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Review

Salmon aquaculture and coastal ecosystem health in Chile: Analysis of regulations, environmental impacts and bioremediation systems

Alejandro H. Buschmann [a,*], Felipe Cabello [b], Kyle Young [a], Juan Carvajal [a], Daniel A. Varela [a], Luis Henríquez [a]

[a] Centro i-mar, Universidad de Los Lagos, Camino Chinquihue km 6, Puerto Montt, Chile
[b] Department of Microbiology and Immunology, New York Medical College, Valhalla, NY 10595, USA

A B S T R A C T

In 2007 salmon, mollusk and seaweed aquaculture production in Chile totaled 904 thousand tonnes, making the nation the leading marine aquaculture producer in the western world. Salmonids grown in open cage net pens account for over 73% of the production. This review summarizes the current status of Chilean aquaculture and proposes the establishment of new regulations and monitoring programmes that encourage and accommodate emerging bioremediation technologies. In contrast to a rapidly expanding, well-financed and technologically advanced industry, the regulatory structure in Chile is outdated and based on insufficient science. The number of publications on the environmental impacts of salmon aquaculture in Chile is low relative to its production level. Nevertheless, the impacts of organic and inorganic waste on benthic communities, pelagic organisms and bird populations are documented. The technology to reduce these impacts using integrated multi-trophic aquaculture (IMTA) strategies exists, but has not been implemented at commercial scales. We call on the government and industry to support the creation of a well-financed and politically independent agency responsible for developing and enforcing science-based environmental regulations in Chile. The agency's immediate goal should be to fund research required to develop a transparent, ecosystem-based regulatory framework that promotes IMTA. Monitoring programs and licensing procedures must consider the impacts of individual sites and the cumulative impacts from multiple sites across a wide range of spatial scales. Before such changes are realized, environmental threats and human health risks will remain unacceptably high and salmon farming in Chile will not meet any reasonable definition of sustainability.

1. Introduction

Marine aquaculture production of fish, shellfish and seaweed in Chile reached 904 thousand tonnes in 2007, making it the leading mariculture producer in the western world [1]. Farmed salmonids account for over 73% of aquaculture production, and this export-driven industry is now the fourth largest contributor to the Chilean economy. Net pen salmon aquaculture began in the 1980s and developed rapidly enough that Chile is now the second largest farmed salmon producer in the world after Norway. Fish are grown to marketable size exclusively in open cage net pen facilities in the protected inner seas of southern Chile. The industry is considered economically consolidated, and is now expanding to the pristine coastal areas of southern Patagonia [2]. Rapid growth and weak government oversight have prevented the adoption of sustainable management practices and given the industry little incentive to modify a successful financial model [3]. Following the trend in northern countries, concerns about the ecological impacts of open net pen aquaculture started to be raised in Chile during the early 1990s [4–6]. The complexity of the management challenge is underscored by evidence suggesting the risk of whole scale ecological regime shifts is more likely when humans decrease ecosystem resilience by reducing biodiversity, removing entire functional groups and trophic levels, and introducing waste and pollutants [7]. It has become increasingly clear that to meet these challenges modern aquaculture must modify practices [8,9] and adopt a balanced ecosystem approach [10].

This paper begins by briefly describing the production trends of the aquaculture industry and the regulatory environment within which the salmon aquaculture industry operates in Chile. We then

* Corresponding author. Tel.: +56 65 322423.
E-mail address: abuschma@ulagos.cl (A.H. Buschmann).

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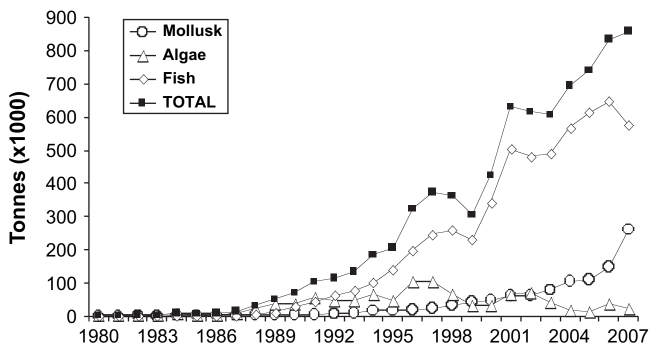

Fig. 1. Change in gross production (tonnes) of fish, shellfish and seaweed aquaculture in Chile.

review documented and potential impacts of open cage aquaculture on marine ecosystems and evaluate potential ecological engineering approaches that can help to mitigate some of these impacts. We conclude by proposing specific actions aimed at protecting coastal environments in southern Chile and highlighting the need for a science-based regulatory system in order to maintain ecosystem health and ecological services.

