Aquaculture 297 (2009) 1–9

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Ecological engineering in aquaculture — Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems

Max Troell [a,b,*], Alyssa Joyce [a,c,d], Thierry Chopin [e], Amir Neori [f],
Alejandro H. Buschmann [g], Jian-Guang Fang [h]

[a] *The Royal Swedish Academy of Sciences, Beijer Institute of Ecological Economics, Box 50005, 104 05 Stockholm, Sweden*
[b] *Stockholm Resilience Centre, Stockholm University, 106 91 Stockholm, Sweden*
[c] *Norwegian University of Life Sciences, P.O. Box 5003, N-1432 Ås, Norway*
[d] *Institute of Resources, Environment and Sustainability, University of British Columbia, 2329 West Mall Vancouver, B.C., Canada*
[e] *Centre for Coastal Studies and Aquaculture, and Centre for Environmental and Molecular Algal Research, University of New Brunswick, P.O. Box 5050, Saint John, New Brunswick, Canada E2L 4L5*
[f] *Israel Oceanographic and Limnological Research Ltd., National Center for Mariculture, P.O. Box 1212, Eilat 88112, Israel*
[g] *Centro i-mar, Universidad de Los Lagos, Camino Chinquihue km 6, Puerto Montt, Chile*
[h] *Mariculture Ecology Division, Yellow Sea Fisheries Research Institute (YSFRI), Chinese Academy of Fishery Science, 106 Nanjing Road, Qingdao, 266071, PR China*

ARTICLE INFO

Article history:
Received 29 March 2009
Received in revised form 9 September 2009
Accepted 10 September 2009

Keywords:
Offshore integrated multi-trophic aquaculture
Bioremediation
Sustainability

ABSTRACT

The marine aquaculture sector is growing rapidly. Offshore aquaculture installations have been drawing increasing attention from researchers, industry and policy makers as a promising opportunity for large-scale expansion of the aquaculture industry. Simultaneously, there has also been increased interest in both land-based and nearshore aquaculture systems which combine fed aquaculture species (e.g. finfish), with inorganic extractive aquaculture species (e.g. seaweeds) and organic extractive species (e.g. suspension- and deposit-feeders) cultivated in proximity. Such systems, described as integrated multi-trophic aquaculture (IMTA), should increase significantly the sustainability of aquaculture, based on a number of potential economic, societal and environmental benefits, including the recycling of waste nutrients from higher trophic-level species into production of lower trophic-level crops of commercial value. Several of the challenges facing IMTA in nearshore environments, are also relevant for offshore aquaculture; moreover, the exposed nature of the open ocean adds a number of technical and economic challenges. A variety of technologies have been developed to deal with these constraints in offshore environments, but there remains a number of challenges in designing farm sites that will allow extractive species (e.g. seaweeds and shellfish) to be integrated in fed aquaculture systems and be able to withstand the strong drag forces of open oceans. The development of offshore IMTA requires the identification of environmental and economic risks and benefits of such large-scale systems, compared with similarly-scaled monocultures of high trophic-level finfish in offshore systems. The internalizing of economic, societal and environmental costs of finfish monoculture production by the bioremediative services of extractive species in IMTA offshore systems should also be examined and analyzed. The results of such investigations will help determine the practical value of adopting the IMTA approach as a strategy for the development of offshore aquaculture.

Contents

---

* Corresponding author. The Royal Swedish Academy of Sciences, Beijer Institute of Ecological Economics, Box 50005, 104 05 Stockholm, Sweden. Tel.: +46 8 673 95 32; fax: +46 8 15 24 64.
E-mail address: max@beijer.kva.se (M. Troell).

0044-8486/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.aquaculture.2009.09.010

1. Introduction

With an average growth rate of 6.9% per annum, aquaculture is the fastest growing food production sector in the world (FAO, 2009). This rapid growth faces, however, some limitations in the availability of suitable sites and in the ecological carrying capacity of existing sites. Offshore aquaculture is increasingly being promoted as necessary to overcome such limitations and meet future world seafood demand. However, considerable controversy has emerged over the proper development of offshore aquaculture, and its actual advantages over existing nearshore aquaculture. Although the term offshore aquaculture has specific implications within the United States, where regulations explicitly define the terms of production (S.1195, the National Offshore Aquaculture Act),[1] a more universal and operational definition of offshore aquaculture is based on the move of farm installations from nearshore sheltered environments to more exposed environments. In some countries, where there are no specific regulations defining offshore culturing, or where there are conflicts over jurisdiction of the Exclusive Economic Zone (e.g. in Asia and Europe, the 200-mile limit is often shared by several countries), offshore aquaculture is better defined not based on distance from shore, per se, as in some locations exposed conditions can be found within less than 2 nautical miles from land, while in others, these conditions exists more than10 miles offshore. Thus it is difficult to develop a precise and universal definition of offshore culturing (Ryan, 2004). However, in general, many of the challenges for offshore aquaculture engineering involve adaptations of farm installation designs and operation protocols for a variety of challenging physical factors, e.g. currents and wave actions, deep water (e.g. difficulty in anchoring structures), shipping routes, migration routes for marine mammals, and logistical difficulties (North, 1987). Solutions to these challenges involve costs, which have implications for market scale and profits (North, 1987; Posadas and Bridger, 2003; NOAA, 2008).

Integrated multi-trophic aquaculture (IMTA) – the integrated culturing of fed species, such as finfish, inorganic extractive species such as seaweeds, and organic extractive species such as suspension- and deposit-feeders – has the promise to contribute to the sustainability of aquaculture (Chopin et al., 2001; Neori et al., 2004; FAO, 2006). It is anticipated that it could also help solve some of the challenges specific to offshore systems. The aim of this paper is to identify and analyze the various challenges that can be resolved, and new ones that may be posed, by adopting the IMTA approach to offshore aquaculture.

2. Ecological engineering in aquaculture

Asian countries, which provide more than two thirds of the world's aquaculture production, have for centuries been practicing IMTA through “trial and error” and experimentation (Li, 1987; Tian et al., 1987; Wei, 1990; Liao, 1992; Edwards, 1992, 1993; Chan, 1993; Chiang, 1993; Qian et al., 1996; Troell, in press). Interestingly, civilizations most successful at developing integrated aquaculture systems treat wastes as valuable resources, and have for a long time integrated nutrient cycling into their agricultural systems (Chopin et al., 2001; Troell, in press).

