FINAL REPORT

NUTRIENT IMPACTS OF FARMED ATLANTIC SALMON (*Salmo salar*) ON PELAGIC ECOSYSTEMS AND IMPLICATIONS FOR CARRYING CAPACITY

Report of the Technical Working Group (TWG) on Nutrients and Carrying Capacity of the Salmon Aquaculture Dialogue

Salmon aquaculture farms in southern Chile
(photo by Dr. A. Buschmann, Universidad de los Lagos).

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Executive Summary: Conclusions and Recommendations of this Study

The three most important factors determining the impact of salmon farming on water column nutrients, water quality, and pelagic ecosystems are the:

1. loading rate of inorganic nutrients, especially nitrogen for marine systems and phosphorus for freshwater ones, the hydrodynamics and depths of cage sites,
2. morphometry and topography (degree of "openness") of bays and the nearshore coastal areas, and,
3. stocking density of fish (local scale) and the density of fish farms (regional scale).

Of these three factors, the most important driver of impacts on pelagic nutrients, water quality, and pelagic ecosystems is ***hydrodynamics***. In stagnant waters, for example, the nutrient concentration following one day of nutrient releases from a modern salmon farm producing 1000 metric tons of fish annually would correspond approximately to a typical spring bloom event in North Atlantic waters, which is a dissolved inorganic nitrogen (DIN) concentration of about 140 mgN/m^3.

Excess inorganic nitrogen from salmon cages is available immediately for phytoplankton uptake with no delay. However, it takes 3-7 days between inorganic nutrient releases and observations of phytoplankton biomass increases, so hydrodynamics of a site are a very important aspect of determinations of impact to the pelagic ecosystem. Only stagnant sites will exhibit increased phytoplankton biomass locally.

Peak soluble nutrient loadings to marine environments from salmon cage aquaculture for a particular growing region are ***seasonal***, since highest feed inputs are delivered when salmon growing temperatures promoting the fastest growth rates occur.

Dissolved inorganic nitrogen (DIN) and phosphorus (DIP) are most important drivers of change to pelagic ecosystems, while particulate organic nitrogen (PON) and phosphorus (POP) from feces and feeds are the major drivers of benthic ecosystem change. As we demonstrate in this review (Chapter 1), release rates of DIN and DIP can be calculated with some degree of accuracy. Inorganic nutrient fractions mix with very high ambient DON and DOP concentrations in aquatic environments. While excess inorganic nitrogen from salmon cages is available immediately for phytoplankton uptake with no delay, dissolved organic nutrients are characterised by relatively long turnover times in seawater (greater than a year). With the potentially large quantity of fines being added to marine ecosystems from salmon cage aquaculture, the fate of these components of the pelagic ecosystem is unknown but can be considered unimportant since heterotrophic bacteria can utilise these compounds readily and rapidly (however, changes to the marine pelagic heterotrophic food web by salmon cage aquaculture are little known).

Salmon cages extend to 15 m depth (12-20 m). It is assumed that all the inorganic nutrients are released to the marine mixed layer thereby becoming available for uptake

by phytoplankton. There is a ***dramatic increase in sedimentation rates*** from salmon cage aquaculture following salmon feeding (feed wastes and feces). Waste feed and feces sink relatively rapidly and affect the immediate site area, but particles formed by primary production will sink further away from the site because it takes 3-7 days between inorganic nutrient releases and uptake and increased phytoplankton biomasses.

Sedimentation rates are non-linear; there is a high amount of sedimentation to primary production, likely indicating the marine planktonic ecosystem is no longer able to assimilate the enhanced nutrient inputs from salmon cage aquaculture, and reflecting the fact that the zooplankton grazers at some point of input are not able to consume and efficiently remove the enhanced primary production near the salmon cages.

There is ***little scientific evidence*** outside of limited laboratory studies and one field report from Chile that nutrient loading from salmon farming is sufficient to initiate and sustain harmful algal blooms (HABs). However, nearly all of the rigorous pelagic ecosystem science related to HABs has occurred outside of the areas directly influenced by salmon farms.

The ***pelagic ecosystems of some Chilean lakes in the Chiloé region are heavily impacted by salmon farming*** due their small size, shallow depths, and low water exchange rates. Larger lakes in the northern Patagonian region having a fewer number of farms have experienced more localized impacts on the lake water column.

Recommendations for priority research

Greater understanding of the impacts of open water, salmon cage aquaculture will be achieved by the *improved* ***development and widespread use of advanced three dimensional hydrodynamic modeling*** to estimate the mean volumetric loading rates of limiting nutrients to follow the spread and fate of excess inorganic nutrients from salmon farms. Hydrodynamic modeling is particularly important regionally — and especially in areas with many salmon farms in the same body of water. Modeling is especially important in Chile where little advanced hydrodynamic modeling of the cumulative impacts of multiple salmon farms in the same water body (higher densities) has been done. Impacts of salmon aquaculture on marine pelagic nutrients, water quality, and pelagic ecosystems can be ameliorated by ***scientific determinations of farm siting***. The density of farms (i.e., number, size, proximity) should thereby incorporate ***advanced, three dimensional hydrodynamic modeling*** to scientifically determine site selection. Improved site selection and better determinations of nutrient flux could ensure that the natural assimilative capacity of the water column is neither exceeded nor changed so significantly that essential pelagic ecosystem functions are compromised.

Greater quantitative understanding of nutrient dose-phytoplankton response relationships, and how these relationships change with hydrodynamic conditions (e.g. see Figure 2, Chapter 2) are needed. This knowledge will improve the ability to determine the ability of the pelagic ecosystem to assimilate nutrient inputs, which is a function of the volumetric loading rates of inorganic nitrogen and water currents.

More research is needed —especially field studies — to answer the concerns that elevated *nutrients within densely-crowded salmon farming areas with limited flushing can promote the establishment of new harmful algal bloom (HAB) seed areas.* Additional field studies are needed since most aquaculture/HAB research has conducted in the laboratory, or using small scale mesocosms. Higher densities of salmon cages in poorly flushed areas could theoretically promote localized nutrient conditions that may be more conducive to enhancing populations of certain HAB species. Empirical studies and modeling for other fish species elsewhere (in coastal areas of China) do suggest that a relationship exists between nutrient loadings from densely-packed aquaculture farms and initiation of HABs. Greater use of monitoring techniques such as satellite imaging is needed to better allow assessment of pelagic waters over a wider geographic scale to assess nutrient impacts from salmon cage farms.

With the dramatic increase in sedimentation rates from salmon cage aquaculture following salmon feeding, there are questions *if zooplankton grazers have an adequate capacity to consume and efficiently remove the enhanced primary production* near the salmon cages. A high amount of sedimentation to primary production is an indication that the marine planktonic ecosystem is no longer able to assimilate the enhanced nutrient inputs from salmon cage aquaculture.

Research is needed to continue the development of nutrient dense feeds to improve feed conversions, reduce the amount of fines in formulated feeds for salmon, and especially to quantify the ranges of digestibilities for each component of the most commonly used salmon feeds in the major farming regions of the world. There is a need for research on the amount of fines entering marine pelagic ecosystems from salmon farming and their ecological impacts.

Research is needed to better understand fecal mass faction settling rates from salmon cage aquaculture in relationship to the most commonly used feed formulations by industry.

Other recommendations

More research in the major salmon farming regions is needed on new, more integrated commercial approaches to aquaculture ecosystem design, planning and operations by combining more detailed knowledge of social and economic systems and innovative, "green" marketing approaches ("sustainable seafoods") with technological innovations in salmon aquaculture. FAO is developing guidelines for an "ecosystem approach to aquaculture" whose adoption by the salmon farming industry might yield beneficial economic, social, and environmental impacts.

Lastly, the TWG agrees that additional marine environmental research associated with salmon aquaculture requires urgent attention in Chile, especially since the salmon industry plans to continue expanding south, toward one of the few remaining pristine, biologically unique, and poorly studied coasts of the world. Salmon aquaculture in Chile is very different from its counterparts in northern parts of the world. Salmon farming in Chile is a highly concentrated activity where wastes from different farm sites have a

much greater potential to interact, with potentially greater alterations to pelagic marine ecosystems, and possibly compromising rich, complex environmental systems. In addition, Chile is now one of the world's largest aquaculture producing countries but has produced only an estimated 2% of the world's aquaculture-environment studies. Multidisciplinary research approaches, including oceanographic and ecological studies, together with ecosystem modeling are urgently needed in Chile.

Objectives and background of the study

The objectives of the nutrients TWG were to: (1) review status of current research and understanding of issues; (2) identify existing research efforts and key research groups; (3) identify significant gaps and/or areas of disagreement; and (4) recommend scope, time frame and costs for addressing gaps.

Background

The World Wildlife Fund (WWF) initiated a series of Aquaculture Dialogues on a number of globally important aquaculture species. Dialogues are species or species-group specific gatherings of a wide range of stakeholders including producers and other members of the market chain, researchers, NGOs, government officials, and investors. The goal of each dialogue is to agree on the main impacts of production of the given species group globally, identify better management practices that reduce those impacts to acceptable levels, and develop performance-based standards that can be used in government permitting processes, investment and buyer screens, and as the basis for a certification program.

WWF initiated the Salmon Aquaculture Dialogue in early 2004 and the initiative has since met eight times in various locations around the world (http://worldwildlife.org/aquadialogues). A nine member steering committee was formed consisting of representatives from industry and NGOs in the major producing countries. Over 250 individuals have participated in the Salmon Dialogue in some form.

Participants agreed upon key impacts and drafted and agreed to goals and objectives for the dialogue. The dialogue identified seven key areas of impact associated with salmon farming and is in the process of forming technical working groups of researchers to draft state of information reports on each of these areas of impact. The reports will identify specific areas where there is scientific consensus, areas where there is disagreement among scientists, and will pinpoint key gaps in the research. The Salmon Dialogue will seek to obtain funding for key gaps in the research that were identified by the technical working groups. The state of information reports produced by the technical working groups will serve as a scientific basis for developing standards.

The seven key areas of impact are:

- Escapes (inter-breeding with wild fish, establishment of escapees in wild)
- Feed (use of fishmeal and fish oil in feeds, feed conversion ratios)
- Disease (transmission of parasites or viral infections between farmed and wild fish)

- Chemical inputs (use of antibiotics, anti-foulants, anti-sea lice medications)
- Benthic impacts and siting (formation of anoxic sediments under farms)
- Nutrient loading and carrying capacity (eutrophication, cumulative impacts)
- Social (impacts on local communities, worker rights)

This report summarizes the state-of-the art knowledge on nutrient loadings by commercial salmon aquaculture in the major farming regions of the world and impacts on the pelagic marine and freshwater Chilean lake ecosystems. Comparison of nutrient additions with farming regions and issues of aquaculture eutrophication are covered. We also review the state of knowledge in nutrient mitigation and treatment technologies for nutrient management in salmon farming. This report has an Executive Summary and five chapters on: (1) nutrient releases from salmon aquaculture; (2) the impact of salmon aquaculture on pelagic ecosystems; (3) pelagic nutrient and ecosystems impacts of salmon aquaculture in Chile, with emphasis on dissolved nutrient loading and harmful algal blooms; (4) salmon aquaculture and harmful algal blooms (HABs); and (5) nutrient impacts of salmon aquaculture on Chilean lakes. Each chapter has a summary and recommendations for future research needs.