2. Aquaculture development, regulations and industry performance

The aquaculture industry is growing exponentially in Chile due principally to the increased production of exotic salmonids (Fig. 1). Present regulations require that salmon farms be separated by at least 3 km, and that 400 m must separate an intensive salmon farm and an extensive mussel or seaweed farm [11]. However, in many cases the density of licensed sites is higher because the licenses were granted prior to the creation of the regulation, and different types of facilities (e.g. salmon and shellfish) are often located in close proximity ($\approx$1 km) (Fig. 2). Such licensing practices make it difficult to evaluate the impacts associated with a single salmonid aquaculture facility. The situation requires a regulatory framework and monitoring standards capable of detecting across a range a spatial scales not only the cumulative impacts of multiple sites, but also potential interactive effects of multiple types of sites.

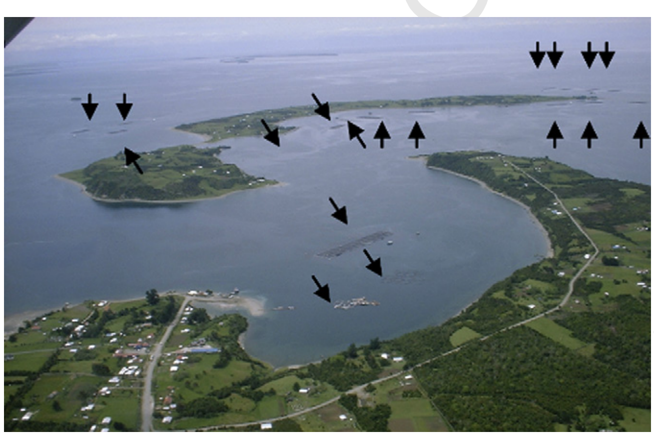
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Fig. 2. Salmon farming around Chiloé Island in southern Chile. Each arrow points to a salmon farm. At this density, cumulative and interactive effects are likely, making it more difficult to monitor impacts and develop enforceable criteria for sustainable aquaculture.

Although environmental and sanitary regulations for salmonid aquaculture exist in Chile [3] and were improved in late 2007, at least four factors limit their effectiveness:

(1) Licensing and monitoring regulations were developed during the mid-1990s, when the number of salmon farming sites was less than 50% of that today. These regulations were designed to monitor the impacts of individual sites, which is unrealistic given the present density of facilities.
(2) A site's environmental impact is determined by monitoring the benthic sediment directly below net pens rather than conditions in the entire water column. The assessment of 'impact' is made principally by measuring dissolved oxygen levels in the sediment and determining whether anoxic (zero oxygen concentration) conditions exist. The inadequacy of defining impact as an extreme value of single proxy is exacerbated by technical limitations and minimal temporal replication in monitoring programs.
(3) The importation of eggs and application of different therapeutic products are officially controlled, but enforcement is Q3 inadequate and controversy surrounds the illegal use of banned products and the poorly controlled application of others. In addition, data relevant to these issues are rarely made public, compromising the transparency of the debate.
(4) Finally, the regulatory system is not based on empirical research on impacts. Relative to Chile's global position as a leading producer, there is a paucity of scientific research on the range of environmental impacts associated with salmon farming. A keyword search done in May 2008 of the ISI web of knowledge database revealed that less than 4% of relevant papers published between 1988 and 2008 were related to Chile (Table 1). The Chilean Parliament publicly recognized this deficiency in 2006, but to date no change in either regulatory policy or financial support has been observed.

Government regulatory, monitoring and enforcement efforts in Chile are compromised by limited financial and technical resources, and a shortage of relevant scientific research [3]. There is an urgent need for the government and industry to collectively support the establishment of independent, open and binding environmental impact assessments. The striking lack of research from Chile on the environmental impacts of salmon aquaculture highlights the need to expand basic research capacity through an independent granting agency jointly funded by the government and industry. To fill this void, the private sector has created different forms of self-regulation. These efforts appear to be modifying the behavior of the salmon producers, but will require an open, multidisciplinary and independent science-based assessment of their ability to control the environmental and social impacts of the industry.