The discipline of ecological engineering addresses and quantifies the processes that are involved with management of wastes as a resource. Such studies consider a variety of complex environmental and social needs, in addition to maximizing short-term profit (Ruddle and Zhong, 1988; Bailey, 1988; Primavera, 1991; Wilks, 1995). Recent advances in IMTA cultivation techniques outside of Asia evolved primarily from ecological engineering experiments on the use of intensive culturing of seaweeds and bivalves as biofilters at sewage outflows (Ryther et al., 1972, 1975; Goldman et al., 1974) and aquaculture outflows (Neori et al., 2004; Shpigel, 2005). Environmental concerns about the rapid expansion of intensive mariculture systems have also recently led to a renewed interest in IMTA (Chopin et al., 2001, 2008; FAO, 2006). However, most studies have focused on land-based systems, and only a few have to-date investigated the possibilities of IMTA farming in open water. In the past fifteen years, the integration of seaweeds with marine fish culturing has been examined and studied in Canada, Japan, Chile, New Zealand, Scotland and the USA (Petrell et al., 1993; Hirata and Kohirata, 1993; Buschmann et al., 1994, 2008; Hirata et al., 1994; Petrell and Alie, 1996; Troell et al., 1997, 2003; Chopin and Yarish, 1998; Chopin et al., 1999, 2001, 2008; Neori et al., 2004; Halling et al., 2005; Kimura et al., 2007; Stenton-Dozey, 2007; Sanderson et al., 2008; Abreu et al., 2009). The integration of mussels and oysters as biofilters in fish farming has also been studied in a number of countries, including Australia, the USA, Canada, France, Chile, Spain (Jones and Iwama, 1991; Taylor et al., 1992; Stirling and Okumus, 1995; Troell and Norberg, 1998; Buschmann et al., 2000; Mazzola and Sara, 2001; Cheshuk, 2001; Langan, 2004). The recent offshore relocation of many coastal finfish farms in Turkey has generated interest in IMTA (Turan et al., 2009). Recent reviews on IMTA research include a focus on seaweeds (Buschmann et al., 2001; Chopin et al., 2001; Neori et al., 2004), bivalves (Troell et al., 1999a; Shpigel, 2005), crustaceans (Troell et al., 1999b; Jones et al., 2002) and on integrated cultures from a coastal zone management perspective (Newkirk, 1996; Brzeski and Newkirk, 1997; Rawson et al., 2002; Buschmann et al., 2006).

3. Integrated multi-trophic aquaculture (IMTA) in the marine environment—concept and drivers

Modern offshore fish-cage aquaculture practices are similar worldwide. Designs and degree of automation may differ, but with the exception of floating closed containment systems (Partridge et al., 2006; Fredriksson et al., 2008) most marine finfish cages are operated as flow-though net-pen systems. This means that water is transported through the cages by currents, resulting in an incomplete utilization of feed resources and a direct release of reduced quality water, laden

---

[1] In the United States, offshore aquaculture refers to marine farming systems outside of the 3-mile state jurisdiction and within the 200-mile EEZ (federal jurisdiction).

with both particulate and dissolved nutrients to the environment. IMTA has been proposed for mitigating aquaculture waste release, which, as compared to other accompanying methods (i.e. improved maintenance, feed development), has advantages that may include a reduced “ecological footprint”, economic diversification and increased social acceptability of finfish culturing systems. Furthermore, IMTA is the only practical remediation approach with a prospect for additional farm revenues by additional commercial crops, while all other biomitigation approaches have generally involved only additional costs to the producer. Thus, the practice of IMTA combines, in the right proportions, the cultivation of fed aquaculture species (principally finfish) with inorganic extractive aquaculture species (principally seaweeds) and organic particulate extractive aquaculture species (principally suspension- and deposit-feeders). It is a balanced ecosystem management approach that takes into consideration site specificity, operational limits, revenues and food safety guidelines, as well as environmental quality and regulations. The aim is to increase long-term sustainability and profitability per cultivation unit (not per species, as is practiced in monocultures), by recapturing some of the nutrients and energy that are lost in finfish monocultures, and transforming them into additional crops with commercial value.

Drivers for practicing IMTA are found at different levels of the production cycle. At the farm level it may be revenues from producing additional crops. From a societal perspective, value of ecosystem services rendered by the extractive species can be estimated and quantified by environmental accounting. Where limitations are proposed on nutrient emissions in environmental regulations, a farmer could expand production, or need to fallow sites less frequently, thanks to the culture of extractive species at the fish farm. Such goals could be accomplished through nutrient trading credits, similar to systems utilized for pollution or carbon credits,[2] or by internalizing the environmental costs of nitrogen, phosphorus and carbon discharges, enhancing the development of recycling technologies (Buschmann et al., 1996; Chopin et al., 2001).

3.1. IMTA in open waters—from experiments to pilots and commercial farms

Results from recent research on marine IMTA systems in industrialized nations have largely been generated from experimental and small-scale operations, which make it difficult for extrapolating to larger industrial scale offshore farms (Troell et al., 2003). However, some marine IMTA systems, primarily in Asia (China), have been commercially successful at industrial scales, while experimental projects are now scaling up towards commercialization in Canada, Chile, the USA and in some European countries. In the following section, we explore the better documented successful commercial IMTA sites with seaweed, shellfish and finfish, and subsequently examine some of the challenges these producers would face in moving towards large-scale offshore production.

3.1.1. Canada

On the East coast of Canada, Atlantic salmon (*Salmo salar*), kelps (*Saccharina latissima* and *Alaria esculenta*) and blue mussel (*Mytilus edulis*) are reared together at several IMTA sites in the Bay of Fundy. Growth rates of kelps and mussels cultured in proximity to fish farms have been 46 and 50% higher, respectively, than at control sites. This reflects increase in nutrients and food availability from the finfish cages (Chopin et al., 2004; Lander et al., 2004). Therapeutants used in salmon aquaculture have not been detected in kelps and mussels collected from the IMTA sites (Haya et al., 2004). Levels of heavy metals, arsenic, polychlorinated biphenyls (PCBs) and pesticides have also been shown for 8 years to be below the regulatory limits prescribed by the Canadian Food Inspection Agency, the USA Food and Drug Administration and the European Community Directives. Taste-tests of mussels grown in conventional aquaculture and mussels grown at these IMTA sites show no discernable difference; meat yield in the IMTA mussels is, however, higher. Preliminary findings of the economic models have also shown that increased overall net productivity of a given IMTA site can lead to increased profitability of the farm compared with salmon monoculture (Ridler et al., 2006, 2007a,b). There may also be social and environmental benefits that IMTA farms confer on producers, such as the ability to green-label products or the reduction in public concerns over the environmental impacts at farm sites[3] (Ridler et al., 2006, 2007a,b; Barrington et al., 2008).

3.1.2. China

In China, the leading seafood producer in the world, the two main forms of marine IMTA systems are sea-ranching and suspended aquaculture. While the former is usually practiced for the enhancement of natural stocks, the scale and intensity of the latter approach intensive aquaculture in some Chinese waters (Yang et al., 2004; Mao et al., 2009). Below we describe two cultivation areas in China, which differ in their applications of IMTA.

3.1.2.1. Aquaculture on Zhangzidao Island. Zhangzidao Island, in the northern Yellow Sea, consists of nine islets situated approximately 40 miles from the mainland of Liaoning Province. Cultivation of shellfish, seaweeds, crustaceans and echinoderms takes place at 10 to 40 m depth, in an area characterized by strong currents (maximum approximatively 100 cm/s). The Zhangzidao Fishery Group Co. Ltd. is authorized to farm an area of nearly 40,000 ha, of which 26,500 ha are used for scallop, *Patinopecten yessoensis*, 660 ha for sea cucumber, *Apostichopus japonicus*, 100 ha for abalone, *Haliotis discus hannai*, and 10,000 ha for arkshell, *Scapharca broughtonii*. The site has been in operation for over a decade, producing in 2005 28,000 tonnes, with a value of more than US $60 million (net profit of US $18 million). Although some of this production would be better described as sea-ranching as opposed to intensive aquaculture, there is some semi-intensive fed aquaculture, and there have been significant efforts to “optimize” or improve ecological conditions at the farm site, including propagation and planting of seaweeds and creation of artificial reefs. Many of the techniques employed at the site benefit from inter-specific relationships and existing infrastructure to co-culture a range of species.

