Cheshuk, 2001). There are relatively few studies investigating the feasibility or application of integrated cultures of seaweeds and shrimps (Chandrkrachang et al., 1991; Lin et al., 1992, 1993; Primavera, 1993; Enander and Hasselström, 1994; Flores-Nava, 1995; Phang et al., 1996; Jones et al., 2001), although this approach has been regarded as promising (Primavera, 1993; Flores-Nava, 1995; Lin, 1995). There are also some studies of integrated cultures with seaweeds using mathematical models to generate data (Petrell et al., 1993; Petrell and Alie, 1996) or develop novel production technologies (Bodvin et al., 1996).

Recent reviews on integrated mariculture research include a focus on seaweed utilization (Buschmann et al., 2001; Chopin et al., 2001), on bivalve utilization (Troell et al., 1999a), on shrimp farming (Troell et al., 1999b) and on integrated cultures from a coastal zone management perspective (Newkirk, 1996; Brzeski and Newkirk, 1997; Rawson et al., 2002). Conclusions from above reviews confirm the suitability of using seaweeds as biofilters. Using bivalves with the same purpose may, however, have certain limitations (Troell and Norberg, 1998; Cheshuk, 2001). With respect to shrimp farming, it is concluded that integration with seaweeds may be positive but more research is needed (Troell et al., 1999b).

4. Integrated seaweed mariculture—analysis of methods and results

The studies on integrated mariculture were divided into three groups: (1) tank cultures (mainly fish-based systems), (2) pond cultures (fish and shrimp-based systems) and (3) open-water cultures (mainly fish systems). Findings from the 28 studies included in the analysis are summarised in Table 1. From this table, we have then formulated questions under the following key issues, which we consider crucial for successful implementation of integrated mariculture on any large scale:

1. Efficiency
    - How efficiently can seaweeds absorb nutrients from mariculture waste?
    - How do seaweed biofilter functions change over time (diurnal and seasonal cycles)?
    - What factors, other than light, nitrogen and phosphorus, may limit seaweed production?
    - What nitrogen and phosphorus fractions should be analysed?

Table 1
Summary of important factors for integrated aquaculture systems that includes seaweeds

Main culture facility	Cultured species	Culture densities[a]	Experimental scale[b]	Time scale	Optimization aims[c]	N uptake removal[d]	Uptake efficiency[e]	Quality[f]	Production factors[g]	Replicates and controls[h]	Economic calculation	References
Tanks and ponds (fish or shrimp)												
Ponds/ aquarium	milkfish/ *Gracilariaopsis*	fish: D; seaweed: D	pond/aquarium: B/D	1–3 months	G	C	–	Eq	T, S, pH, L O2, G	R (6), C	no	Alcantara et al., 1999
Tank	salmon/ *Gracilaria*	fish: D–B; seaweed: B, C	fish; seaweed: B	1 year	G	n.i.	70–95% (NH_4)	Eo, Ay	T, L, pH, CO2, D, F, G, N	R (3), C	no	Buschmann et al., 1994
Tank	salmon/ *Gracilaria*	fish: A, B; seaweed: C	fish; seaweed: B	>1 year	G	C	up to 90% (NH_4)	Eq, Aq	T, G	R (n.i.), C	yes	Buschmann et al., 1996
Tank	salmon/ *Gracilaria*	fish: C, D; seaweed: C	fish; seaweed: A	3–6 months	G	C	–	Eo	T, pH, O2, L, D, G	n.i.	no	Haglund and Pedersén, 1993
Tank	salmon/ *Laminaria*	fish: C; seaweed: A, B	seaweed: D	>1 month	G, N	C, A	45%(NH_4)		T, S, pH, L, D, F, G	R (9–22ps), C	no	Subandar et al., 1993
Tank/ raceway	seabream/algae	fish A; seaweed: n.i.	fish, seaweed: A	>1 year	N	C	30–90% (DIN)		T, S, O2, pH, G	n.i.	no	Pagand et al., 2000
Tank	seabream/*Ulva*	fish: B; seaweed: B	fish: B; seaweed: C	1 year	G, N	C, A	19–97% (DIN)		T, pH, L, D, F, G	R (3 ps), C	no	Jiménez del Rio et al., 1996
Tank	seabream/*Ulva*	fish: FE; seaweed; B, C	seaweed: C	<1 month	G, N	C, A	85%(NH_4)		T, pH, S, F, D, G	R (3)	no	Vandermeulen and Gordin, 1990
Tank	seabream/*Ulva*	fish: FE; seaweed: A–C	seaweed: C	1 year	G, N	C, A	39–96 (NH_4)		T, L, F, D, G	R (3 ps?)	no	Neori et al., 1991
Tank	seabream/*Ulva*	fish: FE; seaweed: A–C	seaweed: C	1 year	G, N	C, A	–		T, L, F, D, G	R (3 ps?)	no	Cohen and Neori, 1991
Tank	seabream/*Ulva*	fish: B, C; seaweed: C	fish: B; seaweed: C; B	>1 year	N, W	C, A	34–49% (DIN)		T, L, S, O2, Chl, G	R (0–3), C	no	Neori et al., 1996