Chapter One: Nutrient Releases from Salmon Aquaculture

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Introduction

Nutrients such as carbon, phosphorus and nitrogen are essential for life. Sugars require carbon, proteins require nitrogen and DNA requires phosphorus. These are but a few examples. These particular elements occur naturally in the water column of both fresh and marine environments. At optimal concentrations these nutrients facilitate healthy ecosystems. When these nutrients are present in excess, they may act like pollutants. Whether a nutrient becomes a pollutant in an aquatic system, is a function of whether it is a limiting nutrient[1] in a given environment and the magnitude of its concentration. In fresh waters, phosphorus is typically the limiting nutrient (Hudsen, Taylor and Schindler, 2000) so its addition will dictate the amount of primary production (algal growth). In marine environments, nitrogen is typically the limiting nutrient (Howarth and Marino, 2005), so its addition will do likewise. Algal booms that occur in high nutrient waters will reduce water clarity (and consequently sunlight availably in the water column to other organisms), and can strip oxygen from the water column when the organisms die, sink and decompose (Wetzel 1983). These effects are conditions of eutrophicaton. Since nitrogen and phosphorus are loaded from fish cages, there is always the potential for fish culture to promote eutrophic conditions; either by supplying a readily available nutrient source directly to phytoplankton; or oxygen removal, accompanied by nutrient releases, via the decomposition of waste solids.

[1] All physical and chemical components necessary for growth (e.g. food, sunlight) are available 'in excess' except for one key component (e.g. a specific nutrient), which by default limits the amount of primary production.

To assess the potential for Atlantic salmon mariculture to cause adverse environmental impacts from nutrient loading; an understanding of the source of nutrient wastes is required. Practically all nutrient waste discharges for Atlantic Salmon aquaculture can be traced to dietary origin, and these are discharged directly into receiving waters under typical cage-culture practices. Figure 1 illustrates the flow and fate of nutrients in a cage aquaculture system.

The following chapter discusses and examines quantitative and qualitative properties of nutrient wastes from Atlantic salmon aquaculture and implications for environmental nutrient loading. Methods for estimating solid (organic) and soluble (inorganic) nutrient waste from fish production (Cho and Bureau 1998; Bureau, Gunther and Cho, 2003; Papatryphon, Petit, Van Der Werf, Kaushik amd Kanyarushoki, 2006) are demonstrated.

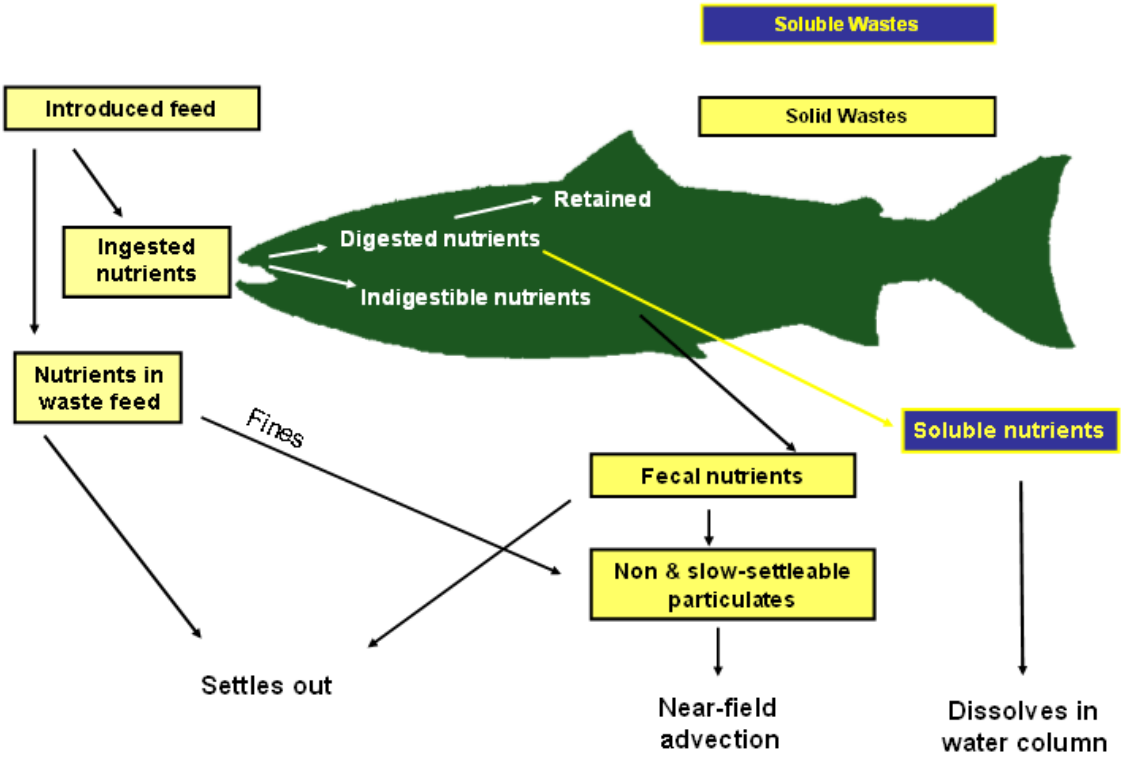

Figure 1: The flow and fate of nutrients in a cage aquaculture system

<u>Composition of modern day Atlantic salmon feed</u>

Complex nutrients (and some associated compounds) fall into several categories such as proteins, lipids (fats), fibre, ash and NFE (nitrogen free extract; mostly carbohydrates). The ratio of these complex nutrient groups is often referred to as the proximate composition[2] (Hardy and Barrows 2002, Lovell 1989). Each group may be comprised of several ingredients. For example, the total protein component may be composed of

[2] Derived from composition of categories in proximate analysis

several ingredients such as fish meal, soybean meal, casein, blood meal, or corn gluten meal (Cho and Bureau 2001, Wilson 2002), or other sources. Each ingredient will also have its own energy content and digestibility. Ingredients may or may not be detailed on feed bags (or totes) depending on regional regulations and the manufacturer. Listing the proximate composition is fairly standard practice (Figure 2).

ALIMENTO PARA SALMONIDOS - TABLA DE NUTRIENTES GARANTIZADOS.

Alimento	Calibre	Uso recomendado para peces desde g	Proteína Cruda % Mín.	Grasa Total % Mín.	Humedad % Máx.	Cenizas % Máx.	Fibra Cruda % Máx.
EWOS® micro	10	> 10	40,0	24,0	10,0	11,0	2,0
EWOS® transfer boost	20	> 20	47,0	19,0	10,0	11,0	2,0
EWOS® transfer boost	50	> 50	47,0	19,0	10,0	11,0	2,0
EWOS® transfer boost	100	> 100	45,0	21,0	10,0	11,0	2,0
EWOS® transfer boost	250	> 250	43,0	23,0	10,0	11,0	2,0
EWOS® transfer	20	> 20	47,0	19,0	10,0	11,0	2,0
EWOS® transfer	50	> 50	47,0	19,0	10,0	11,0	2,0
EWOS® transfer	100	> 100	45,0	21,0	10,0	11,0	2,0
EWOS® transfer	250	> 250	43,0	23,0	10,0	11,0	2,0
EWOS® omega	600	> 600	39,0	28,0	10,0	10,0	2,0
EWOS® omega	1500	> 1.500	35,0	30,0	10,0	10,0	2,0
EWOS® omega	2500	> 2.500	35,0	30,0	10,0	10,0	2,0
EWOS® omega	3500	> 3.500	33,0	32,0	10,0	10,0	2,0
EWOS® van	600	> 600	40,0	24,0	10,0	10,0	2,0
EWOS® van	1500	> 1.500	39,0	25,0	10,0	10,0	2,0
EWOS® van	2500	> 2.500	37,0	26,0	10,0	10,0	2,0
EWOS® gamma	600	> 600	41,0	25,0	10,0	10,0	2,0
EWOS® gamma	1500	> 1.500	40,0	26,0	10,0	10,0	2,0
EWOS® gamma	2500	> 2.500	37,0	27,0	10,0	10,0	2,0
EWOS® boost	600	> 600	39,0	28,0	10,0	10,0	2,0
EWOS® boost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Figure 2: Chilean salmon feedbag label (courtesy of Jose-Luis Iriarte, Universidad Austral de Chile, Chile)

Table 1 shows the proximate composition, of a typical modern Atlantic salmon feed. Nutrient ratios and feed pellet sizes reflect the dietary requirements of different sized fish (Figure 3). High quality proteins and lipids (fats) figure prominently in these diets; ranging from 35-50% and 25-40% respectively. Protein levels were traditionally much higher in the developing stages of intensive salmon aquaculture. The inclusion amount of protein at that time exceeded the minimal amino acid[3] requirements of the animal (Lovell 2002). The 'extra' protein was metabolized for other energetic processes in the fish. During the last decade however, there became a need to reduce protein reliance and specifically fish meal, a significant portion of the overall protein[4]. The amount of protein was consequently reduced with the 'extra' protein replaced by lipids; a process called 'protein sparing' (Wilson 2002). In this way, the minimum amino acid requirements were met, while the increased lipids helped supply the additional energy requirement for growth and other metabolic processes.

[3] Proteins are made up of amino acids

[4] See Tacon (2005)

Table 1: Estimation of fecal composition and the amount produced from the consumption of a typical Atlantic salmon feed[1] for grow out sized (>2000g) fish

	Proximate composition (%[2])	Digestibility[3] (%)	Amount Digested (%)	Amount in faces (%)
Protein (min)	39	90	35.1	3.9 [4]
Fat (min)	33	95	31.4	1.7
NFE[5] (max)	10	60	6.0	4.0
Fibre (max)	1.5	10	0.15	1.35
Phosphorus (approx.[6])	1.2	50	0.60	0.6
Minerals[7] (max)	6.8	50	3.4	3.4
Moisture (max)	8.5			
Total	100			14.9

[1] Optiline 2000 (used on Canada's west coast). Data provided courteously of Skretting
[2] Same as g/100g feed
[3] Protein and fat digestibility are within ranges provided by Skretting. Minerals, phosphorus, fibre and NFE based on Apparent Digestibility Coefficients (Bureau *et al.* 2003) of salmonids (salmon, charr and trout).
[4] The amount of nitrogen in the feces is 0.624% (indigestible protein/ 6.25). This is the same as 6.24 g N/ kg feed fed; or 6.86 g N/ kg growth, with a biological FCR of 1.1
[5] Nitrogen Free Extract: primarily carbohydrates
[6] Phosphorus estimates for Optiline 2000 are based on analysis of 11mm Orion salmon feed (Peterson, Sutherland and Higgs 2005); a Moore-Clark feed prior to takeover by Skretting.
[7] This mineral value (ash) does not include phosphorus (row above). The Skretting supplied value (all minerals) was adjusted (minus phosphorus) accordingly.