3.1.2.2. Suspended culture in Sungo Bay. Sungo (Sanggou) Bay, in the eastern end of Shandong Peninsula (37°01–37°09′ N, 122°24′–122°35′ E), is one of the most important mariculture regions for scallop *Chlamys farreri* and kelp *Laminaria japonica* in northern China (Fang et al., 1996; Bacher et al., 2003; Nunes et al., 2003; Chopin et al., 2008). Abalone *H. discus hannai* is also cultured here, and to a lesser degree blue mussel *M. edulis*. It has been estimated that dissolved nitrogen excreted by scallops in the Bay (2 billion individuals) amounts to 284 tonnes during a kelp culturing period. Similarly, the inorganic nitrogen excretion by mussels in the Bay (0.27 billion individuals) amounts to more than 11 tonnes. Together with the excretion of other fouling animals such as sea squirt and oyster, the total inorganic nitrogen excretion of cultivated and fouling animals in the Bay amounts to more than 300 tonnes. Twenty thousand tons of dried kelps can be produced annually through uptake of inorganic nitrogen from the Bay. Long-line culture of kelps has expanded to areas more than 8 km away from the coast, where water depth is between 20 and 30 m deep and with water currents up to 60 cm/s.

---

[2] For instance, a nutrient credit trading system has been implemented in Sweden wherein polluters (e.g. sewage treatment plants), are able to mitigate their nitrogen inputs by trading nutrient removal credits with mussel farmers (Gren et al., 2009).

[3] Environmental regulations in some countries dictate fallowing or even moving farm sites every few years to reduce benthic impacts, and IMTA has the potential to reduce benthic sediment accumulation, and thus potentially justify fewer fallowing periods, or remove the need for site relocation.

During the culture period of *Laminaria* on long lines, abalones are grown in lantern nets hung vertically from the lines, thus allowing the abalone to feed directly on the kelps. Following harvest of *Laminaria*, abalone are fed with dried *Laminaria* until the next crop matures.

4. Limitation of small-scale experiments

A fish farm can take full advantage of IMTA once the nutrient discharge by the fed (fish) component is fully balanced by the harvest of the extractive components (seaweeds and suspension- and deposit-feeders). The complex interactive processes that connect the biomass, nutrient uptake and nutrient concentration of a balanced IMTA system can be difficult to fully examine under partially-balanced experimental setups. The scaling up of experimental IMTA systems towards commercial operations is necessary for three reasons: 1) the biomitigation effect/efficiency of extractive species cannot be easily measured when their biomass remains small in comparison to the biomass of the fed species; 2) the biomass production potential cannot be accurately predicted; and 3) the economic costs and benefits are also not easy to extrapolate from small experimental systems to commercial operations. Extrapolation of nutrient removal capacity of extractive species in small-scale experiments is not possible, as the removal efficiency is nonlinear, and thus multiplying the results of small-scale experiments by increasing biomass values is not accurate. Further, an understanding of how temporal variability in natural seston and dissolved nutrient concentrations affects extractive species can only be obtained from experiments within commercial-scale systems, as increasing the infrastructure and biomass of extractive species at a site may also have impacts on water and nutrient circulation patterns through negative feedback responses. The optimization of biomitigation requires adjustments of the ratio of fed to extractive organisms for each site, based on local physical, chemical and hydrodynamic characteristics, as well as the physiological and metabolic characteristics of the organisms involved and the local socio-economic situation.

5. Efficiency, quality and economic viability of offshore IMTA

5.1. Viability of seaweed production

Studies, from both land-based and open-water cultures, confirm that nutrients released from fed aquaculture species are suitable for seaweed growth (Troell et al., 2003). Seaweed growth and performance are affected by the choice of fish species cultured, farm design, feed practices and additional site-specific parameters. The economic situation and drivers also vary between sites. Therefore, the installation of each IMTA farm should follow optimization to the site. Data from land-based systems indicate that seaweeds can remove between 35% and 100% of dissolved nitrogen produced by fed species (Troell et al., 2003). These figures, of course, depend on what specific aims the studies have had, i.e. maximization of seaweed growth or maximizing removal capacity (Buschmann et al., 2001; Troell et al., 2003). Under some circumstances, such as in re-circulation systems, nutrient reduction efficiency (defined as the average reduction in percentage of nutrient concentration in the water) may be the primary driver for integration. Under other circumstances, maximization of biomass yield and quality (e.g. high commercial value of the extractive species in an integrated seaweed-abalone culture; Troell et al., 2006) may be the primary driver.

The capacity of seaweeds in open-water cultures to remove nutrients from the water column can be estimated based upon the fraction of available nutrients which are bound by the seaweeds at any given point in time. However, the open-water characteristic of net-pen culturing makes it difficult to accurately measure changes in water nutrient concentrations, given that these will vary considerably based on current directions, depth, time of year, time of day and host of other variables. Such variability has led in different studies to divergent conclusions about the effectiveness of IMTA systems for reduction of nutrient concentrations in the water column (Troell et al., 2003). Experimental data and mass balance calculations indicate that a large area of seaweed cultivation, up to one ha for each ton of fish standing stock, would be required for the full removal of the excess nitrogen associated with a commercial fish farm (Troell et al., 1997). Economic feasibility studies for the integration of seaweeds into offshore IMTA systems are absent from the literature and only a few exist for nearshore integrated open-water systems (Chopin et al., 2001; Ridler et al., 2007b).

The interactions between seaweed density, light levels and nutrient availability (concentration or flux) have been studied under natural conditions (Harrison and Hurd, 2001; Buschmann et al., 2008; Abreu et al., 2009) or in fishpond effluents (Cohen and Neori, 1991; Neori et al., 1991). Seaweed growth under non-limiting conditions depends on saturation kinetics by light intensity, temperature and other environmental factors, as well as ambient nutrient concentrations (Buschmann et al., 2008). In a culture system, as the seaweed biomass density increases, it also reduces the ambient availability of both growth factors (light and nutrients) and thus, growth rates decrease sharply. In addition, seaweed growth and biofiltration performance are functionally independent (Buschmann et al., 2001). As nutrient levels drop, the importance of water turbulence around the seaweeds for the rate of uptake becomes more important (Gonen et al., 1993; Msuya and Neori, 2008). Usually, timely thinning of the seaweed biomass (e.g. frequent harvesting) solves these limitations. In an offshore farm, of course, frequent harvests may have logistical and cost implications.