Tank	seabream/*Ulva*	fish: B, C; seaweed: C	fish: B; seaweed: C; B	>1 year	N, W	C, A	34–49% (DIN)		T, L, S, O2, Chl, G	R (0–3), C	no	Krom et al., 1995
Pond/ditches	shrimp/*Gracilaria*	shrimp: FE; seaweed: D	seaweed: B	>1 month	G	A	–		N, F, G, fert	R (3)	no	Nelson et al., 2001
Pond/canal	shrimp/*Gracilaria*	shrimp: FE; seaweed: C	shrimp comm.; seaweed: C	1–3 months	G	n.i.	–	Eo, Aq	T, pH, S, O2, N, G	R (4), C	no	Phang et al., 1996
Aquaria (mollusca)	Fish/*Gracilaria*; *Ulva*	fish: C; seaweed: A	fish; seaweed: D	< 1 month	N	C	32–112% (NH_4)		T, S, L, O2, pH	R (4), C	no	Harlin et al., 1978
Tank	clams/*Hypnea*	clam: FE; seaweed: A	seaweed: D	< 1 month	N	C, A	–	Ay	T, F, G	n.i.	no	Haines, 1975
Tank	abalone/*Gracilaria*; *Ulva*	abalone: B, C; seaweed: B, C	abalone; seaweed: B	1 year	N	C, A	3–88% (DIN)[i]	Eo, F	T, F, fert, G	n.i. (ps)	no	Neori et al., 1998
Tank	abalone/*Palmaria*	abalone: n.i.; seaweed: A	abalone; seaweed: D	3–6 months	G (abalone), N	C	–	F	T, L, fert, D, G	R (3), C	no	Evans and Langdon, 2000
Tank (polyculture)	Tapes/*Hypnea*	clams: A, B; seaweed: B	clams; seaweed: D	< 1 month	N	C	70% (NH_4)		T, G	R (ps), C	no	Langton et al., 1977
Pond/tanks	seabream/oyster; clams/*Ulva*	fish/seaweed: C; clams/oyster: A	fish: A; oyst; clams: B; seaweed: C	1 year	G, N	C, A	90% (NH_4)		T, G, pH, O2, cells	R (ps)	no	Shpigel et al., 1993a
Tank	fish, oyster, sea urchins/*Gracilaria*	fish: B; oyst: A; urchin: B; seaw: A	fish; oyst; urchin; seaweed: C	6–12 months	G, N	C	100% (NH_4)		T, G	R (3), C	no	Chow et al., 2001
Tank	abalone/seabream/*Ulva*; *Gracilaria*	abal: up to A; fish: B; seaw: A, B	abalone; fish; seaweed: C	1 year	G, N, W	C, A	70–100% (NH_4)	F	T, G, pH, O2	n.i. (ps)	yes	Neori et al., 2000
Tank	sewage/oyster/*Chondrus*; *Ulva*	oyster: n.i.; seaweed: A	oyster: n.i.; seaweed: C	3–6 months	N	C	–		G, S, pH	n.i.	no	Ryther et al., 1975

(continued on next page)

Table 1 (*continued*)

Main culture facility	Cultured species	Culture densities[a]	Experimental scale[b]	Time scale	Optimization aims[c]	N uptake removal[d]	Uptake efficiency[e]	Quality[f]	Production factors[g]	Replicates and controls[h]	Economic calculation	References
Lab study	shrimp effluent/ oyster/ *Gracilaria*	shrimp: A; seaweed: B	shrimp A; oyst; seaweed: D	< 1 month	N	C	2–76% (NH_4)		T, O2, S, Chl, bact, TSS	R (3), C	no	Jones et al., 2001
Open water (fish)												
Cage cultures/ nets; poles	salmon/ *Porphyra*	fish: FE; seaweed: n.i.	n.i.	>1 year	N	A	–		pigment, N	R (3 nutrient), C	no	Chopin et al., 1999b
Cage culture/ frames	salmon/ *Gracilaria*	fish: FE; seaweed: C	fish: comm.; seaweed: B	1–3 months	G, N	A	–	Eo, Ay	G, depth	R (10), C	yes	Troell et al., 1997
Cages/net cages	yellowtail/*Ulva*	fish: FE; seaweed: D	fish: comm.; seaweed: C	1 year	G	n.i.	–		T, G	R (18)	no	Hirata and Kohirata, 1993
Cages/net cages (mollusca)	seabream/*Ulva*	fish: C; seaweed: n.i.	fish: comm.; seaweed: C	< 1 month	G, O2	n.i.	–		O2, CO2, depth, G	R (n.i.), C	no	Hirata et al., 1994
Open culture/ aquarium	oyster/ *Kappaphycus*	oyster: n.i.; seaweed: A/B	oystr; seaweed: comm./C, D	3–6 months	G	C	–		G, T	R (10), C	no	Qian et al., 1996

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[a] Culture densities: fish, shrimp or molluscs: A=>30 kg m^{-3}, B = 10–30 kg m^{-3}, C = 1–10 kg m^{-3}, D = < 1 kg m^{-3}, FE = farm effluent; seaweeds: A=>5 kg m^{-3}, B = 2–5 kg m^{-3}, C = 0.5–2 kg m^{-3}, D = < 0.5 kg m^{-3}, n.i. = no information.

[b] Experimental scale: A=>10,000 l, B = 1000–10,000 l, C = 100–1000 l, D = < 100 l, comm. = commercial, n.i. = no information.

[c] Optimization; aim: G = growth/production; N = nutrient uptake and treatment; W = water saving.

[d] Nutrient uptake and treatment: C = measured concentration changes in water; A = measured nutrient content in algae, n.i. = no information.

[e] Uptake efficiency: data suitable for realistic estimation of reduction of nutrient concentrations in waste water passing seaweed units. – = not measured or data not presented.

[f] Quality of yield for : Eo = epiphytes observed; Eq = epiphytes quantifyed; F = feed; Ay = agar, alginate, carrageenan yield; Aq = agar, alginate, carrageenan quality.

[g] Other production factors measured: T = temp, S = salinity, O2 = dissolved O2, L = light, D = stocking densities, F = flow rates, N = nutrients (in species and accum.), C = nutrient concentrations in water, Chl = chlorophyll *a*, bact = bacteria.

[h] Replicates and controls: R = replicates, C = control, ps = pseudoreplication; number of replicates in brackets, n.i. = no information.

[i] Fertilisers added.

2. Quality
   - Does seaweed quality change in integrated cultures?
   - Does integration with seaweed change the quality and value of the main cultured species?
3. Design and scale of experiments
   - What is a sufficient degree of replication for obtaining statistically significant results?
   - What controls/references should be used for comparison?
   - How should the experiments be designed to allow for extrapolation to scaled up and commercial farming?
4. Economy
   - Can economic benefits from integrated culture be accurately confirmed?

4.1. Efficiency

Many studies from both land-based and open-water cultures confirm that nutrients released from fish, shrimps and bivalves are suitable for seaweed growth. This is not surprising as the nitrogen released from such organisms—NH_3—is often the preferred nitrogen source for seaweeds (Lobban and Harrison, 1994; Carmona et al., 2001). Dissolved release of phosphorus increases phosphate (PO_4^{3-}) concentrations in the water, which is the form of phosphorus most suitable for seaweed growth (Lobban and Harrison, 1994; Neori, 1996; Chopin and Wagey, 1999). In addition, some seaweed species in integrated cultures take up nutrients above and beyond their requirements for growth (Troell et al., 1997; Chopin et al., 1999b). Such "luxury uptake" of nitrogen and phosphorus has been confirmed in earlier studies on seaweed physiology (Lobban and Harrison, 1994; Harrison and Hurd, 2001).