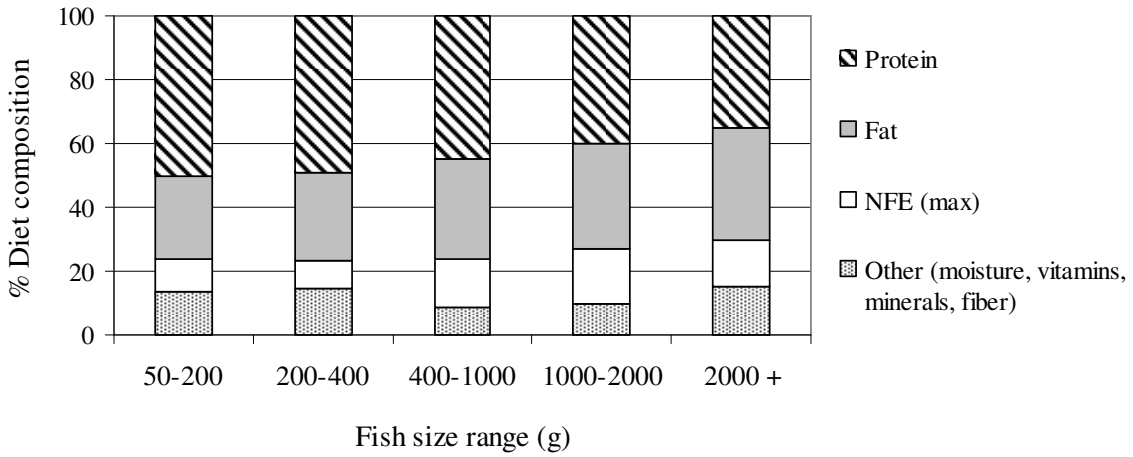

Figure 2: Mean dietary composition vs. fish size. Derived from feed composition data (courteously of Skretting)

Salmon require over a dozen vitamins in their diet to ensure good health and optimal growth (Lovell 2002). Vitamins that are not included in sufficient dietary levels beyond their incidental association with other feed ingredients are added via 'vitamin premixes' (Hardy and Brown 2002). Salmon can absorb some essential minerals[5] from the water column, but others must be supplemented in the diet; such as copper, iodine, selenium and zinc (Lovell 2002).

Solid nutrient waste

Solid aquaculture waste is made up of uneaten feed pellets (which may be accompanied by fine particulates, the 'fines') and fecal material. The physical properties and chemical composition of the solid waste will in part dictate the potential for environmental impact. Figure 1 illustrates the route of solid waste generation in fish culture.

Fecal composition

Fecal waste is the largest contributor to solid waste generation from modern intensive fish culture. The amount and relative composition of fecal material will be determined by the indigestible components of the diet. Calculating fecal waste is relatively straight forward with information on the proximate composition and associated digestiblities. What is eaten but not digested will become feces.

As with complex macronutrients, not all minerals (micronutrients) will be digested and portions will end up in the feces. The deposition of metals such as dietary copper and zinc has lead to some concerns, since under certain concentrations and conditions these can be toxic in the environment. The potential for minerals as well as unintentional

[5] Associated with 'Ash' in proximate composition analysis

contaminants incorporated into the feed (*e.g.* PCBs), and possible adverse effects on health and the environment are addressed in another WWF Salmon Aquaculture Dialog document.

Feed loss

Feed loss has long been cited as a major contributor to waste generation from commercial salmon farms. In the pioneering days of intensive salmon aquaculture, waste feed was a significant contributor of solids exiting fish cages. Early estimates of feed loss in open cage aquaculture were around 20% (Beveridge 1987). Feed loss has been reduced significantly in recent years, in part due to improved waste pellet detection mechanisms such as machine vision (Ang and Petrell, 1997; Parsonage and Petrell, 2003) that prompts cessation of feed delivery upon detection of waste pellets. It is estimated that due to such technologies, feed wastage is routinely below 5% (Cromey, Nickell, and Black, 2002). The actual percentage of feed loss however is difficult to determine since it can vary from operation to operation and even from day to day. Some salmon nutrient, loading and dispersal models use waste feed values between 3% (Cromey *et al*. 2002) and 5% (Bureau et al. 2003). Using a mass balance method of calculating the composition and quantity of faecal waste (detailed in the following section); a waste feed loss of 3% will comprise approximately 12% of the total solid waste from a typical Salmonid feed. The majority of solids lost from intensive cage aquaculture of salmonids will be of faecal origin.

Fines

As feed is shipped, small particulates called 'fines' may brush off pellets and settle in feed bags or totes. This is undesirable as fines are too small to be consumed by the fish and it becomes essentially waste. In the early stages of the industry loss due to fines generation could be significant. Modern pellet extrusion techniques have now reduced this substantially and it is recommend practice to guaranteed feeds with maximum acceptable level of fines (FAO 2002; Tacon and Forster, 2003). Nevertheless, excessive 'handling' can generate fines (Miller and Semmens 2002) and consequently a great deal of effort has gone into feed delivery mechanisms to minimize the generation of fines. Fines are typically included under the classification of 'waste feed'. While the mass of fines is likely small relative to overall feed inputs and feed wastage, there is little in the published literature that addresses the amount of fines entering the water.

Estimation of solid nutrient loadings

A 'nutritional mass balance approach' can be used estimate fecal mass and composition (Cho and Bureau 1998; Bureau et al. 2003, Papatryphon *et al.* 2006). Each dietary component has an associated digestibly. What is consumed but not digested will exit in the feces. Multiplying the percent digestibility[6] by the proximate amount will estimate the amount digested. The difference between the level of inclusion in the feed and the amount digested will be manifested in the feces. Summating the amount of each

[6] Referred to as the apparent digestibility coefficient (ADC) in nutritional literature

indigestible dietary component will determine the overall percentage of feces produced per unit feed consumed. Applying this approach with a common salmon feed in table 1; approximately 15% of consumed feed becomes dry fecal mater. Note that this estimate must be combined with feed loss estimates to get the total solid waste amount generated by a fish farm. Therefore if 98.5% of the feed is consumed (with 15% of consumed feed becoming feces; 14.8% of total), the total solid waste will be 17.3% of feed entering the water. This approach may also be used to calculate specific micronutrient loss to the environment.

Physical properties

The physical properties of solid waste have important implications for dispersal from fish cages. Heavier and denser solid waste such as feed pellets and large fecal particles will settle below cages. Smaller particulates may remain suspended in the water column for a time and consequently dispersed beyond the cage periphery (see Chapter 3).

Predicting where waste solids will settle is a key step to modeling the potential for benthic impacts. Accurate data on settling velocities is required. Settling velocities of feed pellets are rapid and not highly variable (Chen, Beveridge, Telfer and Roy, 2003). However, fecal pellets are irregularly shaped and therefore typical equations used to estimate settling velocities of particles do not work well with fish feces[7] (Elberizon and Kelly, 1998). Settling velocities for Atlantic salmon feces have been reported to range from 3.2 – 6.4 cm/s (Chen, Beveridge and Telfer, 1999; Chen *et al.* 2003; Cromey *et al.* 2002). This range in sinking rates may in part be due to differences in testing methods. However, feed properties and water density also appear to play a significant role. Diet is known to affect fish fecal composition[8], fecal density (Amirkolaie, Leenhouwers, Verreth and Schrama 2005; Brinker, Koppe and Rösch 2005; Ogunkoya , Page, Adewolu and Bureau 2006) and consequently settling rate. An increase in salinity appears to decrease fecal settling velocity (Chen *et al.* 1999).

Most studies test individual fecal pellets and report ranges or variable means of fecal settling rates. However, it is also important to know the settling rates of different mass fractions of the total fecal mass including fine particulates and what proportion is non-settleable. For example, what proportion of fecal mass settles at 3.2 cm/s versus the proportion that settles at 6.4 cm/s? In addition to dispersion modelling, such data will become increasing important as Integrated multi-trophic aquaculture (IMA) develops (Troell, Halling, Neori, Chopin, Buschmann, Kautsky and Yarish 2003); where co-cultured filter feeders need to be placed in optimal locations to siphon appropriately sized particulates. While some investigation has occurred with mass fraction settling curves of rainbow trout faeces in freshwater (Wong and Piedrahita, 2000; Moccia, Bevan and Reid, 2007); this data does not appear to be available for Atlantic salmon in marine systems[9]. It would be useful to measure mass fraction fecal settling rates as new diets are

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[7] Stoke's law assumes spherical shape

[8] Changes in digestibility will affect the amount in feces

[9] Typically a mean settling rate with a standard deviation is reported, not settling rates of specific mass fractions

developed and culture conditions change. The ratio of settleable to suspended solids specifically in cage culture settlings also appears to be largely unknown. Such information would help to predict the fate of solid nutrient waste in receiving waters.

Soluble nutrients

Nutrients that have been digested (absorbed through the intestine wall) are either excreted as metabolic by-products or excreted because the amount digested exceeds metabolic requirements. Soluble nutrients will dissolve in the water column; their initial dilution and transport a function of current dynamics.

Excreted nitrogen is a by-product of protein metabolism. Salmon excrete nitrogen in the form of ionized ammonia (ammonium, NH_4+) through the gills, and urea to a lesser extent in the urine. Phosphorus is excreted as orthophosphate (PO_4+). These forms of nitrogen and phosphorus are readily available to phytoplankton (micoalgae). The amount of phosphorus excreted in salmonids is proportionate to the amount digested in excess of metabolic requirements (Bureau and Cho 1999). The primary by-products of lipid metabolism are water and carbon dioxide; these are not typically considered as part of the nutrient load.

Estimation of soluble nutrient load

The amount of soluble nutrients excreted, equals the amount of nutrient digested minus the amount retained in the fish carcass. While conceptually straight forward, the estimation of soluble nutrient loads are somewhat more difficult than fecal estimates since in addition to feed consumption and digestibility data, growth and carcass retention data are required. Nevertheless, there are a number of carcass retention values in the scientific literature and lab analysis can determine proximate carcass composition for greater accuracy. Table 2 shows the estimation of soluble nitrogen and phosphorus from a typical salmonid feed. It is important to note that this estimates a mass of soluble material only and cannot infer the resultant concentration of the nutrient once it dissolves in the water column. Water volume data (or flushing rate) is required to determine concentration. It is the *concentration* of the limiting nutrient that ultimately dictates primary productivity not simply the *amount* of material. This is discussed in chapter 3.

Table 2: Estimation of soluble nutrient load from Atlantic salmon consuming a typical commercial feed[1]

	Feed composition (%)[2]	Digestibility (%)	Amount digested (%)	Carcass composition[3] (%)	Retained in growth (%) from 1.1 FCR[4]	Not retained[5] (%)	Nitrogen[6] (%)
Protein	39	90	35	18.5	16.8	18.3	2.9
Phosphorus	1.2	50	0.60	0.55	0.50	0.10	

[1] Optiline 2000 (Western Canada). Data provided courteously of Skretting

[2] Same as g/100g of feed

[3] Protein (mean of: Einen and Roem, 1997; Opstvedt et al., 2003 and Skretting supplied valued), phosphorus (Åsgård and Shearer 1997)

[4] Growth of 90.9 kg from 100 kg of feed consumed would be expected with an assumed biological FCR of 1.1; or 100 kg of growth would require 110 kg of feed consumed.

[5] The nitrogenous component (from protein) is composed mostly of ammonia and small amounts of urea.

[6] Calculated using the average protein to nitrogen ratio of 6.25. Excretion is approximately 29 g N / Kg feed consumed or 32 g N / kg of growth. To estimate the mass of ionized ammonia, multiply the % nitrogen value by 1.57

Factors Affecting Nutrient Loading and Other Considerations

Feed Conversion Ratio

Feed conversion ratio or FCR is a commonly used measure in the aquaculture industry to assess the efficiency of growth relative to feed used. Despite its common usage there are several different ways in which FCR can be calculated. The two most commonly used FCRs are 'Economic' FCR which equals, feed purchased / biomass harvested [also called 'Effective' FCR (Stucchi, Sutherland, Levings and Higgs; 2005)], and 'Biological' FCR which equals feed consumed / fish growth (Nordgarden, Oppedal, Taranger, Hemre and Hansen 2003). Occasionally a 'dry' FCR is used where the weight of water is excluded from the feed and/or biomass values (Einen and Roam 1997; Hardy and Barrows 2002; Islam 2005). It is therefore important to understand what has or has not been included in the calculation.