5.2. Filter-feeders and other non-seaweed extractive species

The integration of suspended filter-feeders with cage culture of finfish is not straight forward. Particulate waste materials (i.e. waste feed and faeces from fish cages) and phytoplankton that grows on the fish-excreted nutrients are suitable food for filter feeders. In several studies, mussels and oysters grew faster adjacent to fish cages (Wallace, 1980; Jones and Iwama, 1991; Buschmann et al., 2000; Lefebvre et al., 2000; Lander et al., 2004; Chopin et al., 2008). However, there are other studies showing no, or insignificant, increase in growth (Taylor et al., 1992; Stirling and Okumus, 1995; Gryska et al., 1996; Cheshuk, 2001; Mazzola and Sara, 2001). Differences in success may be due to different environmental conditions and cultivation system designs, as well as sampling protocols. The ambient concentration of particulate organic matter is the single most important factor determining growth rate of mussels. Thus, the existence of both temporal and spatial variation in food availability in natural water bodies has been proposed as an explanation for the varying degrees of success of experimental IMTA sites. Models in Troell and Norberg (1998) identified some constraints in using filter feeders for removing particles from fish-cage farms, which include: 1) dilution of suspended solids by the large volume of water passing through the cages, 2) settling of the particles from the cages below the shellfish installation, 3) variable effects of feeding duration and intensity (e.g. pulse feeding vs. automated control), and 4) total particle retention, as limited for instance by mussel pseudo-faeces threshold level. Troell and Norberg (1998), therefore, concluded that ambient seston concentration is of major importance in controlling mussel growth, and that increases in suspended solids from fish cages may contribute significantly only during periods of low plankton production or low natural organic particle concentration. However, the type of pulse feeding which characterized manual feeding systems has been gradually displaced by automated feeding systems, with inherent consequences for IMTA systems.

As with seaweeds, there is limited amount of information on economic feasibility of co-culturing bivalves with finfish production. Whitmarsh et al. (2006) examined the economic feasibility of nearshore integrated salmon and mussel aquaculture, and concluded that an integrated mussel–salmon system could be economically profitable, depending on the size of the farm, market price for the higher trophic-level species (e.g. salmon), and the intensity of farming practices.

6. IMTA in offshore environments — possibilities and constraints

Existing experience and research on nearshore IMTA systems may be extrapolated to IMTA in offshore environments. This requires identification of the relevant similarities and differences between nearshore and offshore culturing environments. Fish species to be cultivated in both environments will generally be of high commercial value, which, given current market demand, consist largely of carnivorous species in intensive farming practices (Naylor and Burke, 2005). Significant research exists on many of these species in the nearshore environment, but in the future, as new species are introduced that are suitable for offshore environments, stocking densities, feeding behaviours, species-specific feed formulations and food conversion ratios may differ. It is not clear whether waste release (i.e. quality of dissolved and particulate matter) may differ in offshore environments from levels observed currently in nearshore fish-cage farming (Lin and Bailey-Brock, 2008; Reid et al., 2009). However, larger quantities of waste per farm can be expected, as the scale of offshore operations will likely be much larger than in existing nearshore installations. Distribution of wastes from these farms will also differ due to 1) differences in currents and wave action, and 2) distribution of wastes at greater depth, when using submerged cages. Although offshore aquaculture is primarily pelagic, there is nonetheless a risk that currents and settlement may transport wastes from farms to the benthic environment at greater depths, where assimilative capacity is greatly reduced. Inadequate research is currently available on nutrient cycling in offshore environments. IMTA may thus provide a precautionary measure against potential ecological impacts of intensive offshore fish aquaculture. Some of the environmental costs may be greater offshore than nearshore (e.g. waste and energy inputs for transportation of feed and materials), but they may be compensated by the ability to capitalize on economies of scale. Competition with other uses often limits the scale and expansion of nearshore farms.

7. Design considerations for offshore IMTA

7.1. Water currents and hydrodynamic forces

Both current strength and direction are important for IMTA systems, as these determine nutrient and particle fluxes, and thus the appropriate orientation of the different species within culturing units. The importance of the latter can be visualised by considering an integrated kelp–scallop culture. In the late stages of kelp culture, *Laminaria* lengths can reach 2–3 m, which are sufficient to interact with the scallop culture nets. If the direction of long-line ropes is not parallel to the direction of current, the kelps may become wrapped up in the scallop nets. Once this situation occurs, water flow through the nets is greatly reduced, with coincident reduction in particle exchange and food supply. Obviously, the consequence of this situation will be reduced scallop growth, and can under rough conditions, also result in loss of biomass due to entanglement. Similar concerns exist with interactions between shellfish or seaweed culturing in proximity to salmon cages, where the proximity of co-cultured species risks reducing the water flow through cages, and may affect flushing of wastes in the water column.[4]

An important question to answer with respect to IMTA in offshore environments is whether extractive species can withstand prevailing hydrodynamic forces. In addition to strong current velocities, the acceleration due to waves and swell may cause strong forces on the cultured species and the infrastructure (Carrington et al., 2001; Buck and Buchholz, 2005; Gaylord et al., 2008). The orbital motion (Buck and Buchholz, 2005; Holthuijsen, 2007) may be an especially critical factor for the systems' design. Compared to fish grow-out in cages, filter-feeders and seaweeds usually depend on their own ability to attach to a substratum by byssus (mussels) or holdfasts (seaweeds). Culturing techniques generally require that such species are entwined, or fastened, to ropes or contained in nets (Buck and Buchholz, 2004; Chopin et al., 2004). The strong currents in some offshore situations will prevent culture of such species without appropriate attachment methods. Buck and Buchholz (2004) found that rope culture of seaweeds (*Saccharina*), including long line, ladder and grid constructions, was all unsuitable for exposed waters. A “ring design” developed by the authors proved, however, successful. Halling et al. (2005) also reported loss of *Gracilaria* biomass from long lines in exposed waters in Chile. The only method that seemed suitable was a modification of an entwining method developed by Westermeier et al. (1993). Most of existing seaweed culture methods are not designed for open seas (North, 1987), and will require some form of modification to withstand the tougher conditions (especially drag forces; Buck and Buchholz, 2005).

Mussel farming is already taking place in offshore waters in a number of countries (e.g. Ireland, Germany, Scotland, the USA, France, the Netherlands, New Zealand, Japan, and China). These systems can, compared to nearshore applications, better withstand continuous waves, currents and storm events. These systems also often need minimal maintenance and therefore less frequent site visits by personnel. There are still many uncertainties, however, with respect to site selection and design. There are currently few cost-effective and reliable monitoring systems. There is also a need for technological innovation in platform design (Stevens et al., 2008). However, such limitations may be in the future overcome by engineering advances (Stevens et al., 2008). Significant research on offshore culturing systems for finfish is currently being conducted, and this research may be extended to other species should there be adequate incentives for co-culturing in ocean environments.

7.2. Nutrient and energy accessibility

Nutrients and light are key environmental factors that determine growth rates and thus productivity of seaweeds (Harrison and Hurd, 2001). Nitrogen usually limits primary production in coastal areas, and this limitation may be even more severe in offshore non-enriched waters. Ammonia, the main nitrogen compound being excreted by fish, accelerates seaweed growth (Troell et al., 1997). As offshore waters usually have lower background nutrient concentrations than nearshore environments, the positive effect on seaweed growth from fish excretion there may be more pronounced. However, if background levels of dissolved nutrients are too low, this may limit overall seaweed production despite nutrient enrichment from fish farm cages. To achieve ecological balance, the integrated seaweed-culturing component will need to cover a large area (Troell et al., 1997; Buschmann et al., 2001, 2008). A relative large area is required for seaweed culturing due to the fact that the algae depend on the solar radiation reaching the upper ocean surface, whereas other organisms can be cultured more vertically in the water column. Recent results predict that a 100 ha *Gracilaria* farm can remove 80% of the nitrogen loads produced by a 1500 ton salmon farm (Buschmann et al., 2008; Abreu et al., 2009). Nutrient dispersal within farms occupying such a large area requires further study, and is probably specific to site and time; in highly controlled experimental conditions, seaweeds have been shown to remove less than 10 g nitrogen day^{-1} (Cohen and Neori, 1991). In a small fish farm, i.e. producing less than 400 tons, the positive effect on seaweeds may only be detected close to the cages (Troell et al., 1997). However, the impact of a large sized salmon farm (>1500 ton) on seaweed growth can extend to one km from the farm (Abreu et al., 2009). Removal rates may be expected to be lower in an open-ocean environment due to higher

---

[4] Rotating cage designs with a single anchor point can overcome this problem.

dilution. The culturing of seaweeds in the open ocean is also subject to surface conditions such as wind, waves and in some locations, sea ice. Installations for seaweeds may also potentially impede navigation, whereas the culturing of bivalves or fish can be submerged at greater depth.