To allow nonambigous interpretations and meanings (Buschmann et al., 2001), the important concepts related to seaweed nutrient uptake should be clarified. The nutrient *reduction efficiency* is defined as the average reduction (%) in nutrient concentration in water. Nutrient *uptake rate*, on the other hand, is defined as the amount of nutrients removed per unit area of, e.g. seaweed pond per unit time. Both these concepts are important; they will vary depending on culture conditions such as depth, light, stocking density and water turnover rates (Buschmann et al., 2001). Specific properties of the seaweed species, their biology and physiology, will also play a significant role.

High nutrient uptake rates are achieved by supplying the seaweed culture with high areal (per unit area) loads of nutrients, conditions that also maximise seaweed areal yield and seaweed protein content. Under these conditions, however, reduction efficiency is low, and therefore a large fraction of the dissolved nutrients remains in the water. To achieve high nutrient reduction efficiency, a seaweed culture should be "starved"—supplied with a low areal load of nutrients, a situation that supports low seaweed areal yields with low protein content (Buschmann et al., 1994). In an integrated fish farm, it is therefore necessary to optimise the aerial nutrient load to the seaweeds, to reach acceptable levels of both nutrient uptake rate and reduction efficiency. In a recirculating system, high levels of ammonia may be acceptable (depending of the tolerance of the fed organism), allowing operation of the seaweed culture with high areal nutrient loads and achieving high nutrient uptake rates. The system will produce a high areal yield of high protein seaweed. If high nutrient removal (i.e. high reduction efficiency) is necessary for following environmental standards or decreasing ammonia concentrations in recirculating systems, the seaweed culture will be supplied with low areal nutrient loads, but then seaweed areal yield and protein content will be low. Under some circumstances, at some South African abalone aquaculture sites that encounter occasional harmful algal blooms (Sales and Britz, 2001), it may be important to be able to switch from a through-flow high nutrient uptake system that produces good quality seaweed, to a high nutrient reduction efficiency closed recirculating system that maintains good water quality for the abalone.

The only means for optimisation between nutrient uptake rate and reduction efficiency in open-water cultures (e.g. cage cultures) may be through manipulations in seaweed densities, culture depth, species choice or harvesting frequencies (Halling et al., unpublished). However, even if the system can be manipulated to some extent, it will not be possible to achieve the same precision as in land-based cultures.

4.1.1. How efficiently can seaweeds absorb nutrients from mariculture waste?

To simply add additional seaweed units until satisfactory nutrient concentrations have been reached would, from a practical and economical perspective, be an unrealistic solution. Besides optimising the different separate components of the culture, also the overall performance of the culture needs to be optimised. This implies that quantitative information about seaweed culture performance needs to be available, with respect to nutrient uptake rate, reduction efficiency and secondary considerations (e.g. yield and protein content) under various culture conditions that reflect possible commercial situations. It is not only the uptake rate that we are interested in, but also the capacity to reduce nutrient concentrations below appropriate environmental standards. Table 1 shows that almost all of the investigated studies presented data that describe nitrogen removal by seaweeds, either as nutrient content in the harvested seaweeds or as changes in the water nitrogen concentration between the inflows and the outflows of the seaweed ponds. The data indicated that seaweeds efficiently remove dissolved nitrogen, ranging between 35% and 100% of nutrient input (in tanks or ponds). These results are, however, based on studies with different seaweed species and different experimental setups which make it difficult to draw nonambiguous quantitative general conclusions. Different objectives, i.e. some focusing on maximising uptake rates rather than reduction efficiency, also make it difficult to generalise.

To provide valuable information and to be of practical use for integrated mariculture development, the nutrient water concentrations need to be in accordance with concentrations (and water volumes) that would be released by commercial cultures of fed species. It is, otherwise, difficult to use the data in planning for cultures on a commercial scale. Most of the investigated studies used rearing densities similar to what is found in commercial cultures of fed species.

One important aspect for recirculating systems is to keep nutrient concentrations below certain limits. This parameter is affected by nutrient load (concentration and exchange rates), seaweed uptake rate and seaweed culture area. Data on reduction efficiency were presented in 68% of the studies. Open-water studies, however, do not easily permit for such measurements and, therefore, only related to uptake rates (based on the fractions of nutrients bound in seaweed protein).

Even though several seaweed species have proven able to take up nitrogen and phosphorus efficiently and at high rates, several concerns exist in relation to how effective they are on a commercial scale (Buschmann et al., 2001). These concerns are related to the areal nature of the sunlight-dependant seaweed biofilters, whereas intensive fish culture fish that is related to water volume. The extrapolation of some experimental data indicated that a large area of seaweed cultivation would be required for the removal of a significant proportion of the waste nutrients from a commercial fish farm (Troell et al., 1997). Only a very restricted number of studies have tried to address this aspect or develop solutions.

4.1.2. How do seaweed biofilter functions change over time?

In most cases, intensive mariculture production proceeds year-round, and their interactions with most environments vary seasonally. Of course, the sunlight-dependent seaweed biofilter's nutrient uptake rate and areal yield, both vary seasonally, usually being highest in summer. It is, therefore, important to capture the seasonal trends in seaweed biofilter performance over entire annual cycles. Unfortunately, only few studies were conducted long enough, and less than 40% covered even one-year production cycle.

4.1.3. What factors, other than light, nitrogen and phosphorus, may limit seaweed production?

From the perspectives of seaweed growth and environmental waste load, focusing mainly on nitrogen and phosphorus is, in most cases, relevant. These nutrients are usually the main limiting factors of algal growth and also constitute a potential threat to the environment. Other nutrients may, however, also limit seaweed growth and especially in recirculating systems oxygen super-saturation, high pH or inorganic carbon limitation may occur (Craigie and Shacklock, 1995). A buildup of bacteria in the system could potentially impact negatively on seaweed growth or/and co-cultured animals. Only one of the investigated studies controlled bacterial growth. Furthermore, only 25% of the studies were designed to capture the role of seaweed stocking densities and only 30% tried to find out the importance of different light regimes. Epiphytic growth may diminish seaweed production, but only 24% of the studies mentioned anything about this (and only 7% quantified it). Few studies investigated specifically the importance of flow rate regimes (see Buschmann et al., 2001 for discussion). Water turbidity and competition with microalgae are two potentially important factors that not are addressed in any of the studies.