Over the last decade, advances have been made in the salmon aquaculture industry to improve economic FCR. In 2003, world production of salmonids was 1.46 million tonnes (FAO 2005) and the aquafeeds used was 1.9 million tonnes (Tacon 2005). This makes global Salmonid, economic feed conversion about 1.3 in 2003 (the last year of available Salmonid aquafeed consumption data). This is a significant improvement from the previous decade where in 1993, salmonid production was 0.3 million tonnes and aquafeed production was 0.5 million tonnes (FAO 2005); a global economic FCR of 1.7. These are average values however, and it should be noted that there are some regional differences. For example, average FCR in Norway is reported to be 1.1 and in Chile; an FCR of 1.3 (Leyton 2003).

Reduction of feed loss and improvements in nutrient conversion efficiency will reduce (improve) economic FCR. Mortalities and escapes may reduce the production of harvestable biomass; causing an increase (worsen) in FCR. FCR is also affected by fish size (Lovell 1989; Einen amd Roem 1997; Reid and Moccia 2007) and consequently the growth period duration in which measurements are taken[10]. As such, it is not always possible to attribute changes in economic FCR to a specific factor. Nevertheless, assuming similar fish sizes are produced from year to year; improvements in global economic FCR of Salmonid production, do suggest an overall increase in industry efficiency converting nutrients from fish feed to harvestable biomass. Regardless of whether lost nutrients are partitioned as faeces, waste feed; or sequestered in escaped or deceased fish.

While not all changes in economic FCR will necessarily be accompanied by changes in nutrient waste generation[11], there is a relationship between the two. All other factors being equal; increased feed loss or decreased feed digestion will generate more waste and consequently increase FCR (Cho and Bureau 2001). High FCRs have been linked to poor water quality (Kelly and Elberizon 2001). FCR by itself however, cannot reliably determine the amount of waste produced. A biological FCR (wet) of 1.1 does not mean that 91%[12] of the feed consumed is converted to body mass and 9% is therefore nutrient waste. Differences in water content of the

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[10] An FCR from a period, producing fish growth of 50-100g (75g average), will be less than a longer period, growing the same fish from 50-300g (175g average), due to lower FCRs of smaller fish.
[11] *e.g.* in cases where fish mortality reduces harvestable biomass
[12] The reciprocal of FCR (1/1.1 =90.9) shows the percent of growth relative to feed used.

fish (relating to fish size at different life stages) and feed do not make this a viable approach. Sometimes FCR is calculated using dry weights is used to assess feed conversion (Islam 2005), thereby avoiding the confounding effects of water. However, dry FCR alone, is not particularly useful for 'partitioning' nutrient waste, as it will also include losses of soluble carbon, oxygen (e.g. in carbon dioxide) and hydrogen. Nutrient composition and retention details are still required to determine the specific fate of nutrients. FCR is best used as a relative measure of production or nutritional efficiency and should not be used as a singular assessment of nutrient waste production.

Seasonal production

Fish are cold blooded, so under conditions of adequate food supply; temperature dictates metabolic rate and consequently growth rate. Each fish species has an optimal range of temperatures and typically grows faster at the warmer temperatures within their respective range. Salmon aquaculture therefore, has a production cycle that reflects changes in seasonal temperatures. Figure 3 shows typical seasonal feed inputs at a Norwegian salmon farm. The temperatures promoting the fastest grow rate occur in August for that particular region. The highest growth rates correspond with the highest nutrient loading periods. Peak soluble and solid nutrient loading also occurs in August; the proportions changing with feed input.

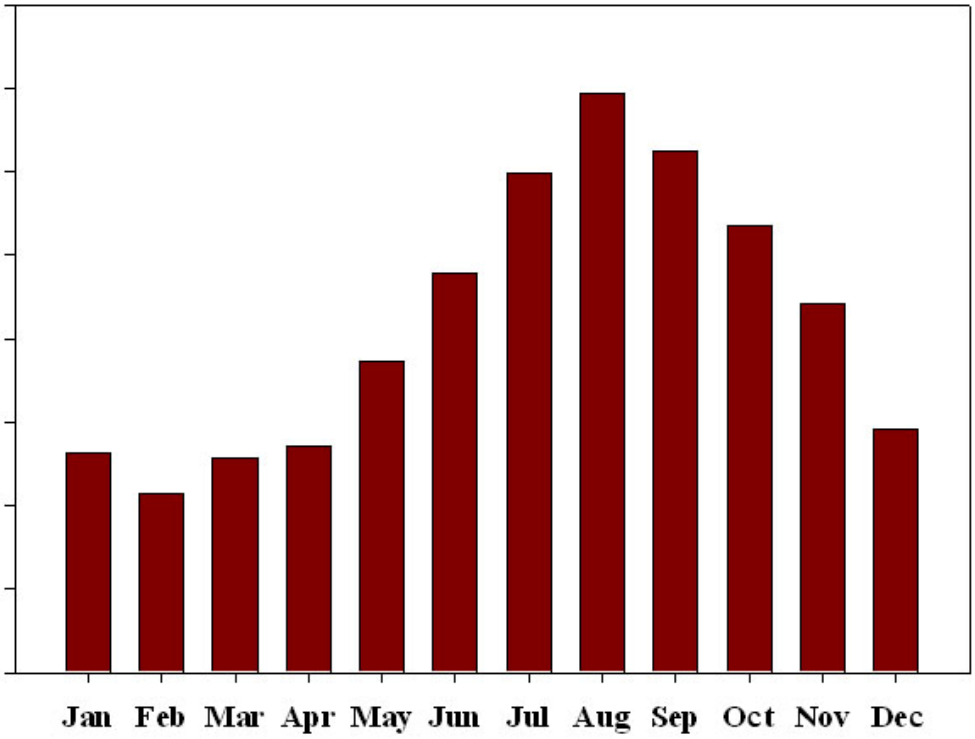

Figure 3: Relative seasonal feed inputs at a typical Norwegian salmon farm (Courtesy of Yngvar Olsen, University of Science and Technology, Norway)

Management and Husbandry

Various management and husbandry practices may affect the amount of nutrients loaded. Feeding may be reduced when fish are sick or if a regulatory feed quota is approaching. Feeding may stop when fish are being transferred between cages or a few days prior to live transport. While these aspects may not have a significant impact on annual feed usage or nutrient loading, there may be implications for discrete water quality samples taken in the water column at fish cages. A reduction of feeding would be accompanied by a reduction in nutrient loading. At a well flushed site, this may also be accompanied by nutrient concentration changes in the adjacent water column (Reid and Moccia, 2007; Reid, Moccia and McMillan 2006) [13].

The mechanism of feed delivery can influence the amount of fines produced. Mechanisms that cause greater agitation and abrasion between feed pellets will generate more fines (*e.g.* an auger delivery may case more fines than a pneumatic delivery).

Comparisons with Municipal and Terrestrial Agriculture Wastes

Waste loading from salmon farms, are occasionally compared to municipal waste or terrestrial agriculture production of a certain size as a means to quantify the scale of loading. Caution is warranted however, as gross comparisons between 'fish waste', 'municipal wastewater effluent' and 'agriculture manure', should be distinguished from specific comparisons between the loading of individual compounds or nutrients within the waste.

While phosphorus, carbon and nitrogen will be loaded from all these sources, there are potential differences in pathogenic and contaminant composition. Salmonids do not produce fecal coliform bacteria (Spanggaard et al. 2000) as do mammals and birds. Fecal coliform bacteria, has serious health implications if consumed, but this risk is largely mitigated by appropriate treatment of municipal sewage and agricultural manure. Municipal wastewater effluent also contains about 200 identified chemicals[14], some of which are persistent; the concentrations dependant on the regional level of treatment (e.g. none, primary, secondary, tertiary, etc.) and whether storm-sewers are connected to sanitary sewers (for treatment), or discharged directly to receiving waters (EC 2001). Some PCBs, heavy metals (i.e. copper, zinc and mercury) and antibiotics have also been associated with salmon feed, and sediment below salmon cages (Hites, Foran, Carpenter, Hamilton, Knuth, Schwager and 2004; Cabello 2006; Debruyn, Trundel, Eyding, Harding, McNally, Mountain, Orr, Urban, Verentich and Mazumder 2006; Sather, Ikonomou, and Haya 2006; Hayward, Wong and Krynitsky 2007; Dean, Tracy, Shimmield, and Black 2007) although these concentrations have generally been low and variable (the implications of this are discussed in another WWF technical working group report). Given

[13] This refers to soluble and particulate nutrients being release in the water column by the fish at any given time. This would not include situations where leached nutrients from settled feces beneath fish cages could well up to surface waters.
[14] This may include physiologically active compounds (Daughton and Ternes 1999; EC 2001; Kanda, Griffin, James and Fothergill 2003) and chemical contaminants such as PCBs and PAHs (Pham, Proulx, Brochu and Moore 1999, EC 2001).

such complexities, loading comparisons on the basis of individual nutrients, contaminants or compounds becomes a simpler and potentially more informative approach.

Quantifying the scale of salmon culture waste using nitrogen as a metric, due to its role as limiting nutrient in most marine systems, becomes a logical step. Goldberg and Naylor (2005) calculated 100 000 mt of nitrogen would be loaded from the proposed 2025 US aquaculture production of 5 billion US$; a nitrogen mass similar to that generated from North Carolina's 2004 hog production or 17.1 million people (untreated). It is uncertain how much of this proposed aquaculture revenue would be from mariculture; as salmon production was less than 5% of the total US aquaculture revenue and finfish production in 2005 (NOAA 2005). Nevertheless, they conclude 100,000 mt of nitrogen loaded from marine finfish aquaculture into oceanic waters is about 1 tenth of 1 percent of the global nitrogen fixation capacity (121 million mt) of the worlds ocean's and is of no cause for alarm, except potentially in poorly flushed areas or areas of high farm density. The 2005 world production of salmonids (i.e. salmon, charr, trout) was 1.99 million mt (FAO 2007), which would have loaded approximately 77,700 mt of nitrogen[15] (using 39 g N per Kg fish produced); but this amount will increase as the industry expands.

The potential for minimal impacts due to nutrient loading from salmon aquaculture, on a global scale, focuses initiative attention to the regional level. A large part of coastal zone management requires the assessment of individual nutrients based on their prevalence and loading potential in a given ecosystem, regardless of source. This is not to suggest a justification for relaxed vigilance in the assessment of potential impacts of aquaculture nutrient loading. Clearly the scale of nutrient loading from individual sources will require quantification to assess a proportionate level of impact; thereby determining relative strategies for management or mitigation. The aforementioned approach described in this chapter will provide a good estimate of nutrient loading from Atlantic salmon aquaculture at different scales, which can then be juxtaposed with the loadings of other sources.

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[15] This is an approximation using average digestibility and carcass retention values for large fish. A portion of this will be loaded into freshwaters, in cases of trout and some charr production

[16]Not including nitrogen from waste feed

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Chapter Two: Impacts on pelagic ecosystems

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Introduction

Impacts on pelagic ecosystems from nutrient releases from salmon aquaculture as well as for other cultured species have generally revealed a lack of ecological response by the plankton community (Sara, 2007). This is because there is no general scientific concept established to understand how such potential effects can be traced. Because N and P are biogenic elements forming parts of all biomass, and not harmful environmental toxins for humans and other animals, these nutrients are rapidly assimilated into microorganisms present in the water column during the summer to autumn period (e.g., Thingstad *et al.*, 1993; Tanaka *et al.*, 2004;). This is why ammonia, for example, which is both the principal excretion product from all aquatic animals and the most common limiting nutrient for the phytoplankton, is not easily found persisting in high concentrations in water masses around and downstream of cages (Sara, 2007). In addition to their rapid assimilation, nutrients are, whether they are in their inorganic form or organically bound in biomass, dispersed downstream of the cage farms by hydrodynamics of variable patterns and strengths.