Several technological obstacles should be overcome in offshore culturing of seaweeds. As with nearshore seaweed culturing, excessive stocking density leads to light and nutrient limitations. Light conditions (i.e. water transparency) are, however, usually better in offshore environments and seaweeds can therefore be cultivated at greater depth, thus avoiding some of the problems with surface mixing and uncontrolled current movements, and even hazards to navigation. However, with respect to nutrient release from submerged fish cages, the effect of nutrient dispersal on seaweeds near fish farms will depend on the depth at which the respective structures are deployed. Deeper installations of fish cages would result in less nutrients reaching near-surface waters, and thus submerged systems would only stimulate growth of seaweeds at the surface if upwelling circulation (either natural or artificially induced) is able to bring nutrients to the surface. Joint ventures between companies interested in underwater turbine energy and offshore aquaculture companies could potentially create interesting synergies, reducing costs, combining technologies and footprints, and harnessing energy and nutrients at the same time.

7.3. Fouling organisms and product quality

Nutrient manipulations (concentrations, nitrogen/phosphorus ratios and application regimes) have been shown to impact seaweed biomass yield, productivity and epiphytic production (Friedlander et al., 1991). Nutrient inputs also impact the product content and quality, e.g. with respect to phycocolloids and proteins (Martínez and Buschmann, 1996; Chopin and Wagey, 1999). The same applies to fouling organisms, such as epiphytes. The applications of freshwater, oxygen (air exposure), chemicals and other management practices for the control of epiphytes have been successfully applied in tank cultures (Buschmann et al., 1994; Fletcher, 1995) and nearshore operations (exposure of *Porphyra* nets at low tide or with specially designed emersion/immersion systems; Oohusa, 1993), but this may not be feasible in open-water system (Buschmann et al., 1997). For example, Halling et al. (2005) experienced heavy loading of settling mussels on *Gracilaria* on long lines next to salmon cages, resulting in large losses of seaweed biomass during the spring. Such problems may be potentially overcome by timing of the transfer of seaweeds to the water. For instance, Chopin et al. (2004) avoided fouling problems by carefully timing the transfer of seaweeds to an integrated salmon aquaculture site, in such a way as to reduce epiphytic growth on kelp ropes.

7.4. Temperature

The species in any culture system, including IMTA, should be physiologically adapted to the temperature regime at the farm's site. For example, low water temperature is beneficial for the growth of kelps such as *Laminaria* and *Saccharina* (Mann, 1972); however, the scallop *C. farreri* prefers warmer water (Kirby-Smith and Barber, 1974). Prior to the development of an offshore IMTA system, the temperature regime at the culture site should be carefully investigated to evaluate suitability for the growth of all the species being considered within the system. Many extractive species inhabit coastal environments and are, therefore, adapted to a wider range of temperature than the regimes offshore environments may offer.

7.5. Basic considerations for economic feasibility of offshore IMTA

In anticipation of future increases in the costs of the main inputs of intensive offshore culture of carnivorous fish – energy and feeds – as well as high construction, maintenance and transportation costs, the economic viability of offshore aquaculture is still unclear. The profit margins of present day large-scale cage fish culture (salmon, seabream, etc.) have declined dramatically in the past fifteen years. These trends may impede the development of offshore fish mono-aquaculture. A key question with respect to IMTA is, then, how seaweeds, filter-feeders, and other extractive species can contribute to the overall economic performance, both for nearshore and offshore systems. As discussed earlier, IMTA provides economic benefits not only at the farm level but also at the broader environmental/societal levels. The broader benefits include a reduction in waste discharges, improvement in social acceptability of the industry, and additional jobs. The primary benefits at the farm level will be maximizing net income, including profit from the production of both fed species (fish) and the extractive species. There are no feed costs for extractive species, but there are other costs for infrastructure and operation to produce additional co-cultured species. Despite a relatively low market price for seaweeds, the millions of tons produced in some countries each year attest that their culture is profitable (Chopin and Sawhney, 2009). The achievement of seaweed profitability in offshore IMTA farms may require identification of species that combine effective biofiltration and productivity with specific qualities that generate higher prices, such as sea-vegetables, nutraceuticals and cosmetics ingredients. Research devoted to the development of higher value products from seaweeds is therefore an additional step towards the incorporation of these organisms into IMTA systems. For instance, *Macrocystis*, a low valued genus that is harvested for its alginates, has recently been used in higher valued edible products, and as feed for abalone (Gutiérrez et al., 2006; Flores-Aguilar et al., 2007). However, the economic success of this type of culturing is not necessarily determined by income at point of sale; rather, the net profits also depend on initial investment costs, costs for maintenance, harvest, handling, and any additional inputs to production (plus the value of ecosystem services which will have to be soon recognized and valuated). Buck and Buchholz (2004) showed that gross profit from an offshore *Saccharina* cultivation (based on production data from experimental setup) was 40 €/yr/culture unit, but that overall investment costs were 100 €/yr/culture unit. The high investment costs were due to the cultivation methodology, which, compared to seaweed farming in nearshore waters, required significant infrastructure and engineering research and development for the installations. In addition, costs for labour or maintenance were not included in this analysis. Even though integration of seaweeds and shellfish with offshore fish cages could benefit from other available structures [e.g. associating aquaculture and wind farm ventures (Buck, 2007) or single point mooring fish-cage systems to which seaweed and invertebrate units could be attached], technological solutions will be required to make such designs economically feasible. The IMTA systems currently being used for commercial applications in Canada and China are relatively simple farming systems (ropes, rafts), and it remains to be seen how new technologies can be applied in highly exposed offshore environments. An important factor in the farming of multiple species is the ability to manage risk through horizontal integration. A diversified product portfolio will increase the resilience of an aquaculture operation in the face of disease outbreak, product gluts, or price fluctuations in one of the farmed species. In such situations, product diversification can increase the survivability of the company.

Seaweed and mussel production in offshore IMTA may be profitable on their own, but if the extractive properties can be translated into economic benefits for the farmer this would create stronger incentives for integration. The challenges for doing this are to 1) identify and quantify the environmental costs from cultivating only fed species, and 2) find ways to internalize the positive effects from integration with extractive species. For instance, in Sweden, a novel program has been initiated for mussel farming, wherein mussel farmers get credits to offset nutrient (carbon, nitrogen, and phosphorus) discharges (e.g. from sewage outfalls) (Sterner, 2005). As wastes from aquaculture are identified as potential threat to the environment, developing IMTA will have societal and environmental as well as economic benefits. An example of this could be reduced risk for HABs and eutrophication. It is, however, difficult to find a specific correlation between loadings and ecosystem effects, as this is usually a nonlinear relationship with thresholds. It is also difficult to estimate the costs for society from the degradation of the environment. Thus, to be able to put a value on nutrient mitigation by biofiltering species, there is a need to know what values of ecosystem goods and services are being generated from natural ecosystems, and how aquaculture wastes affect them. Information about this is scarce, especially for offshore environments.

