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A review of the impacts of salmonid farming on marine coastal ecosystems in the southeast Pacific

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The production of farmed salmonids in Chile reached 550 000 t in 2004. The industry is considered to be consolidated, but with potential for further expansion to the south into pristine coastal areas. The environmental impacts of the salmonid farming industry in Chile were reviewed in 1996, and evidence at that time did not suggest significant adverse effects. However, after almost ten years of sustained growth, current evidence indicates that significant loss of benthic biodiversity and localized changes in the physico-chemical properties of sediments have occurred in areas with salmonid farms. Furthermore, the presence of these farms significantly increases in pulses the density of dinoflagellates. Data suggest that escaped farmed fish may have an impact on native species, although their survival in the wild appears low. The abundance of omnivorous diving and carrion-feeding marine birds increased from twofold to fivefold in areas with salmon farms compared with control areas without them. It is urgent that an ecosystem approach be implemented to assess all impacts of salmonid farming on coastal ecosystems in southern Chile.

Keywords: biodiversity, Chile, environmental effects, fish escapees, nutrient loads, salmon culture.

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Introduction

During the past ten years, salmonid aquaculture has become the fourth largest economic activity in Chile after mining, forestry, and fruit production. Gross production in 2004 was 550 000 t, and the three most important farmed salmonids are Atlantic salmon, *Salmo salar*, coho salmon, *Oncorhynchus kisutch*, and rainbow trout, *O. mykiss* (Figure 1). Farming of Atlantic salmon is the main aquaculture activity in Chile, accounting for 92.5% of all exported aquaculture biomass and 94.9% of the total export revenue derived from aquaculture products. The location of the salmon farming industry in Chile is shown in Figure 2. Concern has been expressed about the environmental impacts of salmon farming in Chile and worldwide. These impacts include modification of benthic communities, increased nutrient loads in coastal waters and the associated problem of harmful algal blooms, increased harvests of wild fish populations for the production of fish feed, use of different types of chemicals, and escapes of farmed salmon into the wild (e.g. Gowen and Bradbury, 1987; Hallaegraeff, 1993; Folke *et al.*, 1998; Naylor *et al.*, 2000; Goldburg and Naylor, 2005). Currently, the environmental effects of intensive salmonid cultivation in Chile are little understood (Castilla *et al.*, 2006), and consequently, industry regulation has been criticized for failing to implement an integrated ecosystem approach to environmental conservation.

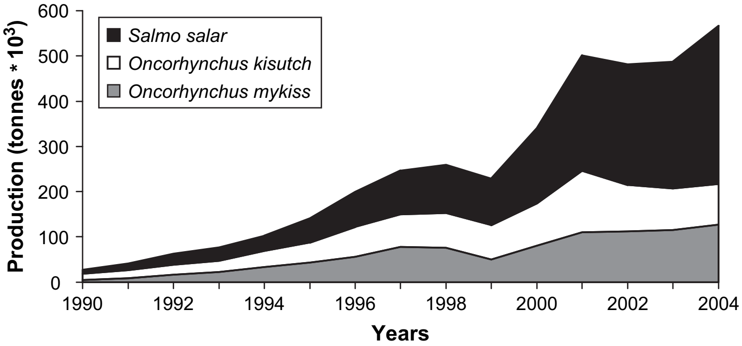

Figure 1. Gross annual production (t) for the three main salmonid species farmed in Chile.

In 1996, a review of the environmental effects of salmon farming in Chile concluded that the industry did not have a significant environmental impact (Buschmann *et al.*, 1996). However, the industry has expanded considerably during the past ten years and is now considered to be economically and technologically consolidated. The industry may expand farther into pristine southern environments of high conservation value. This paper summarizes recent research on the most important environmental effects of salmon farming in Chile, based on published and unpublished information, and makes suggestions for the sustainable management of intensive salmon farming in the southeast Pacific.