The organisms forming the planktonic food web are key actors in the assimilation of excess nutrients in the water column (e.g., Olsen *et al.*, 2007). The main group of organisms are:

- phytoplankton, microscopic photosynthetic algae and cyanobacteria, the main taxonomic groups are picocyanobacteria, diatoms, dinoflagellates, and a diverse group of small eukaryotic flagellates. Sizes typically varies between 2 - 100 µm, colonies may be larger;

- heterotrophic bacteria (and Archaea), small organisms (<1 µm) consuming dissolved organic compounds, but also inorganic nutrients like the phytoplankton;

- heterotrophic nanoflagellates (HNF), small (4 – 8 µm) protozoan grazers that feed on picocyanobacteria and bacteria;

- microzooplankton, often dominated by ciliates in North-eastern (NE) Atlantic waters (5 – 50 µm), protozoan grazers that feed on small phytoplankton mainly, and less important also HNF, the smallest individuals (5-10 µm) may feed on bacteria, and;

- mesozooplankton, larger individuals (>200 µm, but also smaller) often dominated by crustacean zooplankton like copepods in NE Atlantic waters.

Enhanced nutrient supplies result in a stepwise process where the first step includes an increased uptake by phytoplankton (and bacteria) followed by an increased growth rate. In stagnant waters, phytoplankton biomasses then increase, leading to higher food concentrations for all groups of heterotrophs, and in turn to successive responses in their feeding activities and growth responses (bacteria take up dissolved carbon compounds from algae and zooplankton feces). The top predators of the planktonic food web, here defined as the mesozooplankton, are the principal link to higher levels of the food web, and they affect lower levels quite strongly through trophic cascades (Vadstein et al 2004). The trophic interactions of the planktonic food

web following enhanced (or reduced) nutrient inputs are complex; but the bottom line is that the food web acts like a buffer which, within certain limits, may mitigate any extensive blooms of phytoplankton. When the dominant organisms of different types of coastal waters are assigned to functional ecological groups like in Figure 1, both structure and function of the planktonic food web will respond in a predictable way to increased nutrient supplies. The carbon flows (function) have been found to relate equally to nutrient input rate in Baltic, Mediterranean, and NE Atlantic coastal waters (Olsen et al 2006). The dominant mesozooplankton species can, however, affect biomass of phytoplankton and protozoan grazers (structure) in these types of waters. It is important that the the impacts of enhanced nutrient input generally cannot be predicted on the species level, only on the level of the defined functional groups. These groups will for sure contain different species in different types of water (Olsen et al 2006).

Figure 1 shows that enhanced nutrient supplies affect carbon flows to and between heterotrophic food web components more strongly than their biomasses. Phytoplankton biomass responds for sure more strongly (Olsen *et al.,* 2006). Another apparent pattern is that the bacterial part of the food web (the microbial food web, prokaryotes-HNF) responds very little to nutrient addition - it is the larger species of eukaryotic phytoplankton and their grazers which respond.

The most striking message of Figure 1 is the high increase in sedimentation rate which follows enhanced nutrient inputs. This flow to deepwater and sediments represents an organic loading which is important for the oxygen requirements and concentrations in aphotic waters and benthic communities. A non-linear, accelerating increase in sedimentation per primary production reflects the fact that the zooplankton grazers at some point of nutrient input are not any more able to consume, and efficiently remove, the enhanced primary production. A high amount of sedimentation to primary production is an indication that the planktonic ecosystem is no longer able to assimilate the enhanced nutrient inputs.

Scientific concepts for assessing impacts of nutrients in water column ecosystems

All ecosystems have an inherent capacity of persistence; and smaller environmental changes are normally mitigated through adaptive responses of organisms. Major changes in ecosystem structure and function, be it reversible of irreversible changes, will only take place if the environmental signal, or the environmental interaction, is strong. For the pelagic ecosystem we may deduce that nutrients may be efficiently assimilated without any harm as long as the input rate remains below a critical upper level, or the maximum assimilation capacity. The assimilation capacity of the pelagic ecosystem is mediated by two main mechanisms:

(1) Nutrient uptake and assimilation by phytoplankton, with successive trophic transfers of energy and materials (e.g., nutrients) in the planktonic food web to the higher trophic levels, and,

(2) Dilution of nutrients and organisms mediated by hydrodynamics at production sites and their surrounding water masses.

Dilution is independent of the organisms of the pelagic ecosystem. Hydrodynamics are driven by major physical forcing processes. The assimilation capacity of the planktonic community is

strongly dependent on hydrodynamics because dilution leads to a reduction of nutrient concentrations and biomasses, and therefore also to an increase in capacity of nutrient assimilation by the pelagic ecosystem. Both mechanisms are working in concert. Nutrient uptake and allocation in planktonic food webs and hydrodynamics are the fundamental processes determining the assimilation capacity of the water column of coastal waters.

Looking more closely at the biologically mediated assimilation mechanism, the upper panel of Figure 1 is representative of a normal, undisturbed situation in NE Atlantic coastal waters. In this case, the food web organisms are capable to assimilate efficiently nutrient inputs with minor losses to deepwater and sediments. On the other hand, the lower panel, reflecting a situation with a nutrient supply 6-7 times above natural levels describes a situation where the nutrient loading exceeds the rate that can be efficiently assimilated in the pelagic ecosystem, resulting in major losses to deepwater and sediments. Somewhere in between the specified loading rates there must be a critical nutrient loading rate (CNLR), reflecting a maximum assimilation capacity, which cannot be exceeded without loss of ecosystem integrity.

It is still not clear how CNLR can be experimentally or empirically determined. There are no estimated published values. There is, however, some evidence showing that primary production and the zooplankton feeding rates in stagnant systems level off for volumetric loading rates above around 1 mmol N m^{-3} day^{-1} (14 mg N m^{-3} day^{-1}) in NE Atlantic waters (Olsen *et al*., 2006). It is also apparent that the percent sediment C of total primary production reaches values above 30% in mesocosm experiments above this point (37% for situation in lower panel of Figure 1). More research is needed obtain a more comprehensive understanding for determination of CNLR.

Dilution by hydrodynamic forces will continuously reduce nutrient concentrations; therefore, volumetric loading rates need to be known. Assimilation by organisms and hydrodynamics will therefore work in concert and together determine the overall assimilation capacity for nutrients in all coastal waters. Yokoyhama *et al* (2004) have suggested a proxy (ISL) expressing the assimilation capacity represented by physical forces:

$$\mathbf{ISL = D*V^2}$$

where D is the depth and V is the water current velocity. They test this proxy for benthic communities, but it can also be useful for pelagic ecosystems.

Figure 2 illustrates conceptually the "*water current velocity – nitrogen loading rate*" space and the general importance of the two nutrient assimilation mechanisms in that space (see legend). The ultimate research challenges are to:

1. confirm experimentally and empirically the "*water current velocity – nitrogen loading rate*" space where the biological assimilation capacity of open waters may become exceeded (i.e. slope and x-axis intersections of the stippled curves in Figure 2);

2. estimate through 3D modelling how nutrients are dispersed and diluted downstream of sites exposed to different loading rates of nutrients.

Factors that will affect the ecological impacts of salmon farming on pelagic ecosystems

The important factors determining the environmental impact of salmon farming are: (1) the loading rate of inorganic nutrients, (2) water dynamics and depths of site and surrounding waters, and (3) the density of fish farms.

Husbandry practises and the composition and digestibility of feeds, and particularly the N and P components, are important for the emission of nutrients from salmon farming, as discussed in Chapter 1. It is the inorganic nutrients released through salmon excretion which immediately affects phytoplankton growth and thereafter all higher levels of the planktonic food web. It is also important that the inorganic component of nutrient release can be estimated relatively accurately, as the difference between assimilation (the digested N and P, taken up in intestine) and production (incorporated in biomass) (Chapter 1). These components are also characterised by relatively long turnover times in seawater (greater than a year, Eilola and Stigebrandt, 1999). Bacteria can better utilise these compounds, but the availability is still relatively low.

Salmon cages normally extend to 15 m depth (12-20 m). Although a part of these nutrients will be released to aphotic waters, it is fair to assume that all the inorganic nutrients are released to the mixed layer thereby becoming available for the phytoplankton. Nutrient release to aphotic waters, which will take place if the fish resides below the mixed photic water layer, will not have an immediate stimulating effect on the phytoplankton.

The loading rate of inorganic nutrients (here defined as amount per unit time) from a salmon farm will vary as a function of fish biomass, time of the year, and husbandry practises (Chapter 1). Loading rates for May to September, the period when phytoplankton are potentially affected by enhanced nutrient supply at high latitudes (where salmon are grown), are on average 142 kg NH_4-N (range 82-198) and 23 kg PO_4-P (13-30) per day for a farm producing 1,000 tons of fish per year with a FCR of 1.2 (range 1.0-1.4). On average 55% of the feed consumption, and accordingly also the nutrient release, takes part in May – September. The annual average release of inorganic nutrients from this farm producing 1000 tons salmon per year at a FCR of 1.2 is therefore 109 kg NH_4-N and 17 kg PO_4-P per farm and day. Nutrient emission will increase proportionally with the use of feed, meaning that a farm producing 10,000 tonnes (bigger than the biggest farms) will release 10 times more nutrients.

If P_{yr} is tons produced per year and $DIN_{release}$ and $DIP_{release}$ is the daily release of inorganic N and P, respectively, a generalised relationship between fish production and nutrient emission is as follows:

Average for January – December: $DIN_{release}$ (kg NH_4-N day^{-1}) = 0.109 * P_{yr}
Average for May – September: $DIN_{release}$ (kg NH_4-N day^{-1}) = 0.142 * P_{yr}

Average for January – December: $DIP_{release}$ (kg PO_4-P day^{-1}) = 0.017 * P_{yr}
Average for May – September: $DIP_{release}$ (kg PO_4-P day^{-1}) = 0.023 * P_{yr}

This estimate for inorganic nutrient release from salmon cage farms is relatively accurate when compared to the estimates of nutrient loading rates from other anthropogenic and natural nutrient sources. Nutrients released from other sources are drained into a specific volume of water (the volumetric loading rate of inorganic nutrients is here defined as mass of nutrients

released per volume of water and day). The volumetric loading rate determines the concentration of nutrients in surrounding waters (i.e., sum of natural concentration and the excess concentration caused by the fish farm). This rate is not easily estimated, because the volume of water which passes through the fish farm per day, or more specifically the total volume that receives the daily nutrient dose, is heavily dependent of hydrodynamics at and around the production site.

The pattern of water currents in coastal waters is complex, and cannot easily be deduced, even after extensive field surveys. As a first approximation for estimating this volume, we may assume that water passes through a cage farm in a plug flow pattern with no further mixing downstream of the farm site. There is no standardised size of a salmon farm, and our exercise assumes a farm of 160 x 320 m^2 with depth 15 m (area and volume of 51,000 m^2 and 768,000 m^3, respectively). If water enters the cage area directly from the long side, and there is no major resistance in the cages. Figure 3A shows the number of water exchanges per day and the resulting daily total volume passing the cage farm as a function of the water current velocity. Even relatively slow water currents result in a high frequency of water renewal and a total exchange volume of more than 40 million m^3 per day. This is certainly an underestimate of the real exchange because nutrients will become continuously exchanged with and diluted in other water masses downstream of the fish farm.