8. Synthesis

Significant increases in the volume of coastal aquaculture production will likely require expansion into more exposed locations that do not compete with other existing uses of the coastal zone (Skladany et al., 2007). Moving offshore is potentially a way to reduce conflicts over access rights, and to alleviate some environmental concerns. However, this expansion should not be approached with the "out of sight, out of mind" attitude. The solution to nutrification should not be dilution, as it has been the case throughout history in most western countries. Even if faster currents, deeper water and lower nutrient baselines are anticipated to reduce the impacts from offshore operations, it is most likely that offshore farms will be much larger compared to today's farms in nearshore waters, thus implying that more wastes will be generated in each farm. There is a point when eventually even offshore ecosystems will exceed the assimilative capacity of surrounding waters and bottoms. Our limited knowledge about linkages between offshore and nearshore systems could also result in unknown changes in biogeochemical cycling and local ecology, suggesting further that waste mitigation approaches should be considered alongside the development of offshore operations (Chopin et al., 2001).

Methods for farming extractive species like seaweeds and mussels in exposed environments exist but need to be further developed to be able to withstand drag forces from strong currents, waves and swell. Even if it is possible to obtain higher growth rates in the vicinity of fish farms, there is a need for identifying potential risks and also estimating and communicating the bioremediative services of extractive species.

There is currently a need to incorporate knowledge about the assimilative capacity of different extractive species into open-ocean designs and operation practices. To-date, a few promising open-ocean IMTA demonstration facilities exist in different parts of the world, which may be used as protocols for future development (Langan, 2004; Partridge et al., 2006). However, further work is needed to adapt these designs for a variety of species and conditions. As designs are scaled up to commercial production levels, demonstration research sites, with cost sharing arrangements to reduce the very expensive nature of offshore research, will be able to provide invaluable information to the aquaculture sector, and will help in ascertaining the feasibility of IMTA in offshore environments.

Acknowledgments

Financial support was provided by the Swedish International Development Cooperation Agency (SIDA), the Atlantic Canada Opportunities Agency (ACOA), the Israeli Ministry for National Infrastructures (AN), and FONDECYT (Chile).

References

Abreu, M.L., Varela, D.A., Henríquez, L., Villarroel, A., Yarish, C., Sousa-Pinto, I., Buschmann, A.H., 2009. Traditional vs. integrated multi-trophic aquaculture of *Gracilaria chilensis* C.J. Bird J. McLachlan & E.C. Oliveira: productivity and physiological performance. Aquaculture 293, 211–220.

Bacher, C., Grant, J., Hawkins, A.J.S., Fang, J., Zhu, M., Besnard, M., 2003. Modelling the effect of food depletion on scallop growth in Sungo Bay (China). Aquatic Living Resources 16, 10–24.

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

Barrington, K., Ridler, N., Chopin, T., Robinson, S., Robinson, B., 2008. Social aspects of the sustainability of integrated multi-trophic aquaculture. Aquaculture International (published online on 13 December 2008. doi:10.1007/s10499-008-9236-0).

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

Buck, B.H., 2007. Experimental trials on the feasibility of offshore seed production of the mussel *Mytilus edulis* in the German Bight: installation, technical requirements and environmental conditions. Helgoland Marine Research 61, 87–101.

Buck, B.H., Buchholz, C.M., 2004. The offshore-ring: a new system design for the open ocean aquaculture of macroalgae. Journal of Applied Phycology 16, 355–368.

Buck, B., Buchholz, C., 2005. Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea. Aquaculture 250, 674–691.

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

Buschmann, A.H., López, D.A., Medina, A., 1996. A review of the environmental effects and alternative production strategies of marine aquaculture in Chile. Aquacultural Engineering 15, 397–421.

Buschmann, A.H., Retamales, C., Figueroa, C., 1997. Ceramialean epiphytism in an intertidal *Gracilaria chilensis* (*Rhodophyta*) bed in southern Chile. Journal of Applied Phycology 9, 129–135.

Buschmann, A.H., López, D., González, M., 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. Cahiers de Biologie Marine 42, 83–90.

Buschmann, A.H., Riquelme, V.A., Hernández-González, M.C., Varela, D., Jiménez, J.E., Henríquez, L.A., Vergara, P.A., Guíñez, R., Filún, L., 2006. A review of the impacts of salmon farming on marine coastal ecosystems in the southeast Pacific. ICES Journal of Marine Science 63, 1338–1345.

Buschmann, A.H., Varela, D.A., Hernández-González, M.C., Huovinen, P., 2008. Opportunities and challenges for the development of an integrated seaweed-based aquaculture activity in Chile: determining the physiological capabilities of *Macrocystis* and *Gracilaria* as biofilters. Journal of Applied Phycology 20, 571–577.

Carrington, E., Grace, S.P., Chopin, T., 2001. Life history phases and the biomechanical properties of the red alga *Chondrus crispus* (Rhodophyta). Journal of Phycology 37, 699–704.

Chan, G.L., 1993. Aquaculture, ecological engineering: lessons from China. Ambio 22, 491–494.

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.

Chiang, Y.M., 1993. Seaweed cultivation in Taiwan. In: Liao, I.C., Cheng, J.H., Wu, M.C., Guo, J.J. (Eds.), Proceedings International Symposium on Aquaculture, Beijing 21–23 December 1992. Taiwan Fisheries Research Institute, Keelung, pp. 143–151.

Chopin, T., Sawhney, M., 2009. Seaweeds and their mariculture. In: Steele, J.H., Thorpe, S.A., Turekian, K.K. (Eds.), The Encyclopedia of Ocean Sciences. Elsevier, Oxford, pp. 4477–4487.

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 on residual nutrient concentration in seawater. Botanica Marina 42, 23–31.

Chopin, T., Yarish, C., 1998. Nutrients or not nutrients? That is the question in seaweed aquaculture and the answer depends on the type and purpose of the aquaculture system. World Aquaculture 29, 31.

Chopin, T., Yarish, C., Wilkes, R., Belyea, E., Lu, S., Mathieson, A., 1999. Developing *Porphyra*/salmon integrated aquaculture for bioremediation and diversification of the aquaculture industry. Journal of Applied Phycology 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. Journal of Phycology 37, 975–986.

Chopin, T., Robinson, S., Sawhney, M., Bastarache, S., Belyea, E., Shea, R., Armstrong, W., Stewart, I., Fitzgerald, P., 2004. The AquaNet integrated multi-trophic aquaculture project: rationale of the project and development of kelp cultivation as the inorganic extractive component of the system. Bulletin of the Aquaculture Association of Canada 104, 11–18.

Chopin, T., Robinson, S.M.C., Troell, M., Neori, A., Buschmann, A.H., Fang, J., 2008. Multitrophic integration for sustainable marine aquaculture. In: Jørgensen, S.E., Fath, B.D. (Eds.), The Encyclopedia of Ecology, Ecological Engineering, vol. 3. Elsevier, Oxford, pp. 2463–2475.