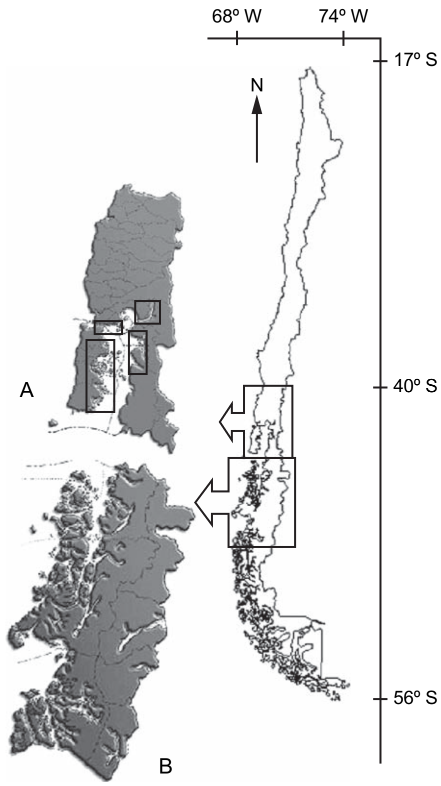

Figure 2. Map of Chile showing the main salmon farming areas. A = the Los Lagos region showing the location of the most important salmon farming sites (rectangular boxes) and B = the Aysen region where salmon farming is currently developing in pristine coastal ecosystems.

Developments in salmon farming in Chile

Commercial salmon farming began in Chile with the importation of eggs from the northern hemisphere. In recent years, the use of innovative technologies, particularly for Atlantic salmon culture, e.g. photoperiod and temperature manipulation, has permitted the transfer of fish to sea at different times of the year and harvesting throughout the year, reducing the need to import ova and, consequently, reducing the risk of introducing exotic parasites and diseases. Other positive developments include improvements in feed quality and conversion rates (ca. 1.2). Notwithstanding these improvements, several environmental issues remain unstudied or unregulated, resulting in pressure on producers and the government from environmental groups (Buschmann *et al.*, in press).

Impacts of salmonid farming on the Chilean coastal environment

Research conducted since 1996 suggests that there have been localized adverse impacts on the seabed in the licensed farming areas associated with physico-chemical changes to sediments and significant losses of benthic biodiversity (Buschmann, 2002; Soto and Norambuena, 2004). Research at eight salmon farm sites located along 300 km of coastline demonstrated that the benthic biodiversity was reduced by at least 50% on average in the licensed salmon farming areas in southern Chile. This loss of biodiversity appears related not only to organic matter loading and low oxygen levels in the sediments (Soto and Norambuena, 2004), but also to the deposition of copper

(Buschmann, 2002). Recently, the channels and fjords of southern Chile have been shown to possess a unique benthic fauna comprising endemic cold-water corals, anemones, and other species (e.g. Försterra *et al.*, 2005). Interest in protecting these ecosystems has increased, and a network of conservation areas has been proposed (Castilla, 1996).

The Chilean regulations require that any farm causing the formation of anoxic sediments must reduce its production by 33% and, if the sediments have not recovered after one year, production must be reduced by a further 33%. Thereafter, if the level of oxygen in the sediments does not recover, the farm must close. However, benthic wastes have high levels of phosphorus (Soto and Norambuena, 2004), and it is not known how long these accumulations can persist and remain a source of nutrients in Chilean waters.

The occurrence of harmful algal blooms resulting from the input into coastal waters of nitrogen from salmonid farms is another major topic of concern in Chile. Harmful algal blooms have been recorded in Chile during the past three decades and have affected human health and natural and cultured marine resources (Table 1). The first instances to affect human health were reported in 1970 and 1972, and involved the species *Dinophysis acuta* and *Alexandrium catenella*; in 1993, diatoms of the genus *Pseudo-nitzschia* were implicated in a harmful algal bloom. These algae are sources of diarrhoetic, paralytic, and amnesic shellfish poisons, respectively. *A. catenella* blooms have affected Chile's austral region (42°S–52°S), whereas *D. acuta* and *Pseudo-nitzschia* have resulted in blooms in various enclosed coastal areas (Table 1). The algal species that have affected marine resources include Dinophyceae (*Prorocentrum micans*, *Gymnodinium* cf. *cloroforum*, and *Gymnodinium* spp.); Bacillariophyceae (*Leptocylindrus minimus*, *Chaetoceros convulutus*, and *Chatonella* sp.); Raphydophyceae (*Heterosigma akashiwo*); and Chrysophyceae (*Dictyocha speculum*) (Table 1). These blooms have mainly affected the channels and fjords of the Chiloé region (41°S–43°S), causing behavioural changes and mortality in wild and cultured aquatic resources. Although the number of these harmful species appears to have declined in Chile, reports of new harmful species and bloom events have increased in the past three decades; the impacts of species in Chile that are recognized as being harmful in other parts of the world (Table 1) must be given careful consideration.