Quantification of the nutrient loading rate and the receiving water volume allow estimation of the volumetric loading rates of inorganic N and P (Figure 3B), which decreases rapidly as the water current velocity increases. The critical (volumetric) loading rate to coastal waters is unknown; experiments have indicated values in the range of 10-20 mg N per m^{-3} day^{-1} (see above, Olsen *et al*., 2006). The natural supply rates of nitrogen in a coastal lagoon off Central Norway has been estimated to 4 mg N per m^{-3} day^{-1}, this may serve as a general reference for evaluation of the loading rates.

The exercise illustrates how important hydrodynamics are to mitigate negative environmental effects of nutrients released from salmon fish farms and other point sources of nutrients. If conditions were stagnant, the nutrient concentration following one day of emission would correspond approximately to the concentration prior to a spring bloom event in Atlantic waters (typical DIN concentration of 140 mg N m^{-3}). It is easy to understand that this stagnant situation would have become an immediate disaster for both the salmon and the producer.

This type of exercise clearly concludes that advanced 3D hydrodynamic modelling is needed to estimate the mean volumetric loading rates and to demonstrate the spreading pattern of the excess nutrients from the fish farm to the surrounding waters. This is particularly important for nutrient assessments undertaken on a regional scale with more than one fish farm draining to the same body of water.

Classical assessment criteria for trophic state

Further studies to assess assimilation capacities and critical nutrient loading rates will require quite advanced measurements. The classical measurements made to assess impacts of cage fish farms in surrounding water bodies involve physical, chemical, and biological measurements, for example:

- Water current velocity
- Depth
- Salinity, temperature (TS profiles)
- Inorganic nutrients
- Dissolved organic nutrients
- Particulate nutrients
- Total nutrients
- Oxygen profiles
- Chlorophyll *a*, as a measure of phytoplankton biomass
- Chlorophyll *a* fluorescence, *in vivo* or *in vitro*
- Seston concentration, dry matter, ash contents
- Secchi depth transparency

The major problem in diagnosing trophic state in pelagic ecosystems is the very fast accumulation of the inorganic nutrients into phytoplankton biomass and the dispersion of released nutrients caused by hydrodynamic forces. The amount of nutrients released is always higher than the amount that can be found by classical measurements. Different from the benthic ecosystem, which accumulates nutrient wastes supplied in particulate form, both inorganic nutrients and the planktonic organisms which accumulates these nutrients become dispersed. The consequence is that the biological response of an increased nutrient supply will be realised downstream, and sometimes far downstream, from the nutrient sources. At that point, nutrients are normally diluted and, dependent on the dynamic state, oftentimes no longer detectable above background levels.

Inorganic N and P are for example taken up within minutes to a day, dependent of the extent of nutrient limitation in the phytoplankton. An efficient diagnostic approach must consider the time lags between the nutrient supply and the realisation of the nutrients in *de novo* biomass. These steps and time lags, which are almost always overlooked, are as follows:

- Phytoplankton uptake of NH_4 and PO_4, the macronutrients which normally are limiting for growth, is immediate (hours- day), and is dependent on the nutritional state of the phytoplankton and its biomass. Uptake causes an immediate increased endogenous nutrient concentration in phytoplankton cells. Inorganic nutrients in the water may accumulate temporarily if the nutrient input rate is high and sustained (e.g., in stagnant cages, Olsen *et al.,* 2007).

- Primary production of the phytoplankton can respond and increase 2-5 days after an increased supply of nutrients, and the lag period is dependent of the initial nutritional state of the phytoplankton.

- Measurable accumulations of phytoplankton biomass can occur 1-2 days after the increase in primary production, or 3-7 days after an increase in nutrient input rates.

It follows that an increased phytoplankton biomass following enhanced nutrient supply may be expressed as late as 3-7 days after the nutrients are taken up by the phytoplankton. In the case of strong currents, the potential phytoplankton response will take place far downstream from the emission point, the fish farm, and nutrients will also be strongly diluted at that point. No

enhanced primary production should then be expected in the close vicinity of the nutrient source; the salmon farm.

Monitoring techniques which allow assessment of pelagic waters over a wider geographic scale are therefore paramount for detecting nutrient impacts from nutrient sources like salmon cage farms. The most apparent options are satellite imaging and 3D modeling of coastal regions (Figure 4). Satellite images can document the situation for phytoplankton blooms in surface waters at any given time, but cannot easily distinguish between variable natural situations. 3D hydrodynamic-ecosystem models produce a virtual world, not a real one, but can cover the entire water column continuously with time. Moreover, modeling allows us to distinguish between natural and anthropogenic signals, and can predict phytoplankton production and effects on higher trophic levels. Models can be run with and without nutrient emissions from fish farms included, and the difference, termed the "excess" nutrient concentration, phytoplankton production, or phytoplankton biomass can be estimated. Classical measurements must be used to validate the major trends found by satellite images and modeling at specific locations.

Case studies of environmental impacts for priority areas

A literature search on ISI Web of Science revealed 258 papers for key words "aquaculture AND ammonia", but only one for "salmon aquaculture AND ammonia". "Salmon AND nutrients" gave 22 papers, but few were relevant for the impact on the pelagic ecosystem. "Salmon AND chlorophyll" gave one irrelevant paper. The limited efforts made is most likely a result of the problems to detect clear environmental signals of wastes from salmon farms in the water masses and the fact that there is no general applicable scientific concept established for assessing and judging impacts of nutrients released from fish farms in water column ecosystems.

A number of review papers mention pelagic effects of cage aquaculture, but the overall topics treated is the total nutrient loading rate of the environment and the impact on the benthic ecosystem (Merceron *et al.* 2002; Islam, 2005; Mente *et al.*, 2006, and references therein). Nordvarg and Johansson (2002) provide a comprehensive list of references for earlier papers on pelagic effects of fish farming. The volumetric loading rate, as defined here (i.e., Vollenweider, 1976), is not covered, but some studies report the concentrations of nutrient components, particularly ammonia (NH_4) and phosphate (PO_4) around and downstream of cages farms, including some few salmonid farms. Merceron et al. (2002) studied pelagic waters around a brown trout farm located in the Northern coast of France. The site was well flushed; the water current velocity was 2 - 25 cm sec^{-1} in surface waters. The authors found an excess concentration of NH_4 within and shortly downstream of the site, but the nutrient was not present not far from the farm. Concentrations of PO_4 and chlorophyll *a* remained at background levels. Soto and Norambuena (2004) examined the pelagic effects of 29 salmon farms grouped in 9 locations in southern Chile and found no effect on water column variables like ammonia, orthophosphate, and chlorophyll *a*, but found significant effects for benthic variables. Nordvarg and Johansson (2002) found a positive pelagic effect of some studied fish farms on total P and periphytic growth in the Baltic Sea. Some other farms had no measurable impacts. Secchi depths and oxygen saturation was not affected in any farm. Maldonado et al (2005) studied a number of

chemical and biological variables in five Mediterranean fish farms exploiting semi-offshore conditions but found no substantial differences between farm and control sites.

Another type of method used is bioassays where growth of algae is monitored. Dalsgaard and Krause-Jensen (2006) used macroalgal and phytoplankton bioassay methods to detect pelagic impacts of Mediterranean fish farms. They found growth responses above the background level in within a distance <150 m downstream of the cages, but no effects at greater distances. The results from this type of phytoplankton bioassays cannot be directly transferred to open systems if the grazers are removed from the bioassay chambers.

An experimental study examining loading and spreading of inorganic nitrogen from 3 hypothetical fish farms in Norway can serve to illustrate how a 3D simulation modeling can be used to assess concentrations and distribution of any component, including released inorganic nitrogen and phosphorous from fish farms (Olsen *et al*., 2005). The virtual farms were located in northern Norway (Figure 5) at variable hydrodynamic conditions (Table 1).

The excess N concentration (N released from the fish farm, dissolved or taken up by organisms) for a 30 day simulation period showed regular oscillations with tides, but the values remained stable for all sites through the simulation period (Figure 6). The mean excess N concentration at the farm hot-spot (the model grid where the farm were placed) in the outer exposed site at Langøya showed very low N values, hardly measurable with analytical techniques (<1% of natural PON concentration, Table 1). Nitrogen was dispersed immediately, and neither enhanced primary production nor enhanced phytoplankton biomass could be traced downstream of the farm in detectable amounts.

The excess N concentration for the farm situated in Langøysundet, a straight between islands, was higher (Table 1), corresponding to 11% of the natural particulate organic nitrogen (PON) concentration at the site. Tides moved the water back and forth in the straight, and the surrounding water masses on both sides were to some extent affected locally (<1 km). Hydrodynamic forces were strong, and nutrients were widely dispersed. The residence time of the water was, however, too short to allow a significant enhanced primary production and phytoplankton biomass around the fish farm (simulations not shown). This is simply because of the time delay between emission and ecological response.

The third site (Eidsfjorden), which is a relatively stagnant fjord, was characterised by regular anti-clockwise water currents with a main pattern not much affected by the tide cycle (Figure 7). The concentration of excess N oscillated, however, quite pronouncedly during the tidal cycle, because water current velocity varied with tides (Figure 6). Water entered the inner fjord along the south coast and left along the north. The farm clearly affected the water masses locally downstream of the site, and the mean hot-spot concentration of excess N was around 30% of the natural PON concentration.

Also areas characterised by sustained enhanced primary production and phytoplankton biomass were identified downstream of the fish farm at the Eidsfjorden location (simulations not shown), which was characterised by relatively stagnant water bodies along the southern coast (Figure 7). Such impacts are to be expected when the retention times of the water is longer or similar to the response time of the phytoplankton on enhanced nutrient input. The excess biomass concentration was generally <25% of the natural biomass level of phytoplankton.

The outer water masses of the fjord were not very significantly affected by excess N, primary production, or biomass. Currents were surprisingly strong downstream of the farm along the north coast of the fjord, and the nutrients were spread rapidly to large water masses.

The virtual fish farm site in Eidsfjorden affected the pelagic ecosystem quite substantially. The site will be less suited for salmon production, but may be suitable for integrated aquaculture of mussels. It is noted, however, that these types of locations are not very often used for salmon production in Norway any more. The farms have also grown much bigger (>1000 tons per year) and have tended to move out to more open, although still protected, waters.

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Table 1. Hydrodynamic characteristics and mean excess nitrogen concentrations of the 3 virtual salmon farms studied. Values express the concentration of excess N in the water occupied by the fish cages (hot-spot, one model grid of 160 x 320 m^2). The situations are representative for a farm producing 1000 tonnes fish per year, which is well below today's production (up to 7000 tons per year), but the results nevertheless demonstrates the options of the method. PON concentration in undisturbed coastal waters is set to 60 mg N l^{-1}, which is representative for the region. From Olsen et al (2005), model data provided by D. Slagstad, SINTEF

Fish farm number and location	Location conditions	Excess N in farm hotspot, mg N m^{-3} (mmol N m^{-3})	% Excess N of natural PON in farm hotspot, %
1 - Langøya, outer exposed area	Strongly exposed, water is efficiently mixed with open the ocean	0.6 (0.04)	<1
2 - Langøysundet, a straight between islands	Tidal driven water exchange, efficiently mixed	6.4 (0.46)	11
3 - Eidsfjorden, a relatively stagnant fjord bottom	Unidirectional, steady water currents	17.9 (1.3)	30

Figure 1. Schematic view of carbon flow networks during (A): a normal summer situation in NE Atlantic coastal waters and (B): conditions of high nutrient input. Arrows shows flows, boxes show biomasses (and their allocation of energy). AMP: Feeding of large sized phytoplankton (20-200µm), ANP: Feeding of medium sized phytoplankton (2-20µm), APP: Feeding of small sized phytoplankton (<2 µm); HNP: Heterotrophic nanoplankton (<20µm); CIL: ciliates, main constituent of microplankton; COP: Copepods, main constituent of meso-zooplankton; DIC: CO2 release (respiration); DOC: released of dissolved organic components; DeC: release of particulate organic components; SeC: sedimented carbon; a_c: assimilation rate; g_c: growth and reproduction rate. All concentrations are expressed in terms of µg C l^{-1} and rates as µg C l^{-1} d^{-1} (taken from Olsen *et al.*, 2007).