Table 1
Summary of the relative importance of Chile in the production of scientific papers (as an indicator of knowledge development) in three different fields between 1988 and 2008: (1) environmental impacts; (2) fish diseases; and (3) fish escapes. The information is presented for the total number of Chilean papers (TNChP), the global number paper (GNP) and finally the % contribution of Chile (%).

Indicator	1. Environmental impacts	2. Fish diseases	3. Fish escapes
TNChP	15	9	2
GNP	305	389	45
%	4.9	2.3	4.4

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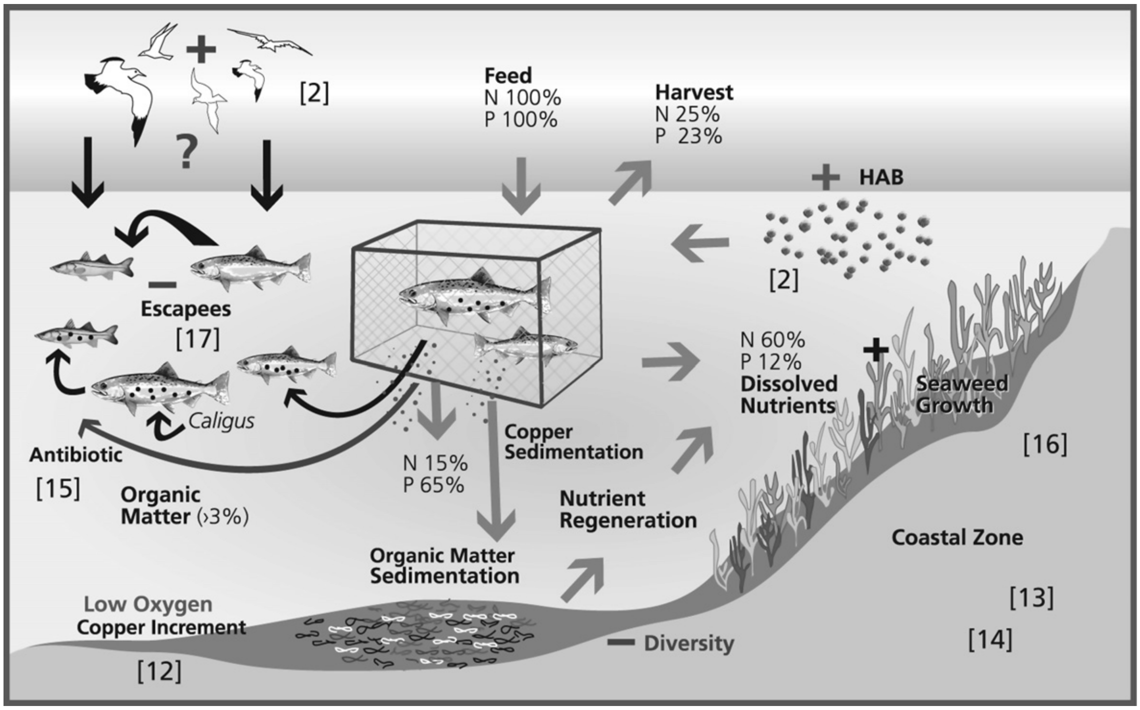

Fig. 3. Summary of environmental impacts on the benthic and pelagic systems of Chilean salmon aquaculture. Percent values of nitrogen and phosphorus flows were calculated from an annual mass balance obtained from a marine land-based farm in Chile [11]. The numbers in brackets in the figure correspond to the reference numbers of the relevant study.

3. Environmental impacts of salmon aquaculture in Chile

Fig. 3 summarizes research to date on the environmental impacts of salmon net pen aquaculture in the inland seas of southern Chile. It is well established that organic waste from salmon farms changes the physio-chemical properties and changes microflora biodiversity of benthic sediments [11,13,14,18,19]. Inor-
Q4 ganic dissolved waste also enhances the growth of algae, leading to algal blooms with poorly understood, producing cascading effects on the trophic web [2]. These studies are consistent with those from the northern hemisphere suggesting that inputs of waste material disrupt benthic ecosystems beneath salmon culture pens (see recent reviews [9,20,21]). Recent improvements in feeding technology have reduced the amount of food waste introduced to benthic environments, but such advances will be less effective at reducing metabolic waste because the assimilation capacity of salmon is finite.