In most locations, there have been no detectable increases in nitrogen concentration in the water column near salmon farms (Soto and Norambuena, 2004). However, in an intensively farmed channel in southern Chile (Calbuco), significantly higher concentrations of ammonium nitrogen were detected near the cages, compared with control areas without fish pens (Figure 3). Seaweeds were shown to exhibit faster growth rates and higher nitrogen content in their tissues when cultured near fish farm cages (Figure 4), suggesting higher nitrogen availability as a result of the presence of the farms (Troell *et al.*, 1997). In an experiment to assess the effect of salmon farms on phytoplankton communities, 1500-l tanks, filled with either effluent from salmon farms (see Buschmann *et al.*, 1994, for details of the experimental protocol) or with seawater pumped directly from the sea, were used to culture dinoflagellates. The results indicated that the density of dinoflagellates increased significantly ($p < 0.05$) when reared in fish farm effluent, while diatoms tended to disappear (Figure 5). In addition, a study using the "beyond BACI" (Before-After-Control-Impact) methodology (Underwood, 1994) suggested that salmon farms enhanced dinoflagellate abundance for short periods (Figure 6). An analysis of variance showed that no persistent effect could be detected on dinoflagellate abundance because the ratios of *F*-values $T(\text{Aft}) \times I/T(\text{Bef}) \times I = 38.61$ (Table 2) and $T(\text{Aft}) \times I/T(\text{Aft}) \times C = 48.28$ (Table 2) are both significant ($p \leq 0.05$), whereas $T(\text{Aft}) \times C/T(\text{Bef}) \times C = 0.24$ ($p \geq 0.05$) is not significant. These results indicate that the presence of salmon farms led to a significant increase in the abundance of dinoflagellates in short-term pulses and suggest that, to detect any increases in abundance of phytoplankton associated with them, it is necessary to implement an appropriate sampling protocol that facilitates detection of these pulses.

The use of various chemical compounds in salmonid farming has also raised public concern in Chile, particularly following the detection of some compounds at high levels in other countries (Easton *et al.*, 2002; Hites *et al.*, 2004; Foran *et al.*, 2005). In this context, initiatives between the government and private companies in Chile have been set in motion. The effects of antibiotics on the microbial flora have received little attention, although resistance to antibiotics is a problem for the salmon farming industry, e.g. Miranda and Zemelman (2001). Statistics on the imports of antibiotics to Chile suggest their usage in large quantities in salmon farming (Cabello, 2003). It is necessary to reduce this usage to avoid a major environmental sanitary problem (Wolff, 2004). The environmental impacts of using malachite green, antifouling paints, and other chemicals have not been studied.

Escaped farmed salmon

The reported number of fish escaping from salmon farms in Chile varies annually, but the existing regulations have not led to a reduction in the reported biomass of escapees (Table 3). Independent assessment of the validity of the reports is necessary. Farmed salmon released into the wild appear to have a rather short life expectancy (<1 y) in Chilean coastal waters (Soto *et al.*, 2001), as has been reported for the North Atlantic (Fleming *et al.*, 1996). Previous attempts at salmon ranching in Chile were not successful, owing to the low survival of the released fish.

There is concern in Chile, however, about the impact of escaped farmed salmon on the native fish fauna,

Table 1. Harmful algae blooms in Chile during the past three decades, with the year of the bloom and its effects and details of potentially harmful algal species recorded in Chile.