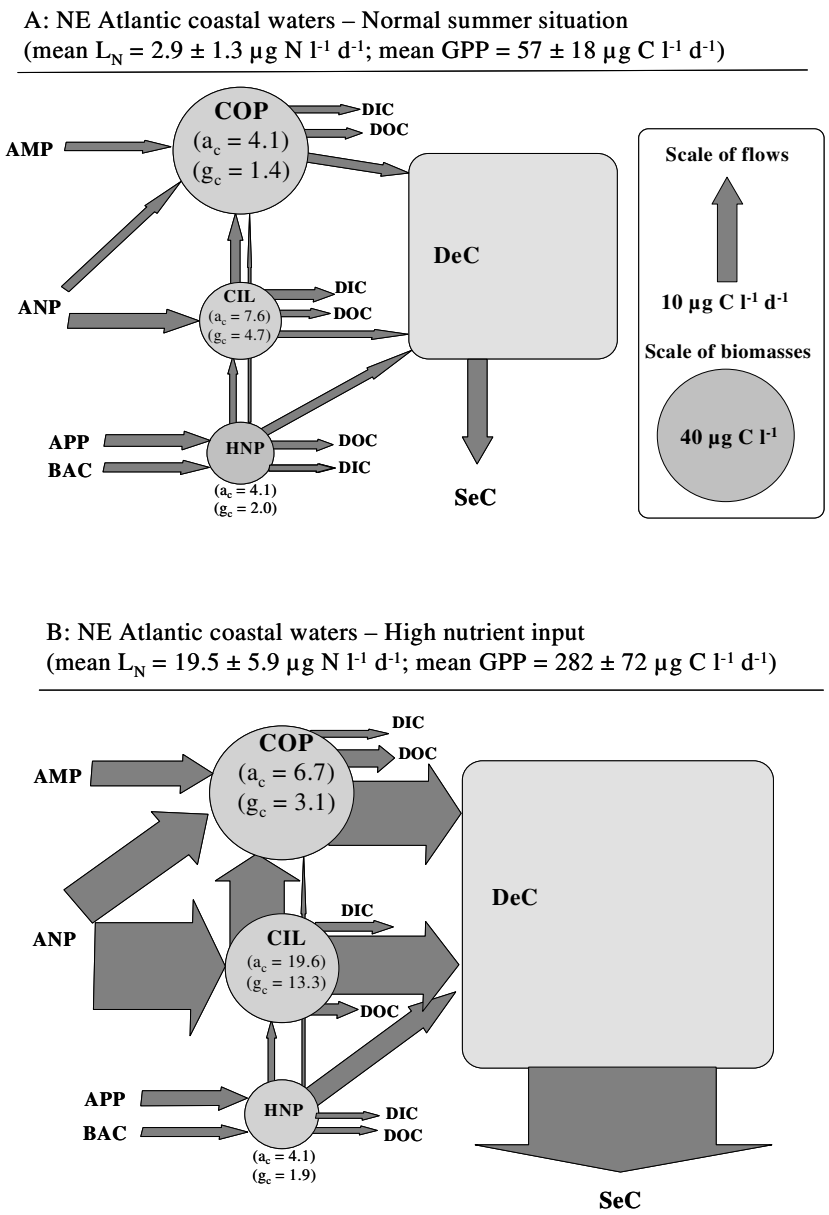


Figure 2. Conceptual relationship describing the ability of the water column ecosystem to assimilate nutrient input as a function of the volumetric loading rate of inorganic nitrogen and the water current velocity. Area I: Water dynamics are strong enough to maintain nutrient loading within the limits of the assimilation capacity of the water column ecosystems; Area II: The critical zone where loading rate is coming close to the critical nutrient loading that exceeds assimilation capacity. The situation represent increased risks and calls for special attention; Area III: Nutrient loading exceeds the limits of the assimilation capacity; the water column ecosystem can loose its integrity, which may cause harmful coastal eutrophication. The figure is preliminary, slopes and exact x-axis intersections of the indicated lines are not known.

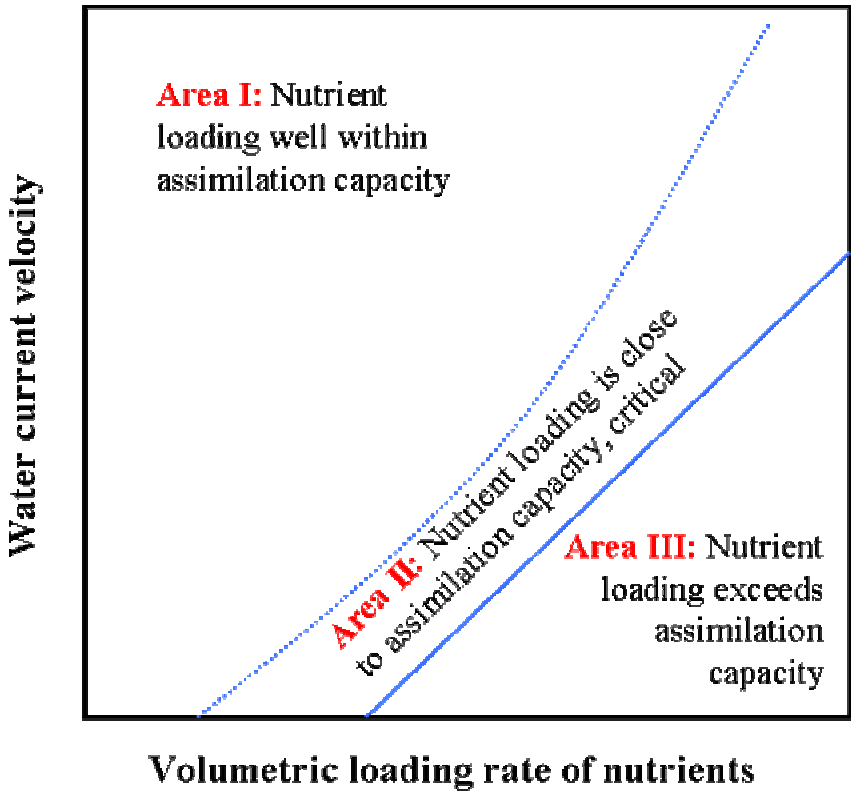


Figure 3. Water exchange (A) and volumetric loading rates of N and P (B) as functions of the water current velocity (revised from Olsen et al 2005).

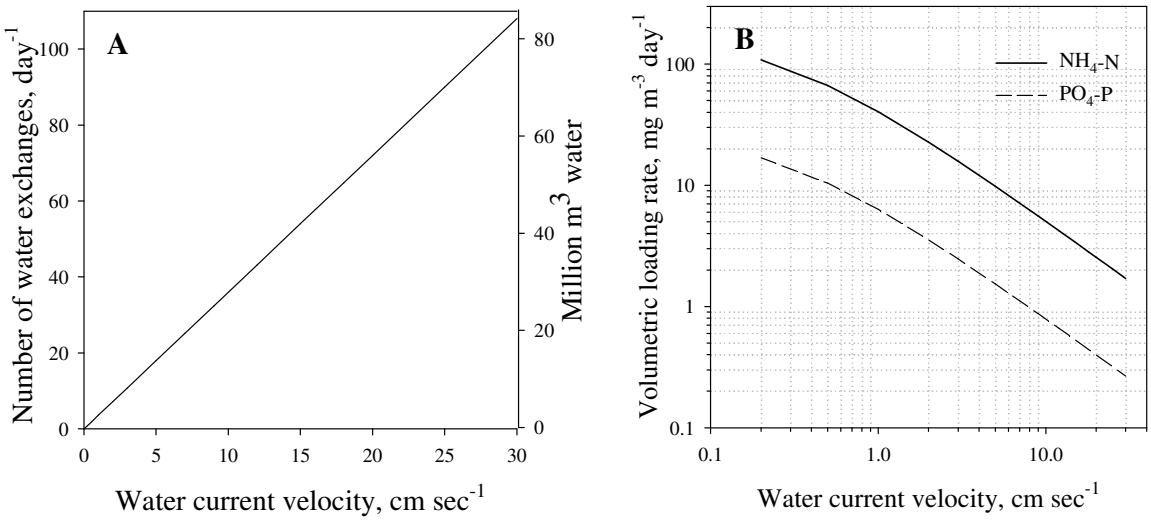


Figure 4. Examples of a satellite image and the results of 3D modelling of coastal waters. The satellite image (left) from Southern Vancouver Island, British Columbia shows phytoplankton fluorescence from MERIS orbital platform. The 3D modelling is made for a coastal region in Vesterålen, Northern Norway, red colour reflects high, yellow intermediate and blue low phytoplankton production per m^2 per day (Satellite image provided by Stephen F. Cross, model data by D. Slagstad).

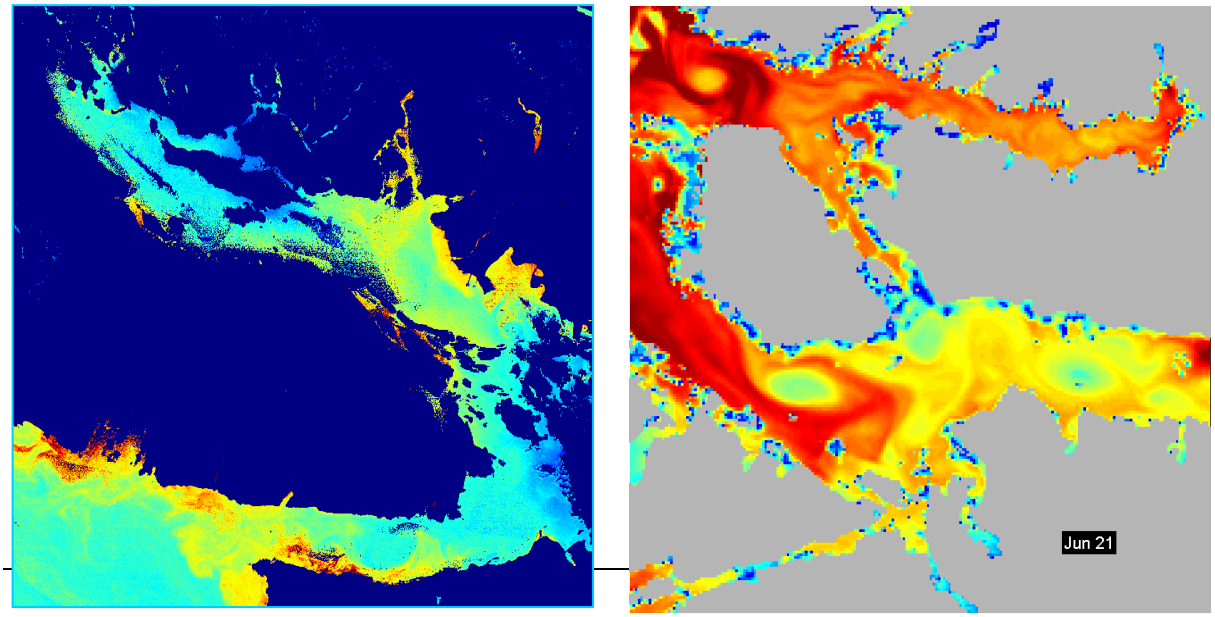


Figure 5. Geographic position of the virtual salmon farms studied (from Olsen *et al.,* 2005).