Salmonid aquaculture delivers chemical and drug contaminants to the environment through various pathways with potentially long lasting ecological and evolutionary impacts [9]. Precipitation of copper in sediments, presumably from antifouling paints and uneaten fish wastes, has been associated with benthic biodiversity loss [11]. Antibiotic use is higher in Chile than in other countries and has recently been strongly criticized by consumer and environmental interest groups. For example in the year 2003, salmon aquaculture in Chile used approximately 133,800 kg of antibiotics to produce 280,481 metric tons of salmon [22]. In the same year Norway used 805 kg of antibiotics to produce 509,594 metric tons of salmon. Tetracycline and quinolones have been found in native fish near net pens (Fig. 3) [15] and antibiotic laden organic waste may modify the resistance of benthic bacteria [23–26]. Several chemicals are used to treat sea lice outbreaks [9,27], and the indiscriminate use in Chile of some of these products appears to have the potential to increase resistance levels in the lice [28,29]. These products can affect other crustaceans, such as copepods, potentially exacerbating food web disruptions and the risk of harmful algal blooms [9]. Though the use of malachite green is presently prohibited in Chile, other products continue to enter the environment and are poorly documented. We suggest the use and ecological implications of drug use in salmon aquaculture require immediate regulatory and scientific attention.

Salmon farms can disrupt marine food webs by attracting carnivorous birds and mammals [2]. Though Chilean regulations recognize the potential threat to such organisms, the direct and indirect ecological and evolutionary effects of such behavioral modifications remain unstudied. Farmed salmon escape from marine net pens through persistent low-level leakage (1–5%) and by millions when extreme weather events destroy entire facilities [17]. In the northern hemisphere, farmed salmon have lower survival rates than wild salmon (e.g. [30]), but in the marine environment escapes display similar body condition and feed on the same prey items as wild salmon [31]. Data collected following a catastrophic escape event in Chile suggest farm-raised salmon feed on wild prey, maintain positive growth rates, and reduce the abundance of native marine fish species through competition and/or predation [17]. Evidence from the northern hemisphere (e.g. [32,33]) suggests that escaped salmon can enter and successfully reproduce in Chilean rivers [34,35], and exotic salmonids originally introduced to Chile have begun colonizing the West Atlantic coast of Argentinean Patagonia [36]. In the northern hemisphere, the negative impacts of escape reproduction on con- and hetero-specific salmonid populations are well documented (e.g. [30,37,38]). In the coastal rivers of southern Chile farm escapes are common and stomach content analysis reveals they frequently feed on freshwater prey. Recently evidence of natural reproduction has begun to accumulate, though it remains unknown how escapes and their offspring might impact the native freshwater fish of southern Chile.

In addition to introducing live salmon to the environment, net pens serve as sources of diseases and parasites whose negative effect on wild salmonid populations is well documented [39]. In Chile salmon lice (*Caligus rogercresseyi*; Fig. 4A) outbreaks have negatively affected salmon aquaculture [40] and there is evidence that the species has switched hosts and infested wild populations of the coastal fish *Eleginops maclovinus* (Fig. 4B). How farm locations and oceanographic dynamics interact to regulate the dispersal of parasites and their impact on farmed and native fish populations require urgent attention in Chile. This issue seems also relevant for recent viral (ISA) outbreaks in southern Chile. There is also evidence suggesting that raising smolts in Chilean Lakes region and the escape of salmon from pens may have triggered the national and international spread of *Diphyllobothrium latum*, the fish tape worm, extending the range of this parasite in Chile and the world [42–44].