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

Edwards, P., 1992. Reuse of human wastes in aquaculture, a technical review. Water and sanitation report no. 2. UNDP-World Bank Sanitation Program, World Bank, Washington, DC, pp. 33–50.

Edwards, P., 1993. Environmental issues in integrated agriculture–aquaculture and wastewater fed fish culture systems. In: Pullin, R., Rosenthal, H., Maclean, J.L. (Eds.), Environment and aquaculture in developing countries: ICLARM Conf. Proc., vol. 31, pp. 139–170. 359 pp.

Fang, J.G., Hui-ling, S., Jing-ping, Y., Shi-huan, K., Feng, L., Newkirk, G., Grant, J., 1996. Polyculture of scallop *Chlamys farreri* and kelp *Laminaria japonica* in Sungo Bay. Chinese Journal of Oceanology and Limnology 14 (4), 322–329.

FAO, 2006. State of World Aquaculture, FAO Fisheries Technical Paper. No. 500. FAO, Rome. 134 pp.

FAO, 2009. The State of World Fisheries and Aquaculture - 2008 (SOFIA). FAO Fisheries and Aquaculture Department.176 pp.

Fletcher, R.L., 1995. Epiphytism and fouling in *Gracilaria* cultivation: an overview. Journal of Applied Phycology 7, 325–333.

Flores-Aguilar, R.A., Gutierrez, A., Ellwanger, A., Searcy-Bernal, R., 2007. Development and current status of abalone aquaculture in Chile. Journal of Shellfish Research 26 (3), 705–707.

Fredriksson, D., Tsukrov, W., Hudson, P., 2008. Engineering investigation of design procedures for closed containment marine aquaculture systems. Aquacultural Engineering 39 (2–3), 91–102.

Friedlander, M., Krom, M.D., Ben-Amotz, A., 1991. The effect of light and ammonium on growth, epiphytes and chemical constituents of *Gracilaria conferta* in outdoor cultures. Botanica Marina 34, 161–166.

Gaylord, B., Denny, M.W., Koehl, M.A.R., 2008. Flow forces on seaweeds: field evidence for roles of wave impingement and organism inertia. Biological Bulletin 215, 295–308.

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 efficiencies. Water Research 8, 45–54.

Gonen, Y., Kimmel, E., Friedlander, M., 1993. Effect of relative water motion on photosynthetic rate of red alga *Gracilaria conferta*. Hydrobiologia 260 (261), 493–498.

Gren, I.-M., Lindahl, O., Lindqvist, M., 2009. Values of mussel farming for combating eutrophication: an application to the Baltic Sea. Ecological Engineering 35, 935–945.

Gryska, A., Parsons, J., Shumway, S.E., Geib, K., Emery, I., Kuenster, S., 1996. Polyculture of sea scallops suspended from salmon cages. Journal of Shellfish Research 15, 481.

Gutiérrez, A., Correa, T., Muñoz, V., Santibañez, A., Marcos, R., Cáceres, C., Buschmann, A.H., 2006. Farming of the giant kelp *Macrocystis pyrifera* in southern Chile for development of novel food products. Journal of Applied Phycology 18 (3), 259–267.

Halling, C., Aroca, G., Cifuentes, M., Troell, M., Buschmann, A.H., 2005. Comparison of suspended cultivation methods of *Gracilaria chilensis* in an integrated seaweed and fish cage culture. Aquaculture International 13, 409–422.

Harrison, P.J., Hurd, C., 2001. Nutrient physiology of seaweeds: application of concepts to aquaculture. Cahiers de Biologie Marine 42, 71–82.

Haya, K., Sephton, D.H., Martin, J.L., Chopin, T., 2004. Monitoring of therapeutants and phycotoxins in kelps and mussels co-cultured with Atlantic salmon in an integrated multi-trophic aquaculture system. Bulletin of Aquaculture Association Canada 104, 29–34.

Hirata, H., Kohirata, E., 1993. Culture of the sterile *Ulva* sp. in marine fish farm. Israeli Journal of Aquaculture-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. Suisan Zoshoku 42, 277–381.

Holthuijsen, L.H., 2007. Waves in Oceanic and Coastal Waters, Cambridge University Press, Cambridge, UK, 387 pp.

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., Preston, N., Dennison, W., 2002. The efficiency and condition of oysters and macroalgae used as biological filters of shrimp pond effluent. Aquaculture Research 33 (1), 1–19.

Kimura, H., Noyoya, M., Fujita, D., 2007. Nutrient uptake by *Undaria undarioides* (Yendo) Okamura and application as an algal partner of fish-alga integrated culture. Bulletin Japanese Fisheries Research Agency 19, 143–147.

Kirby-Smith, M.W., Barber, R.T., 1974. Suspension-feeding aquaculture systems: effects of phytoplankton concentration and temperature on growth of the bay scallop. Aquaculture 3, 135–145.

Lander, T., Barrington, K., Robinson, S., MacDonald, B., Martin, J., 2004. Dynamics of the blue mussel as an extractive organism in an integrated multi-trophic aquaculture system. Bulletin of the Aquaculture Association of Canada 104, 19–28.

Langan, R., 2004. Balancing marine aquaculture inputs and extraction: combined culture of finfish and bivalve molluscs in the open ocean. Bulletin of the Japanese Fisheries Research Agency, Supplement 1, 51–58.

Lefebvre, S., Barille, L., Clerc, M., 2000. Pacific oyster (*Crassostrea gigas*) feeding responses to a fish-farm effluent. Aquaculture 187, 185–198.

Li, S., 1987. Energy structure and efficiency of a typical Chinese integrated fish farm. Aquaculture 65, 105–118.

Liao, I., 1992. Aquaculture in Asia: status, constraints, strategies, and prospects. In: Liao, I. C., Shyu, C.Z., Chao, N.H. (Eds.), Aquaculture in Asia: Proceedings of the 1990 APO Symposium in Aquaculture. Taiwan Fisheries Research Institute, Keelung, pp. 13–27.

Lin, D.T., Bailey-Brock, J., 2008. Partial recovery of infaunal communities during a fallow period at an open-ocean aquaculture. Marine Ecology Progress Series 371, 65–72.

Mann, K.H., 1972. Ecological energetics of the seaweed zone in a marine bay on the Atlantic coast of Canada: productivity of the seaweeds. Marine Biology 14, 199–209.

Mao, Y., Yang, H., Zhou, Y., Ye, N., Fang. J., 2009. Potential of the seaweed *Gracilaria lemaneiformis* for integrated multi-trophic aquaculture with scallop *Chlamys farreri* in North China. Journal of Applied Phycology (published online: 28 January 2009. doi:10.1007/s10811-008-9398-1).

Martínez, A., Buschmann, A.H., 1996. Agar yield and quality of *Gracilaria chilensis* (Gigartinales, Rhodophyta) in tank culture using fish effluents. Hydrobiologia 326 (327), 341–345.

Mazzola, A., Sara, 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.

Msuya, F.E., Neori, A., 2008. Effect of water aeration and nutrient load level on biomass yield, N uptake and protein content of the seaweed *Ulva lactuca* cultured in seawater tanks. Journal of Applied Phycology 20, 1021–1031.

Naylor, R., Burke, M., 2005. Aquaculture and ocean resources: raising tigers of the sea. Annual Review of Environment and Resources 30, 185–218.