Taxonomic group	Algal species involved	Year of event	Approximate area affected	Effects	Source
Dinophyceae	*Alexandrium catenella*	1972, 1981, 1989, 1991, 1994, 1995–2002	42°S–55°S	Toxic, source of PSP*	Guzmán *et al.* (2002), Molinet *et al.* (2003)
	Dinophysis acuta	1970, 1979, 1986, 1991, 1993, 1994	41°S–46°S	Toxic, source of DSP*	Lembeye (1994), Suárez *et al.* (2003)
	Prorocentrum micans	1983	41°S–43°S	Fish mortality	Lembeye and Campodónico (1984)
	Gymnodinium cf. *clorophorum*	1989, 2003, 2005	41°S–43°S	Loss of appetite in aquaculture fish	Iriarte *et al.* (2005)
	Gymnodinium spp.	1999	42°S–54°S	Benthic and pelagic resources mortality	Clément *et al.* (2001), Uribe and Ruiz (2001)
	Potentially harmful species present in Chile†: *Alexandrium ostenfeldii*, *Dinophysis acuminata*, *Dinophysis fortii*, *Dinophysis rotunda*, *Dinophysis tripos*, *Gonyaulax polyhedra*, *Gymnodinium catenatum*, *Gymnodinium splendens*, *Prorocentrum gracile*, *Ceratium tripos*, *Ceratium furca*, *Scrippsiella trochoidea*, *Noctiluca scintillans*.				Avaria (1992)
Diatomophyceae	*Pseudo-nitzschia*	1993, 1997, 1999, 2000	27°S–30°S and 41°S–43°S	Toxic, source of ASP*	Clément and Lembeye (1993), Suárez *et al.* (2003)
	Leptocylindrus minimus	1989, 1993, 1998	41°S–43°S	Behaviour change and mortality in aquaculture	Clément (1994), Rojas (1998), Seguel (1999)
	Chaetoceros convulutus	1991, 1995	41°S–43°S	Fish mortality	Rojas (1998)
	Chatonella	2004	41°S–43°S	Fish mortality	A. Clément (pers. comm.)
	Potentially harmful species present in Chile†: *Skeletonema costatum*				Rojas (1998), Seguel (1999)
Raphydophyceae	*Heterosigma akashivo*	1988	41°S–43°S	Salmonid mortality	Clément and Lembeye (1993), Rojas (1998)
Chrysophyceae	*Dictyocha speculum*	1995	41°S–43°S	Salmonid mortality	Rojas (1998)

*Shellfish poisons: PSP, paralytic; DSP, diarrhoetic; ASP, amnesic.
†Species present in Chile recognized as harmful in other parts of the world.

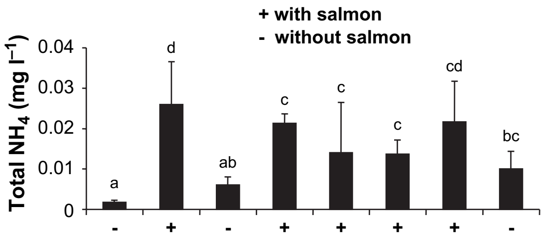

Figure 3. Ammonium concentrations (mg l^{-1}) in seawater along a 20-km channel (Calbuco, 41°47′S 73°12′W) at sites with (+) and without (−) salmon farms. Different letters denote significant ($p \leq 0.05$) differences between sites after a Tukey's test. The same letter indicates no significant difference between sites.

although, because there are no natural populations of salmonids in Chile, escapees should not have the genetic impacts on indigenous populations reported in the North Atlantic (e.g. Fleming and Einum, 1997; Gross, 1998; Youngson and Verspoor, 1998; McGinnity *et al.*, 2003; Roberge *et al.*, 2006). Ecological interactions have been reported between farmed Atlantic salmon escapees and native Pacific salmon species (Volpe *et al.*, 2000), and understanding the ecological effects that escapees have on native fish communities in Chile is a research priority. Although limited studies of the prey of escapees have been undertaken, existing studies indicate that benthic invertebrates are the main prey items.