4. Environmental strategies for sustainable development

The potential for ecological engineering approaches to mitigate the impacts of aquaculture on coastal ecosystems has been recognized for over a decade (e.g. [45,46]). For example, authors have indicated the relevance of natural populations that could help to mitigate the impacts of intensive aquaculture, like bacteria enhancing the recycle of organic material deposits under the cages and reducing emissions to the water column or natural fish populations near the cages recycling waste particles or waste reduction by natural fish populations [19]. The recycling of finfish (fed aquaculture) organic waste by filter feeders and seaweeds (extracting species) has been denominated integrated multi-trophic aquaculture (IMTA) and is one strategy to help mitigate waste-associated impacts [10,46–48]. Examples of approaches in Canada, South Africa, Israel, China and Chile have been recently described in detail, considering semi-enclosed land-based systems, closed floating pens that allow waste collection and recycling, as well as extracting organisms cultivated near intensive fish culture with a more diffuse waste production have been also tested in different regions of the world [46]. A pilot study in Atlantic Canada Q5 indicate showed that by growing seaweed (*Laminaria saccharina* and *Alaria esculeta*) mussels and (*Mytilus edulis*) and Atlantic salmon (*Salmo salar*) together, demonstrating biological and technical feasibility and the beneficial impact on mussel and seaweeds growth and biomass production from absorbing organic and inorganic salmon wastes [49,50]. Relevant studies modeling water and waste flows inside aquaculture intensively used Q6 embayments are also providing additional relevant information about environmental mitigation (e.g. [51,52]). By using three-dimensional physical, chemical and biological simulation models, Rawson et al. [53] demonstrated the importance of extractive organisms to reduce wastes produced by fed aquaculture in China. However, this study [53] shows that the results are complex due to interacting factors and therefore they require multidisciplinary approaches to achieve an environmentally sustainable production model.

The IMTA approach was first explored in Chile during the late 1980s when rainbow trout (*Oncorhynchus mykiss*) were grown at high densities in land-based tanks using pumped seawater. The fouled water was used to cultivate oysters (*Crassostrea gigas*) and agar-producing alga *Gracilaria* [54]. The results showed that tank cultivation of trout was technically feasible, that seaweed could effectively assimilate waste nitrogen (above 80%, [12]), and that the system was economically viable if high densities of fish could be farmed at a large enough scale to pay for the investment [48,55].

Similar IMTA approaches have been proposed for mitigating the negative impacts of rearing smolts in lakes [56]. Even more promising is the possibility of moving the freshwater phase to completely closed land-based facilities. Technological advances have made smolt production in closed-freshwater systems an economically viable alternative to open net pen rearing in lakes and some companies in Chile have already invested in such facilities [57]. In marine coastal systems, extractive organisms (seaweeds and shellfish species) have also demonstrated high bioremediation capabilities [58–61]. There are, however, economic challenges to establishing IMTA for producing multiple products consumed in Chile. Like Asian countries, Chile has a long tradition of shellfish and seaweed consumption. However, the domestic price for these goods is still too low to attract investment for their production and efforts to develop added value to these resources are required [62]. The ability of the emerging abalone cultivation industry to secure export markets may foretell the success of IMTA in Chile. If economically viable, IMTA will be an important driver for the development of seaweed farming and mussel aquaculture (Fig. 5). If profitable, there is real promise that in the coming years IMTA will help bring together these new cultivation approaches and reduce the amount of waste produced by salmonid aquaculture.

Clearly, IMTA cannot remove all the organic and inorganic waste from salmon farms and monitoring strategies must be flexible enough to accommodate a wide range of scenarios. The accumulation of chemicals and drugs in extracting species poses an additional challenge if IMTA approaches are to provide multiple consumable resources. Despite these challenges, we feel IMTA Q7 should play a central role in the development of ecological sustainable net pen aquaculture in Chile and elsewhere (Fig. 6). It is clear that IMTA can increase profitability and reduce economic