4.1.4. What nitrogen and phosphorus fractions should be analysed?

The nitrogen fractions being analysed are mainly total ammonia nitrogen (TAN; i.e. the sum of NH_4^+ and NH_3), ammonium (NH_4^+) and total nitrogen (as the sum of TAN + nitrite + nitrate + dissolve organic nitrogen, DON). As relatively few of the studies on tanks or ponds (15%) investigated the possibilities for closed recirculation systems, it is easy to understand why focus on identification of the toxic ammonia form, i.e. the concentration of un-ionic ammonia (NH_3) is absent. As the equilibrium between ionised and un-ionised forms depends on temperature and pH, it should, however, be possible to calculate the concentration of the toxic form if these variables were monitored. In most cases, data on temperature were available and in 40% of the studies pH was also monitored. Phosphorus and its role(s) are rarely investigated as (a) phosphorus effluent discharges are generally an order of magnitude less than nitrogen effluent discharges (Chopin et al., 1999b), (b) generally considered the second limiting factor of seaweed growth, far behind nitrogen in temperate regions (but not in subtropical or tropical regions), and (c) the chemistry of the different phosphorylated fractions in seawater remains complex. Phosphorus speciation can, however, be instrumental for the energetic metabolism and energy redistribution among the different components of an integrated aquaculture system.

4.2. Quality

4.2.1. Does seaweed quality change in integrated cultures?

Seaweeds produced in integrated systems may serve as nutrient scrubbers in some cultures and then be discarded. In other cultures, seaweeds either add to the overall income of the operation by possessing a value on their own (phycocolloid, pigment, food, feed, etc.) or provide an indirect value as a feed component for other co-cultured animals (e.g. abalone and sea urchins). It is, therefore, important to obtain high quality seaweeds, i.e. considering aspects dealing with both direct price-generating qualities (e.g. phycocolloid quality) as well as nutritional qualities (proteins, pigments, nutraceutical value, etc.).

A few of the studies (22%) included detailed information about how the quality of the cultured seaweeds (e.g. phycocolloid production or protein content) is affected by the culture system. Only two of the studies on *Gracilaria* presented data on agar strength or melting point. In cases in which seaweeds were fed to animals, only 12% of the studies looked closer into nutritional qualities. Also related to quality is the condition of the seaweeds with respect to epiphytic growth of other algae and/or invertebrates (see Section 4.1.3).

4.2.2. Does integration with seaweed change the quality and value of the main cultured species?

A very important aspect in recirculating systems is the effect that recirculated water may have upon the cultivated animal. The removal of nutrients and water re-oxygenation by seaweeds are positive for the animals, but the presence of seaweeds may also have negative implications. This may also be true for open cultures if the density of seaweed is very high or water flow rates are low. As mentioned earlier (under Section 4.1.3), no studies have looked at the pathogen transfer from the seaweed unit to the cultured animals. The influence of seaweeds on oxygen concentrations in culture waters, on a diurnal basis, has only been considered in some of the studies. The fact that only few studies focused on possibilities for closed integrated systems probably explains why most of the studies did not include effects on the co-cultivated animals.

4.3. Design and scale

There is generally a tendency for poor replication of experimental units within large-scale aquaculture studies. Many of the investigated studies also failed in this respect. To be able to use and compare findings from research on integrated cultures, it is important that experimental work is carried out with a sufficient degree of replication. This, however, is not always easy to accomplish. When conducting studies looking at properties of culture systems, a balance is needed between he capture of temporal/spatial details and the long-term/commercial scale "real" culture system performance. Moreover, often scientists have only restricted access to industrial aquaculture sites, due to divergences between academic/scientific priorities and commercial priorities or regulatory/legislative barriers.

4.3.1. What is a sufficient degree of replication for obtaining statistically significant results?

It is of course impossible to give a general answer to this question as the type of experiment and experimental conditions varies, generating different amounts of variance. But it is a fact that many of the investigated studies failed, for reasons outlined in the previous section, to replicate their experimental units. Statistical analysis was therefore missing from 60% of the studies. Some studies also failed in separating true replicates from pseudo-replication.

4.3.2. What controls/references should be used for comparison?

A control should reflect a 0-treatment, i.e. an experimental procedure the tested experimental treatments can be compared against. The 0-treatment is important, as it will give indications of the true effects of tested treatments. Many of the investigated studies did not use any true 0-treatment but instead discussed their results by either comparing different treatments, comparing to results from other experiments or not making any comparison at all. It may be important to be able to separate the influence of factors such as bacteria, phytoplankton, periphyton, epiphytes, etc., from the "true" seaweed effect. Admittedly, for open-water studies in heavily developed aquaculture regions, it may be extremely difficult to find real "control" sites, remote enough from any other aquaculture operation and still presenting comparable hydrodynamic, chemical, physical and biological conditions. Often regional reality forces statistical compromises with the selection of "reference" sites.

4.3.3. How should the experiments be designed to allow for extrapolation to scaled up and commercial farming?

An important aspect, that in many cases is quite frustrating for people working within certain sectors of aquaculture research, is the conflict between obtaining results with high accuracy and obtaining results with sufficient relevance for industry. This is, of course, a problem shared with other sectors within natural science. Thus, there is a danger that precise (spatial and/or temporal) results from the laboratory cannot be extrapolated to larger-scale systems. Even though most of the investigated studies consisted of small systems, their experimental designs generated results relatively suitable for extrapolation to commercial situations.

4.4. Economy

4.4.1. Can economic benefits from integrated cultures be accurately confirmed?

The ultimately essential economic aspect of integrated mariculture was missing from most of the studies investigated. Only 7% of the studies presented any economic calculations; moreover, they only incorporated incomes from production, i.e. omitting costs for various investments or management practices. Information about profitability is crucial when comparing different species and experimental designs. This is also important as the objective for integration may differ between users. Thus, to be able to validate the concept, there is a need to show upon feasibility both regarding technology and economy.