Commercial fishing for salmon is prohibited in Chile, although illegal fishing does occur. It has been proposed that fishing for salmon by craft fishers could be used to reduce the impact of escaped farmed fish (Soto *et al.*, 2001), although efforts to recapture escapees in the 1980s were unsuccessful. It has been suggested, however, that

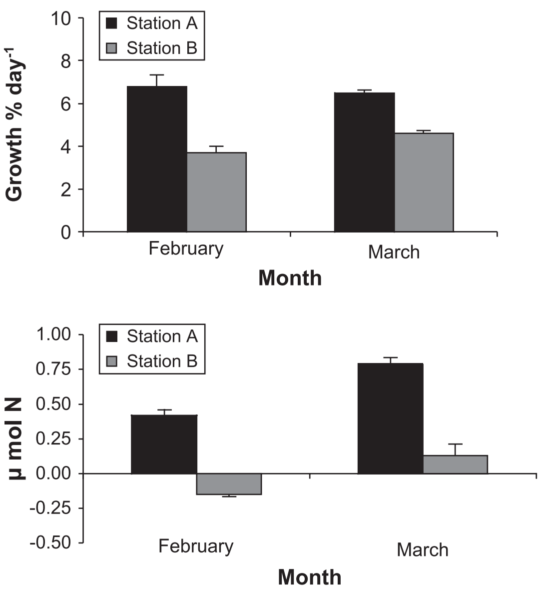

Figure 4. Growth rate (top) and nitrogen content of tissue (bottom) for the red algae, *Gracilaria chilensis*, cultivated on suspended longlines at sites with salmon farms (Station A) and at control sites 1000 m away from the salmon farms (Station B). The experiment was replicated in two different seasons with the same results but of different intensity as a result of variability in local environmental conditions. Data from Troell *et al.* (1997). The figures present mean values and standard errors ($n = 10$).

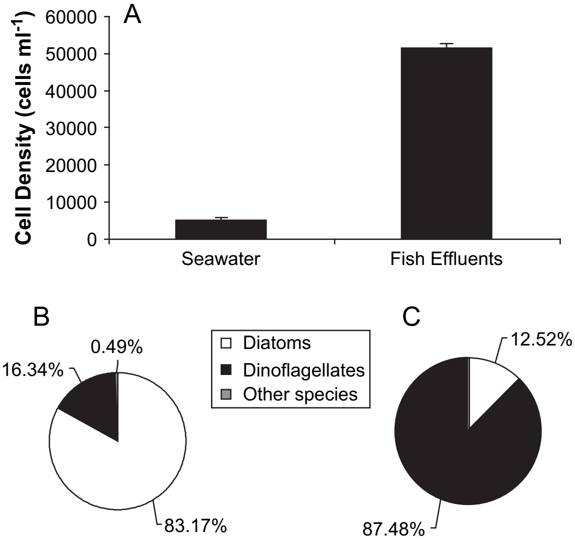

Figure 5. Experimental induction of algal blooms in 1500-l outdoor tanks using water pumped directly from salmon rearing tanks and from the sea. (A) Phytoplankton cell density after a 15-d cultivation period ($n = 5$), (B) the proportion of the different taxonomic groups of algae present in tanks fed by salmon farm effluent, and (C) pumped seawater (AHB, unpublished data).

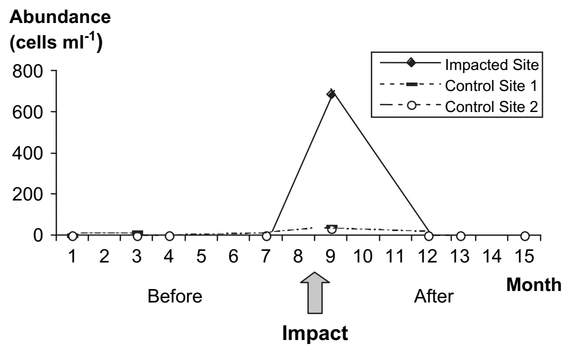

Figure 6. Changes in dinoflagellate abundance at a salmon farm site producing 100 t and at two control areas without salmon farms in the months before and after the installation (arrow) of the farm in Metri Bay (41°36′S 72°42′W). The sampling protocol involved the impacted site and two control areas located 1.5 km from the impacted site. Three samples were taken at the farm site and three in each control site during each sampling period. Each sample consisted of an integrated sample taken at 1, 6, and 12 m depth with a Nansen bottle. The data were analysed with SAS following the method of Underwood (1994).