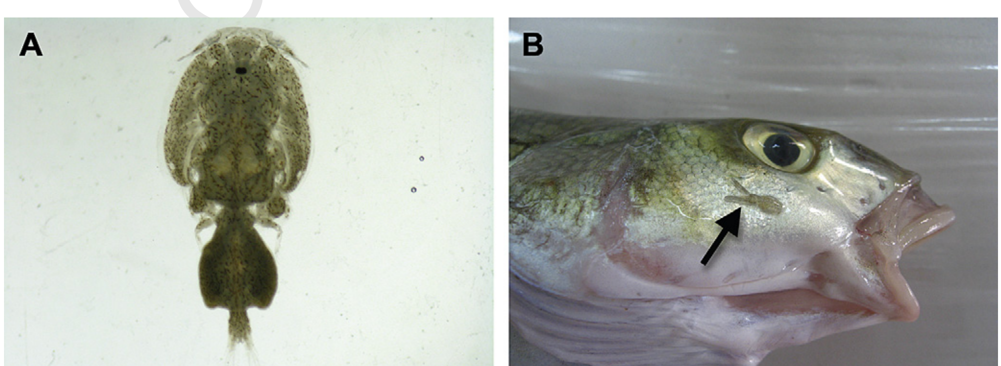

Fig. 4. (A) Sea lice *Caligus rogercresseyi* (adults can reach 4.8–5.2 mm) can be found in abundances above 400 individuals per salmon (adult individuals of 6–7 kg). As the water temperature is higher in the Chilean coast than in other salmon culture regions sea lice life cycle is shorter and greater infestation numbers can be found. (B) *C. rogercresseyi* is naturally present (arrow) on native *Eleginops maclovinus*. Its effects as a dispersal agent between salmon farms remain to be established. See Asencio et al. [41].

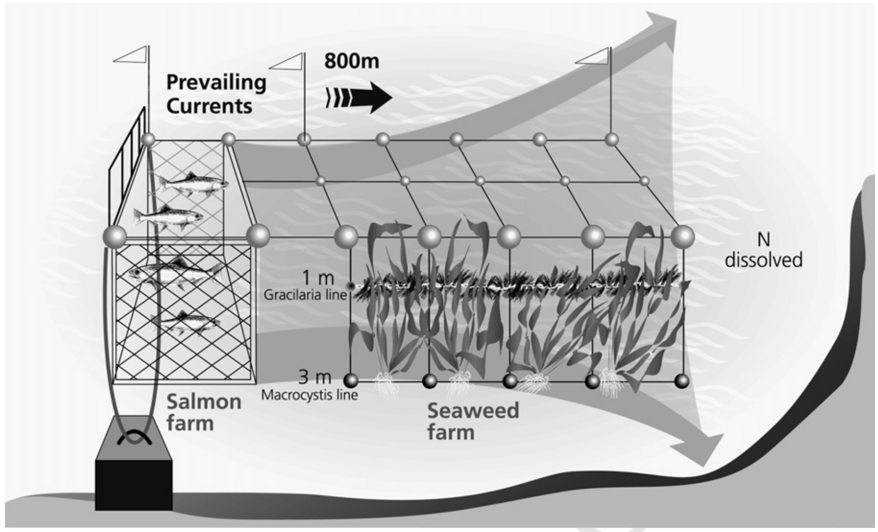

Fig. 5. An example of how the IMTA approach can reduce the impact of salmonid aquaculture. A salmon farm producing 1500 tonnes yearly (gross production) occupies an area of ca. 0.8 hectares. With a feed conversion ratio of 1.1, the farm will produce approximately 65.9 tonnes dissolved nitrogen [21]. Buschmann et al. [55] estimate that culturing 50–60 hectares of red algae *Gracilaria chilensis* and brown algae *Macrocystis pyrifera* down current of the salmon farm would reduce by 80% the amount of nitrogen entering the ecosystem.