To our knowledge, no country in the world regulates (paying for pollution) and/or enforces the treatment of aquaculture discharges/effluents, and therefore no large-scale farms treat their effluents (settling ponds in some shrimp farms makes one exception). It is, therefore, quite difficult to calculate such costs for the current industrial mariculture techniques/practices. Still, the cost of an alternative technology for restoring water quality and coastal health downstream of any commercial mariculture farm is a value added to the seaweed nutrient retention technology for the same service. This value has to be recognised and quantified. It should be added to the production cost of the principal crop culture (e.g. fed finfish or shrimp), and should constitute an income to the seaweed culture. By performing the environmental remediation service, the extractive component of an integrated aquaculture system will significantly improve and sustain the economics of the modern mariculture farm. When upcoming effluent regulations will force aquaculture companies to internalize the total environmental costs of their operations according to the "user pays" principle, the economic benefits of integrated aquaculture systems will become much clearer and monetary quantifiable. Moreover, by implementing better management practices, the aquaculture industry should increase its social acceptability, a variable to which it is very difficult to give a monetary value, but an imperative condition for the development of its full potential.

It is important to emphasise that the yield and culturing of each species must not be evaluated and compared with a monoculture in isolation from the other species in the integrated system. It is the total ecological economic benefits of the whole integrated system that needs to be evaluated (cf. Folke and Kautsky, 1992).

5. Conclusions and suggestions for future research efforts

Most studies confirmed that nutrients from land-based and open-water mariculture operations are suitable for seaweed growth. However, an authoritative synthesis is still lacking on the many factors that can determine seaweed culture design and functioning in commercial integrated mariculture.

Even though very few studies focused on closed recirculation systems, many studies report on the capacity for seaweed to dramatically reduce nutrient concentrations in effluents, to convert in the process large quantities of nutrients into useful seaweed biomass, and to improve additional water quality parameters. Many of the investigated studies also managed to capture the behaviour of integrated cultures sufficiently enough for the results to be extrapolated to larger-scale cultures. Research on land-based systems has been most successful in this respect, but more work is needed on open cultures. To be useful, such research should be made on a large commercial scale, and should address the biology, engineering, operational protocol, and economics of the technology.

Looking especially at closed recirculating systems, we found that some research groups managed to address critical issues more successfully than others. Nevertheless, there is a general need for including other factors that may limit seaweed growth, and also look at various aspects of seaweed quality. The experimental design could generally be improved, i.e. by increasing replication and using more accurate control/reference sites. This would facilitate more statistical analyses and comparisons. Moreover, temporal variations were omitted in many studies. Finally, economic considerations should get much more attention.

Besides a general increase in research efforts on integrated techniques, i.e. allocation of research funds and exploration of various possible combinations, we suggest the following directions for future research:

1. Understand in detail the important biological/biochemical processes in closed recirculating and open seaweed culture systems.
2. Conduct research into these advanced aquaculture technologies at scales relevant to commercial implementation or suitable for extrapolation.
3. Broaden the focus to include factors affecting seaweed growth and uptake capacity.
4. Improve experimental design for statistical calculations.
5. Attain a detailed understanding of the temporal variability in seaweed-filtered mariculture systems.
6. Define numerical design parameters critical for engineers in designing commercial recirculation systems with seaweed filters.
7. Study the influences of location-specific parameters, such as latitude, climate and local seaweed strains/species, on seaweed filter performance.
8. Include economic components, considering the added value of seaweeds, and feasibility aspects.
9. Analyse the role and function of integrated aquaculture practices for improved environmental, economic and social acceptability within the broader perspective of integrated coastal management initiatives.
10. Develop educational, training and financial incentive approaches to transfer these novel and somewhat complex technologies of integrated mariculture from the scientists to the industry.

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References

Alcantara, L.B., Calumpong, H.P., Martinez-Goss, M.R., Menez, E.G., Israel, A., 1999. Comparison of the performance of agarophyte, *Gracilariopsis bailinae*, and in the milkfish, *Chanos chanos*, in mono- and biculture. Hydrobiologia 398/399, 443–453.

Bailey, C., 1988. The social consequences of tropical shrimp mariculture development. Ocean Shorel. Manag. 11, 31–44.

Bergheim, A., Åsgård, T., 1996. Waste production from aquaculture. In: Baird, D.J, Beveridge, M.C.M., Kelly, L.A., Muir, J.F. (Eds.), Aquaculture and Water Resource Management. Blackwell, Oxford, pp. 50–80.

Beveridge, M.C.M., Ross, L.G., Kelly, L.A., 1994. Aquaculture and biodiversity. Ambio 23, 497–502.

Bodvin, T., Indergaard, M., Norgaard, E., Jensen, A., Skaar, A., 1996. Clean technology in aquaculture—a production without waste products? Hydrobiologia 326, 83–86.

Bonsdorff, E., Blomqvist, E.M., Mattila, J., Norkko, A., 1997. Coastal eutrophication: causes, consequences and perspectives in the archipelago areas of the northern Baltic Sea. Estuar. Coast. Shelf Sci. 44, 63–72.

Braaten, B., Poppe, T., Jacobsen, P., Maroni, K., 1988. Risks for self-pollution in aquaculture: evaluation and consequences. In: Grimaldi, E., Rosenthal, H. (Eds.), Efficiency in Aquaculture Production. Disease Control. Edizioni del Sole 24 Ore Milano, pp. 139–166.

Briggs, M.R.P., Funge-Smith, S.J., 1994. A nutrient budget of some intensive marine shrimp ponds in Thailand. Aquac. Fish. Manage. 34, 789–811.

Brzeski, V., Newkirk, G., 1997. Integrated coastal food production systems—a review of current literature. Ocean Coast. Manag. 34, 66–71.

Buschmann, A.H., Mora, O.A., Gómez, P., Böttger, M., Buitano, S., Retamales, C., Vergara, P.A., Guiterrez, A., 1994. *Gracilaria chilensis* outdoor tank cultivation in Chile: use of land-based salmon culture effluents. Aquac. Eng. 13, 283–300.

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

Buschmann, A.H., López, D., González, M.L., 2000. Cultivo integrado de moluscos y macroalgas en líneas flotantes y en estanques. In: Faranda, F.M., Albertini, R., Correa, J.A. (Eds.), Manejo Sustentable de los Recursos Marinos Bentónicos en Chile Centro-Sur: Segundo Informe de Avance. Pontificia Universidad Católica de Chile, Santiago, pp. 7–16.

Buschmann, A., Troell, M., Kautsky, N., 2001. Integrated algal farming: a review. Cah. Biol. Mar. 42, 83–90.

Caddy, J.F., Garibaldi, L., 2000. Apparent changes in the trophic composition of world marine harvests: the perspective from the FAO capture database. Ocean Coast. Manag. 43, 615–655.