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

Neori, A., Chopin, T., Troell, M., Buschmann, A., Kraemer, G.P., Halling, C., Shpigel, M., Yarish, C., 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture 231, 361–391.

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

NOAA July 2008 (pre-publication copy), Offshore Aquaculture in the United States: Economic Considerations, Implications & Opportunities. www.aquaculture.noaa.gov/pdf/econ/Econ_rpt_all.pdf.

Yang, Y.F., Li, C.H., Nie, X.P., Tang, D.L., Chung, I.K., 2004. Development of mariculture and its impacts in Chinese coastal waters. Reviews in Fish Biology and Fisheries 14, 1–10.

North, W.J., 1987. Oceanic farming of *Macrocystis*. The problems and non-problems. In: Bird, K.T., Benson, P.H. (Eds.), Seaweed Cultivation for Renewable Resources. Developments in Aquaculture and Fisheries Sciences, vol. 16. Elsevier, pp. 39–67.

Nunes, J.P., Ferreira, J.G., Gazeau, F., Lencart-Silva, J., Zhang, X.L., Zhu, M.Y., Fang, J.G., 2003. A model for sustainable management of shellfish polyculture in coastal bays. Aquaculture 219, 257–277.

Oohusa, T., 1993. The cultivation of *Porphyra* “Nori”. In: Critchley, A.T., Ohno, M. (Eds.), Seaweed Cultivation and Marine Ranching. Japan International Cooperation Agency, Yokosuka, pp. 57–73.

Partridge, G.J., Sarre, G.A., Ginbey, B.M., Kay, G.D., Jenkins, G.I., 2006. Finfish production in a static, inland saline water body using a Semi-Intensive Floating Tank System (SIFTS). Aquacultural Engineering 35, 109–121.

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. Journal of Applied Phycology 5, 1–14.

Posadas, B.C., Bridger, C.J., 2003. Economic feasibility of offshore aquaculture in the Gulf of Mexico. In: Bridger, C.J., Costa-Pierce, B.A. (Eds.), Open Ocean Aquaculture: From Research to Commercial Reality. World Aquaculture Society, Baton Rouge, pp. 307–318.

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

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., 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.

Reid, G.K., Liutkus, M., Robinson, S.M.C., Chopin, T., Blair, T., Lander, T., Mullen, J., Page, F., Moccia, R.D., 2009. A review of the biophysical properties of salmonid faeces: implications for aquaculture waste dispersal models and integrated multi-trophic aquaculture. Aquaculture Research 40 (3), 257–273.

Ridler, N., Robinson, B., Chopin, T., Robinson, S., Page, F., 2006. Development of integrated multi-trophic aquaculture in the Bay of Fundy, Canada: a socio-economic case study. World Aquaculture 37, 43–48.

Ridler, N., Barrington, K., Robinson, B., Wowchuk, M., Chopin, T., Robinson, S., Page, F., Reid, G., Szemerda, M., Sewuster, J., Boyne-Travis, S., 2007a. Integrated multi-trophic aquaculture. Canadian project combines salmon, mussels, kelps. Global Aquaculture Advocate 10, 52–55.

Ridler, N., Wowchuk, M., Robinson, B., Barrington, K., Chopin, T., Robinson, S., Page, F., Reid, G., Szemerda, M., Sewuster, J., Boyne-Travis, S., 2007b. Integrated multi-trophic aquaculture (IMTA): a potential strategic choice for farmers. Aquaculture Economics & Management 11, 99–110.

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.

Ryan, J., 2004. Farming the Deep Blue. Bord Iascaigh Mhara (BIM), Dublin, Ireland.

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.

Sanderson, J.C., Cromey, C.J., Dring, M.J., Kelly, M.S., 2008. Distribution of nutrients for seaweed cultivation around salmon cages at farm sites in north–west Scotland. Aquaculture 278, 60–68.

Shpigel, M., 2005. The use bivalves as biofilters and valuable product in land based aquaculture systems—review. In: Dame, R., Olenin, S. (Eds.), The Comparative Roles of Suspension-Feeders in Ecosystems. Kluwer Academic Pub, Dordrecht, The Netherlands. 400 pp.

Skladany, M., Clausen, R., Belton, B., 2007. Offshore aquaculture: the frontier of redefining oceanic property. Society and Natural Resources 20, 169–176.

Stenton-Dozey, J., 2007. Finding hidden treasures in aquaculture waste. Water and Atmosphere 15, 10–11.

Sterner, H., 2005. Obtaining access to coastal areas for large-scale mussel farming: obstacles and possibilities. Ambio 34, 151–156.

Stevens, C., Plew, D., Hartstein, N., Fredriksson, D., 2008. The physics of open-water shellfish aquaculture. Aquacultural Engineering 38, 145–160.

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

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.

Tian, Z.P., Gao, F.M., Sun, S., Liu, S.Q., Zhang, Y.L., Li, L.X., 1987. Effects of the interculture of *Mytilus edulis* and *Laminaria* on the environment condition. Transactions of Oceanology and Limnology 2, 60–66.

Troell, M., in press. Integrated mariculture in the tropics. In: Soto, D. (Ed.), Integrated Mariculture: Global reviews. FAO Fisheries Technical Paper.

Troell, M., Norberg, J., 1998. Modelling output and retention of suspended solids in an integrated salmon–mussel culture. Ecological Modelling 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., Kautsky, N., Folke, C., 1999a. Applicability of integrated coastal aquaculture systems. Ocean and Coastal Management 42, 63–69.

Troell, M., Rönnbäck, P., Halling, C., Kautsky, N., Buschmann, A., 1999b. Ecological engineering in aquaculture: use of seaweeds for removing nutrients from intensive mariculture. Journal of Applied Phycology 11, 89–97.

Troell, M., Halling, C., Neori, A., Buschmann, A.H., Chopin, T., Yarish, C., Kautsky, N., 2003. Integrated mariculture: asking the right questions. Aquaculture 226, 69–90.

Troell, M., Robertson-Andersson, D., Anderson, R.J., Bolton, J.J., Maneveldt, G., Halling, C., Probyn, T., 2006. Abalone farming in South Africa: an overview with perspectives on kelp resources, abalone feed, potential for on-farm seaweed production and socio-economic importance. Aquaculture 257, 266–281.

Turan, G., Tekogul, H., Koru, E., Cirik, S., 2009. Contribution of seaweed culture in IMTA systems to shaping the sustainable aquaculture in Turkey. Aquaculture Europe 2009. Book of Abstracts, p. 619.

Wallace, J.F., 1980. Growth rates of different populations of the edible mussel, *Mytilus edulis*, in north Norway. Aquaculture 19, 303–311.

Wei, S.Q., 1990. Study of mixed culture of *Gracilaria tenuistipitata*, *Penaeus penicillatus*, and *Scylla serrata*. Acta Oceanologica Sinica 12, 388–394.

Westermeier, R., Gomez, I., Rivera, P., 1993. Suspended farming of *Gracilaria chilensis* (*Rhodophyta, Gigartinales*) at Cariquilida River, Maullin, Chile. Aquaculture 113, 215–229.

Whitmarsh, D., Cook, E., Black, K., 2006. Economic prospects for an integrated salmon–mussel production system. Marine Policy 30, 293–298.

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