Table 2. ANOVA table for the detection of the effects of salmon farms on dinoflagellate abundance. The design allows for the detection of human impact when presenting a significant interaction between the control and the potentially impacted location and times and/or periods of sampling (see analysis after Underwood, 1994). The statistical analysis was performed with PROC GLM from SAS 6.12 for Windows. B = effect of the impact, T = effect of time, $T(B)$ = effect of time nested in impact, L = effect of the locality, BL = interaction between B and L, LT = interaction between L and T, and $LT(B)$ = interaction between L and $T(B)$.

Variation source	d.f.	SS	MS	F	p
B	1	0.2224	0.2224	8.67	0.0039
T(*B*)	6	1.1702	1.1702	4.56	0.0123
L	2	0.5644	0.5644	1.03	0.3857
I	1	0.4576	0.4576	1.78	0.2067
C	1	0.712	0.0712	0.28	0.608
BL	2	0.3815	0.1908	0.74	0.4965
BL:*BI*	1	0.3702	0.3702	14.43	0.0002
BL:*BC*	1	0.0113	0.0113	0.44	0.5086
LT(*B*)	12	3.082	0.2568	10.01	<0.0001
T(Bef) × *L*					
T(Bef) × *L*	3	0.0705	0.0235	0.92	0.4356
T(Bef) × *C*	3	0.2339	0.078	3.04	0.0318
T(Aft) × *L*					
T(Aft) × *I*	3	2.7213	0.9071	35.35	<0.0001
T(Aft) × *C*	3	0.0564	0.0188	0.73	0.5348
Residual	120	3.0792	0.0257		

a legal fishery for escapees will encourage premeditated destruction of net pens to increase the availability of fish to support the fishery. The lack of clear evidence about the environmental impact of escapees and the absence of political support for a fishery targeting escapees (Buschmann *et al.*, in press) suggest that this management tool is unlikely to be introduced.

Other impacts of salmonid farming

Salmonid farms can alter the natural transmission dynamics of sea lice to wild juvenile salmon with infestation pressures four orders of magnitude greater than the natural ambient level (Krkošek *et al.*, 2005). In Chile, preliminary data indicate that salmon farming can increase sea louse infestations on native fish populations (Sepúlveda *et al.*, 2004).

The abundance of marine birds is also affected by the presence of salmon farms, with the observed abundance of omnivorous diving and carrion-feeding birds increasing twofold to fivefold in some areas with salmon farms (66.2−77.2 birds h^{-1}) compared with control areas without them (13.8−31.0 birds h^{-1}). However, the top-down ecological consequences of these changes remain unstudied. In addition, the effects of salmon farms on marine mammals have not been evaluated. The South American sea lion, *Otaria flavescens*, frequently attacks salmon farms, although the frequency of attacks varies markedly and is not correlated with the proximity of the nearest sea lion colony (Sepúlveda and Oliva, 2005). It is important that the impacts of salmon farms on marine mammals be considered in future research.

Table 3. Official reported biomass of salmonid escapees (t) in southern Chile.

Year	Biomass (t)	Source
1993	1 170	Soto *et al.*, 2001
1994	1 721	Soto *et al.*, 2001
1995	875	Soto *et al.*, 2001
1996	315	Soto *et al.*, 2001
1997−2003	No data	—
2004	309	Sub-secretary of fisheries
2005	1 883	Sub-secretary of fisheries

Conclusions

Salmon farming is one of the most important economic activities in Chile, but its development has environmental impacts (Buschmann and Pizarro, 2001) that should be taken into account in regulating the industry. Further research is urgently required in Chile to increase understanding of these impacts, especially if the industry is to expand to the far south, a pristine coastal area that needs a sound conservation policy. It is important that a balance is maintained between further aquaculture development in Chile and environmental conservation through the development of integrated cultivation of extractive (i.e. macroalgae and filter-feeders) and fed organisms (fish) in the same waterbodies (e.g. Buschmann *et al.*, 2001; Chopin *et al.*, 2001; Troell *et al.*, 2003; Neori *et al.*, 2004). Ideally, Chile's low level of research capacity should be increased to improve current understanding of aquaculture−environment interactions.

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