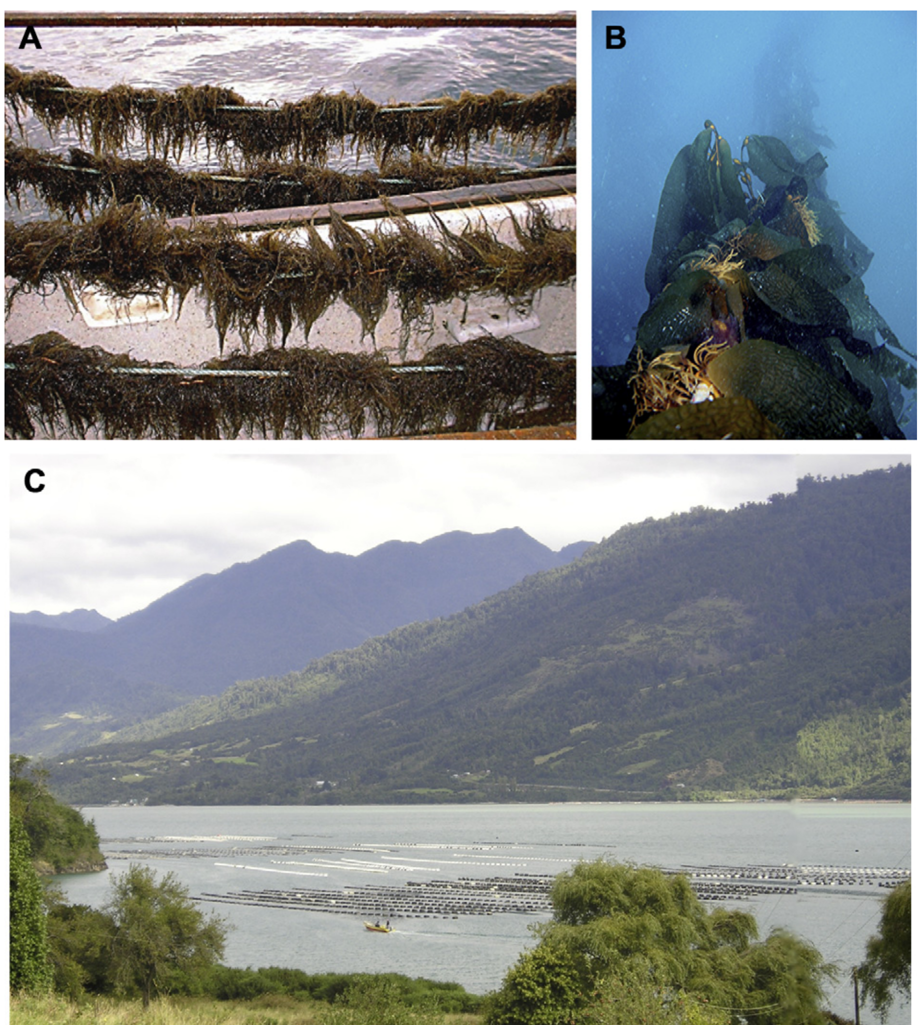

Fig. 6. Aquaculture practices that should contribute to the development of an IMTA strategy in Chile: (A) red seaweed (*Gracilaria chilensis*), (B) brown seaweed (*Macrocystis pyrifera*) and (C) mussel (*Mytilus chilensis*) cultivation in the south.

risks, as well as present a better environmental perception to the general public as compared to salmon monoculture [63].

5. Conclusions

In summary, the environmental impacts of salmon aquaculture are varied and interactions between different factors may produce complex changes in coastal ecosystems. Such interactions are particularly likely to occur in Chile because of the high density of aquaculture sites. Despite the need for more empirical research, the environmental impacts of salmon aquaculture in Chile remain largely unstudied. Nevertheless, there are clearly numerous benthic and pelagic impacts, which could be reduced by the creation and enforcement of science-based regulations. These regulations will need to explicitly consider and monitor impacts resulting from cumulative effects at spatial scales ranging from a single site to the entire region. Logically, the new regulatory framework should encourage and accommodate emerging IMTA technologies.

6. Perspectives

The establishment of well-financed and politically independent agencies to fund research and enforce regulations is essential. Until these basic conditions are met, open net pen salmon aquaculture in Chile will not meet international standards. More urgently, fundamental changes in the industry are required to ensure the health of a unique coastal ecosystem and the cultures and communities it supports in Chilean Patagonia. Following Primavera [8], we recommend the use of a holistic integrated coastal management approach based on stakeholder needs, using conflict resolution tools, carrying capacity modeling, protection of community resources, rehabilitation of degraded habitats to improve science-based environmentally-balanced aquaculture practices, like IMTA approaches. Finally, regional monitoring programs and licensing procedures must consider the impacts of individual sites and the cumulative impacts from multiple sites across a wide range of spatial scales to ensure sustainable aquaculture practices. To achieve this goal, we strongly recommend the government and industry to support the creation of a well-financed and politically independent agency responsible for developing and enforcing environmental regulations in Chile. The agency's immediate goal should be to fund research required to develop a transparent, ecosystem-based regulatory framework.

Uncited reference

[16].

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