Carmona, R., Kraemer, G.P., Zertuche, J.A., Chanes, L., Chopin, T., Neefus, C., Yarish, C., 2001. Exploring *Porphyra* species for use as nitrogen scrubbers in integrated aquaculture. J. Phycol. 37, 9–10 (Supplement).

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

Cheshuk, B.W., 2001. The potential of integrated open-water mussel (Mytilus planulatus) and Atlantic salmon (Salmo salar) culture in North West Bay. Tasmania. PhD Thesis. University of Tasmania, Launceston. 281 pp.

Chopin, T., Wagey, B.T., 1999. Factorial study of the effects of phosphorus and nitrogen enrichments on nutrient and carrageenan content in *Chondrus crispus* (Rhodophyceae) and in residual nutrient concentration in seawater. Bot. Mar. 42, 23–31.

Chopin, T., Sharp, G., Belyea, E., Semple, R., Jones, D., 1999a. Open-water aquaculture of the red alga *Chondrus crispus* in Prince Edward Island, Canada. Hydrobiologia 398, 417–425.

Chopin, T., Yarish, C., Wilkes, R., Belyea, E., Lu, S., Mathieson, A., 1999b. Developing *Porphyra*/salmon integrated aquaculture for bioremediation and diversification of the aquaculture industry. J. Appl. Phycol. 11, 463–472.

Chopin, T., Buschmann, A.H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G.P., Zertuche-Gonzalez, J.A., Yarish, C., Neefus, C., 2001. Integrating seaweeds into marine aquaculture systems: a key towards sustainability. J. Phycol. 37, 975–986.

Chow, F., Macciavello, J., Santa Cruz, S., Fonck, O., 2001. Utilization of *Gracilaria chilensis* (Rhodophyta: Gracilariaceae) as biofilter in the depuration of effluents from tank cultures of fish, oyster, and sea urchins. J. World Aquac. Soc. 32, 214–220.

Cohen, I., Neori, A., 1991. *Ulva lactuca* biofilters for marine fishpond effluents: I. Ammonia uptake kinetics and nitrogen content. Bot. Mar. 34, 475–482.

Craigie, J.S., Shacklock, P.F., 1995. Culture of Irish moss. In: Boghen, A.D. (Ed.), Cold-Water Aquaculture in Atlantic Canada, 2nd ed. The Canadian Institute for Research on Regional Development, Moncton, pp. 241–270.

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

Evans, F., Langdon, C.J., 2000. Co-culture of dulse *Palmaria mollis* and red abalone *Haliotis rufescens* under limited flow conditions. Aquaculture 185, 137–158.

FAO (Food and Agriculture Organization of the United Nations), 2001. The State of World Fisheries and Aquaculture 2000. Food and Agriculture Organisation of the United Nations, Rome.

Flores-Nava, A., 1995. Some considerations on sustainable shrimp mariculture. Jaina 6, 8.

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

Goldman, J.C, Tenore, K.R., Ryther, J.H., Corwin, N., 1974. Inorganic nitrogen removal in a combined tertiary treatment–marine aquaculture system: I. Removal efficencies. Water Res. 8, 45–54.

Gowen, R.J., Bradbury, N.B., 1987. The ecological impact of salmonid farming in coastal waters: a review. Oceanogr. Mar. Biol. Annu. Rev. 25, 563–575.

Gowen, R.J., Weston, D.P., Ervik, A., 1991. Aquaculture and the bentic environment. In: Cowey, C.B., Cho, C.Y. (Eds.), Nutritional Strategies and Aquaculture Waste. Proceedings of the First International Symposium on Nutritional Strategies in Management of Aquaculture Waste (NSMAW). Dept. of Nutritional Science, Univ. of Guelph, Guelph, Ontario, pp. 187–206.

Haglund, K., Pedersén, M., 1993. Outdoor pond cultivation of the subtropical marine red algae *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, K.C., 1975. Growth of the carrageenan-producing tropical seaweed *Hypnea musciformis* in surface water, 870 m deep water, effluent from a clam mariculture system, and deep water enriched with artificial fertilizers or domestic sewage. 10th European Symposium on Marine Biology, Ostend, Belgium, 17–23 Sept., vol. 1, pp. 207–220.

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

Hambrey, J., Tuan, L.A., Thuong, T.K., 2001. Aquaculture and poverty alleviation: II. Cage culture in coastal waters of Vietnam. World Aquac. 32, 34–38, 66–67.

Hänninen, J., Vuorinen, I., Helminen, H., Kirkkala, T., Lehtilä, K., 2000. Trends and gradients in nutrient concentrations and loading in the Archipelago Sea, Northern Baltic, in 1970–1997. Estuar. Coast. Shelf Sci. 50, 153–171.

Hardy, R.W., 1999. Collaborative opportunities between fish nutrition and other disciplines in aquaculture: an overview. Aquaculture 177, 217–230.

Hardy, R.W., Tacon, A.G.J., 2002. Fish meal production and sustainable supplies. In: Stickney, R.R., McVey, J.P. (Eds.), Responsible Marine Aquaculture. CABI Publishing, Oxon, pp. 311–325.

Harlin, M.M., Thorne-Miller, B., Thursby, G.B., 1978. Ammonium uptake by *Gracilaria* sp. (Florideophyceae) and *Ulva lactuca* (Chlorophyceae) in closed system fish culture. In: Jensen, A., Stein, R.J. (Eds.), Proceedings of the Ninth International Seaweed Symposium. Science Press, Princeton, pp. 285–292.

Harrison, P.J., Hurd, C., 2001. Nutrient physiology of seaweeds: application of concepts to aquaculture. Cah. Biol. Mar. 42, 71–82.

Hew, C.L., Fletcher, G.L., 2001. The role of aquatic biotechnology in aquaculture. Aquaculture 197, 191–204.

Hirata, H., Kohirata, E., 1993. Culture of the sterile *Ulva* sp. in marine fish farm. Isr. J. Aquac.-Bamidgeh 45, 164–168.

Hirata, H., Yamasaki, S., Maenosono, H., Nakazono, T., Yamahuchi, T., Matsuda, M., 1994. Relative budgets of pO_2 and pCO_2 in cage polycultured Red Sea Bream, *Pagrus major* and sterile *Ulva* sp. J. Jpn. Aquac. Soc./ Suisan Zoshoku 42, 277–381.

Holby, O., Hall, P.O.J., 1991. Chemical fluxes and mass balance in a marine fish cage farm: II. Phosphorus. Mar. Ecol., Prog. Ser. 70, 263–272.

Hopkins, J.S., Hamilton, R.D., Sandifer, P.A., Browdy, C.L., 1993. The production of bivalve molluscs in intensive shrimp ponds and their effect on shrimp production and water quality. World Aquac. 24, 74–77.

Iwama, G.K., 1991. Interactions between aquaculture and the environment. Crit. Rev. Environ. Control 21, 177–216.

Jacob, G.S., Pruder, G.D., Wang, J.-K., 1993. Growth trail with the American oyster *Crassostrea virginica* using shrimp pond water as feed. J. World Aquac. Soc. 24, 344–351.

Jiménez del Rio, M., Ramazanov, Z., García-Reina, G., 1996. *Ulva rigida* (Ulvales, Chlorophyta) tank culture as biofilters for dissolved inorganic nitrogen from fishpond effluents. Hydrobiologia 326/327, 61–66.

Jones, T.O., Iwama, G.K., 1991. Polyculture of the Pacific oyster, *Crassostrea gigas* (Thurnberg) with chinook salmon, *Oncorhynchus tschawytscha*. Aquaculture 92, 313–322.

Jones, A.B., Dennison, W.C., Preston, N.P., 2001. Integrated treatment of shrimp effluent by sedimentation, oyster filtration and macroalgal absorption: a laboratory scale study. Aquaculture 193, 155–178.

Krom, M.D., 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.

Krom, M.D., Neori, A., van Rijn, J., Poulton, S.W., Davis, I.M., 2001. Working towards environmentally friendly marine farming. Ocean Chall. 10, 22–27.

Langton, R.W., Haines, K.C., Lyon, R.E., 1977. Ammonia-nitrogen production by the bivalve mollusc *Tapes japonica* and its recovery by the red seaweed *Hypnea musciformis* in a tropical mariculture system. Helgol. Wiss. Meeresunters. 30, 217–229.

Lin, C.K., 1995. Progression of intensive marine shrimp culture in Thailand. In: Browdy, C.L., Hopkins, S.J. (Eds.), Swimming Through Troubled Water. Proceedings of the Special Session on Shrimp Farming, Aquaculture '95. World Aquaculture Society, Baton Rouge, pp. 13–23.

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

Lin, C.K., Ruamthaveesub, P., Wanuchsoontorn, P., 1993. Culture of the green mussel (*Perna viridis*) in waste water from an intensive shrimp pond: concept and practice. World Aquac. 24, 68–73.

Lobban, C.S., Harrison, P.J., 1994. Seaweed Ecology and Physiology. Cambridge Univ. Press, Cambridge. 366 pp.

Lyndon, A.R., 1999. Fish growth in marine culture systems: a challenge for biotechnology. Mar. Biotechnol. 1, 376–379.

MacIntosh, D.J., Phillips, M.J., 1992. Environmental issues in shrimp farming. Shrimp'92, Hong Kong. Proceedings of the 3rd Global Conference on Shrimp Industry Hong Kong, 14–15 Sept. INFOFISH, Kuala Lumpur, Malaysia, pp. 118–145.

Mattila, J., Räisänen, R., 1998. Periphyton growth as an indicator of eutrophication: an experimental approach. Hydrobiologia 377, 15–23.

Mazzola, A., Sarà, G., 2001. The effect of fish farming organic waste on food availability for bivalve molluscs (Gaeta Gulf, central Tyrrhenian, MED): stable carbon isotopic analysis. Aquaculture 192, 361–379.

McVey, J.P., Stickney, R.R., Yarish, C., Chopin, T., 2002. Aquatic polyculture and balanced ecosystem management: new paradigms in seafood production. In: Stickney, R.R., McVey, J.P. (Eds.), Responsible Marine Aquaculture. CABI Publishing, Oxon, pp. 91–104.

Melamed, P., Gong, Z., Fletcher, G., Hew, C.L., 2002. The potential impact of modern biotechnology on fish aquaculture. Aquaculture 204, 255–269.

Myers, J.M., Heggelund, P.O., Hudson, G., Iwamoto, R.N., 2001. Genetics and broodstock management of coho salmon. Aquaculture 197, 43–62.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., Troell, M., 2000. Effect of aquaculture on world fish supplies. Nature 405, 1017–1024.

Nelson, G.S., Glenn, E.P., Conn, J., Moore, D., Walsh, T., Akutagawa, M., 2001. Cultivation of *Gracilaria parvispora* (Rhodophyta) in shrimp-farm effluent ditches and floating cages in Hawaii: a two-phase polyculture system. Aquaculture 192, 239–248.

Neori, A., 1996. The type of N-supply (ammonia or nitrate) determines the performance of seaweed biofilters integrated with intensive fish culture. Isr. J. Aquac.-Bamidgeh 48, 19–27.

Neori, A., Shpigel, M., 1999. Using algae to treat effluents and feed invertebrates in sustainable integrated mariculture. World Aquac. 30, 46–49.

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

Neori, A., Krom, M.D., Ellner, S.P., Boyd, C.E., Popper, D., Rabinovitch, R., Davison, P.J., 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.

Neori, A., Ragg, N.LC., Shpigel, M., 1998. The integrated culture of seaweed, abalone, fish and clams in modular intensive land-based systems: II. Performance and nitrogen partitioning within an abalone (*Haliotis tuberculata*) and macroalgae culture system. Aquac. Eng. 17, 215–239.

Neori, A., Shpigel, M., Ben-Ezra, D., 2000. Sustainable integrated system for culture of fish, seaweed and abalone. Aquaculture 186, 279–291.

Newkirk, G., 1996. Sustainable coastal production systems: a model for integrating aquaculture and fisheries under community management. Ocean Coast. Manag. 32, 69–83.

Osorio, V., Akaboshi, S., Alvarez, R., Lombeida, P., Ortega, D., 1993. Cultivo integrado de la ostra del pacifico (*Crassostrea gigas*) y el camarón blanco (*Penaeus vannamei*) en Ecuador. Acuic. Trop. 1, 1–15.

Pagand, P., Blancheton, J.-P., Lemoalle, J., Casellas, C., 2000. The use of high rate algal ponds for the treatment of marine effluent from recirculating fish rearing system. Aquac. Res. 31, 729–736.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres Jr., F., 1998. Fishing down marine webs. Science 279, 860–863.

Petrell, R.J., Alie, S.Y., 1996. Integrated cultivation of salmonids and seaweeds in open systems. Hydrobiologia 326/327, 67–73.

Petrell, R.J., Tabrizi, K.M., Harrison, P.J., Druehl, L.D., 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.

Pitta, P., Karakassis, I., Tsapakis, M., Zivanovic, S., 1999. Natural vs. mariculture induced variability in nutrients and plankton in the eastern Mediterranean. Hydrobiologia 391, 181–194.

Primavera, H.J., 1991. Intensive prawn farming in the Philippines: ecological, social and economical implications. Ambio 29, 28–33.

Primavera, H.J., 1993. A critical review of shrimp pond culture in the Philippines. Rev. Fish. Sci. 1, 151–201.

Qian, P.Y., Wu, C.Y., Wu, M., Xie, Y.K., 1996. Integrated cultivation of the red alga *Kappaphycus alvarezii* and the pearl oyster *Pinctada martensi*. Aquaculture 147, 21–35.

Rawson Jr., M.V., Chen, C., Ji, R., Zhu, M., Wang, D., Wang, L., Yarish, C., Sullivan, J.B., Chopin, T., Carmona, R., 2001. Integration of fed and extractive aquaculture. Paper Collection of International Symposium on Marine Fishery and Aquatic Products Processing Technology, 11–13 Sept., Rongcheng, China, pp. 263–278.

Rawson Jr., M.V., Chen, C., Ji, R., Zhu, M., Wang, D., Wang, L., Yarish, C., Sullivan, J.B., Chopin, T., Carmona, R., 2002. Understanding the interaction of extractive and fed aquaculture using ecosystem modeling. In: Stickney, R.R., McVey, J.P. (Eds.), Responsible Marine Aquaculture. CABI Publishing, Oxon, pp. 263–296.

Richardson, K., Jørgensen, B.B., 1996. Eutrophication: definition, history and effects. In: Richardson, K., Jørgensen, B.B. (Eds.), Eutrophication in Coastal Marine Ecosystems. Coastal and Estuarine Studies, vol. 52. American Geophysical Union, Washington, pp. 1–20.

Robertson, A.I., Phillips, M.J., 1995. Mangroves as filters of shrimp pond effluent: predictions and biogeochemical research needs. Hydrobiologia 295, 311–321.

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.

Ruddle, K., Zhong, G., 1988. Integrated Agriculture–Aquaculture in the South of China: The Dike–Pond System of the Zhujiang Delta. Cambridge Univ. Press, Cambridge. 173 pp.

Ryther, J.H., Dunstan, W.M., Tenore, K.R., Huguenin, J.E., 1972. Controlled eutrophication-increasing food production from the sea by recycling human wastes. Bioscience 22, 144–152.

Ryther, J.H, Goldman, J.C., Gifford, C.E., Huguenin, J.E., Wing, A.S., Clarner, J.P., Williams, L.D., Lapointe, B.E., 1975. Physical models of integrated waste recycling–marine polyculture systems. Aquaculture 5, 163–177.

Sales, J., Britz, P.J., 2001. Research on abalone (*Haliotis midae* L.) cultivation in South Africa. Aquac. Res. 32, 863–874.

Shpigel, M., Blaylock, R.A., 1991. The pacific oyster, *Crassostrea gigas*, as a biological filter for marine fish aquaculture pond. Aquaculture 92, 187–197.

Shpigel, M., Neori, A., Gordin, H., 1991. Oyster and clam production in the outflow water of marine fish pond in Israel. Spec. Publ. Eur. Aquac. Soc. 14, 295.

Shpigel, M., Neori, A., Popper, D.M., Gordin, H., 1993a. A proposed model for "environmentally clean" land-based culture of fish, bivalves and seaweed. Aquaculture 117, 115–128.

Shpigel, M., Lee, J., Soohoo, B., Friedman, R., Gordin, H., 1993b. The use of outflow water from fish ponds as a good source for Pacific oyster (*Crassostrea gigas*) Thunberg. Aquac. Fish. Manage. 24, 529–543.

Stirling, H.P., Okumus, I., 1995. Growth and production of mussels (*Mytilus edulis* L.) suspended at salmon cages and shellfish farms in two Scottish sea lochs. Aquaculture 134, 193–210.

Subandar, A., Petrell, R.J., Harrison, P.J., 1993. *Laminaria* culture for reduction of dissolved inorganic nitrogen in salmon farm effluent. J. Appl. Phycol. 5, 455–463.

Tacon, A.G.J., Forster, I.P., 2001. Global Trends and Challenges to Aquaculture and Aquafeed Development in the New Millennium. International Aqua Feed Directory and Buyer's Guide. Turret RAI PLC, Uxbridge, pp. 4–24.

Taylor, B.E., Jamieson, G., Carefoot, T.H., 1992. Mussel culture in British Columbia: the influence of salmon farms on growth of *Mytilus edulis*. Aquaculture 108, 51–66.

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

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

Troell, M., Rönnbäck, P., Halling, C., Kautsky, N., Buschmann, A., 1999a. Ecological engineering in aquaculture: use of seaweeds for removing nutrients from intensive mariculture. J. Appl. Phycol. 11, 89–97.

Troell, M., Kautsky, N., Folke, C., 1999b. Applicability of integrated coastal aquaculture systems. Ocean Coast. Manag. 42, 63–69.

Vandermeulen, H., Gordin, H., 1990. Ammonium uptake using *Ulva* (Chlorophyta) in intensive fishpond systems: mass culture and treatment of effluent. J. Appl. Phycol. 2, 363–374.

Wang, J.-K., Jacob, G.S., 1991. Pond design and water management strategy for an integrated oyster and shrimp production system. Agricultural Engineering Dep., Univ. of Hawaii at Manoa, Honolulu, Hawaii. Aquac. Eng. 2, 70–82.

Wilks, A., 1995. Prawns, profit and protein, aquaculture and food production. Ecologist 25, 120–125.

Williams, M.J., Bell, J.D., Gupta, M.V., Dey, M., Ahmed, M., Prein, M., Child, S., Gardiner, P.R., 2000. Responsible aquaculture can aid food problems. Nature 406, 673.