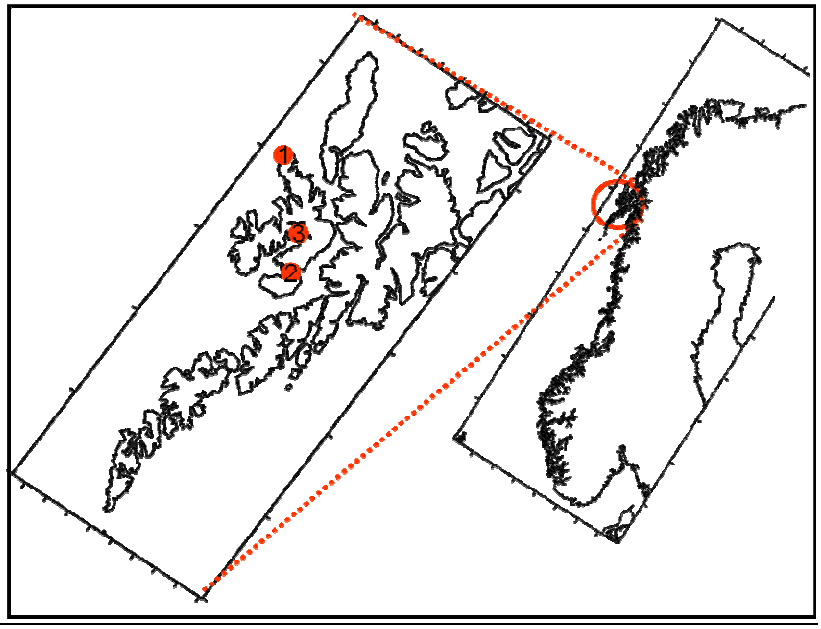


Figure 6. Simulated concentrations of excess N in the three farm hot-spot water masses (the model grid 160 x 320 m²) illustrated for one month of the summer steady-state situation. From Olsen et al (2005), model data provided by D. Slagstad, SINTEF.

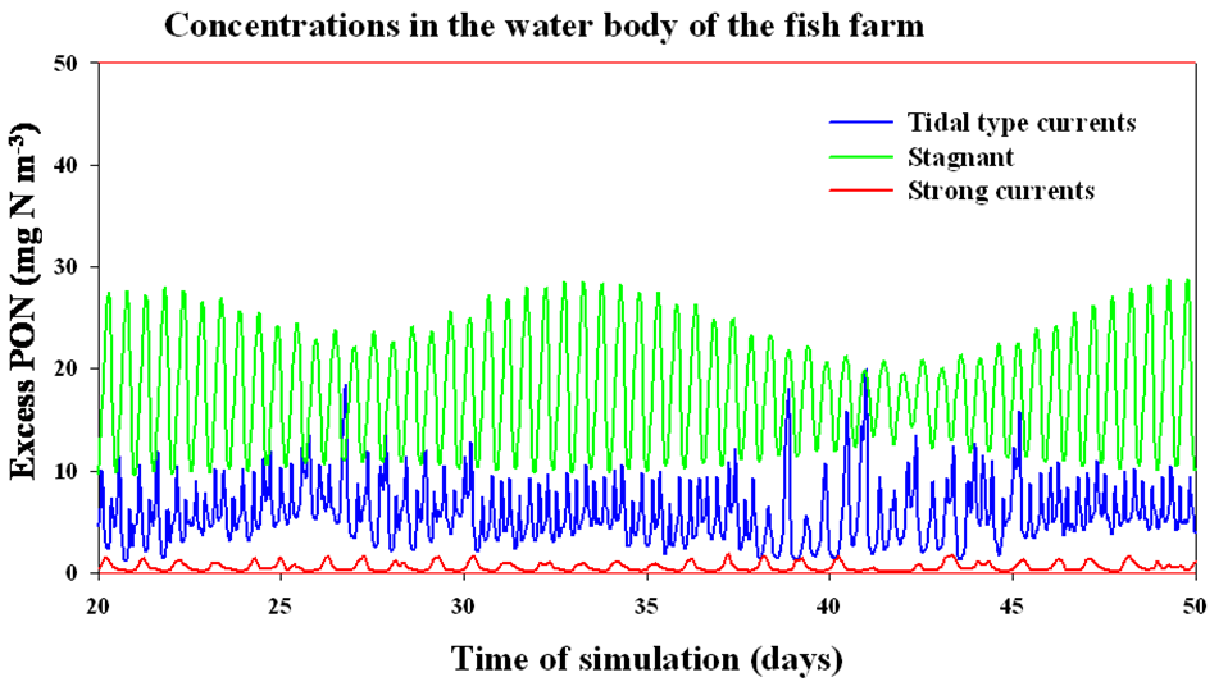
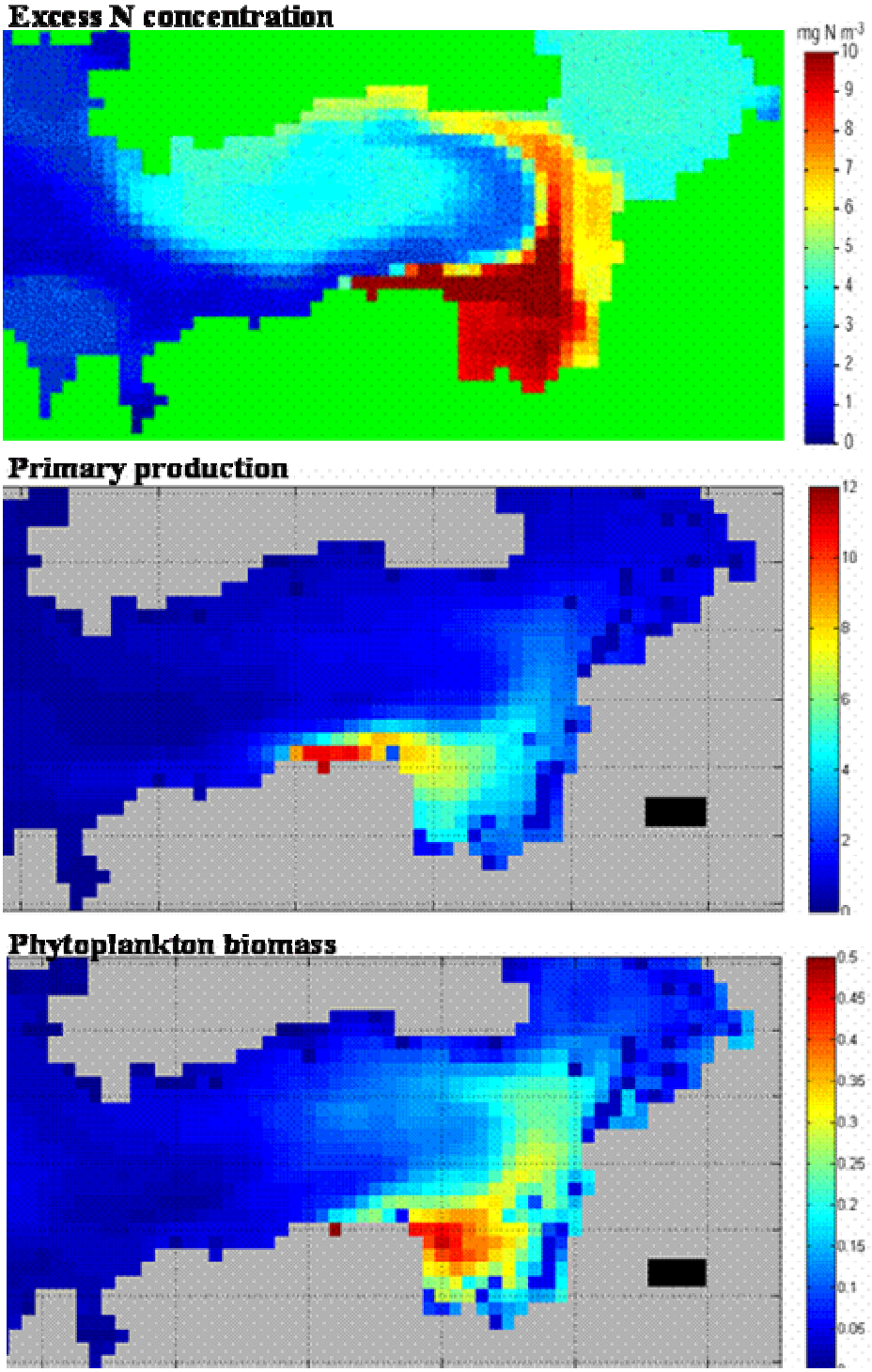


Figure 7. Modelling results for the relatively stagnant virtual salmon farm located in Eidsfjorden. A: Excess N concentration (mg N m^{-3}); B: Accumulated excess primary production during 40 days of modelling (gC m^{-2} 40 $days^{-1}$); C: Mean excess phytoplankton biomass during the 40 days period (mg Chl *a* m^{-2}). Model data provided by D. Slagstad, SINTEF.



CHAPTER 3: Pelagic nutrient and ecosystems impacts of salmon aquaculture in Chile, with emphasis on dissolved nutrient loading and harmful algal blooms

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Introduction

Marine shellfish and fish aquaculture have grown rapidly during the last decade in Chile. Chile is now one of the 10 most important marine aquaculture producers in the world and the largest aquaculture producer in the western hemisphere. During the last 25 years, a general tendency towards an increased production and a reduction in the commodity prices. The response of Chilean salmon farmers has been to increase production in order to develop an economy of scale to reduce costs and retain profitability (Barton, 2003; Liverman and Vilas, 2006).

Feeds are the most significant cost for salmon production. In the past decade, better feeding practices and feed formulations have improved food conversion efficiencies (FCEs) (Chilean farms now have FCEs ca. 1.2), thereby reducing nutrient loading to the environment from salmon cage aquaculture. However, the overall growth in salmon aquaculture production has resulted in significant increases in nutrient inputs to the southern channels and fjords of southern Chile (Buschmann and Pizarro, 2002). While improved governance and more integrated regulations are needed; there is an urgent need to obtain additional science-based knowledge to ensure environmental sustainability while allowing the growth of a more visionary salmon aquaculture development model that respects the limits imposed on it by the environment. This chapter describes very briefly the Chilean aquaculture situation, summarizes the available research on the impacts of salmon aquaculture to coastal areas of southern Chile with an emphasis on nitrogen loading to the water column, and relationships with harmful algal blooms (HABs), plus includes recommendations for future research.

Status of salmon aquaculture in Chile

Over the last 10 years salmon aquaculture has become the 4th largest economic activity in Chile, after mining, forestry, and fruit production. Salmon gross production in 2006 was 630,820 tons. The three most important farmed salmonids are Atlantic salmon, *Salmo salar*, coho salmon, *Oncorhynchus kisutch,* and rainbow trout, *O. mykiss*. Salmon farming accounts for 78% of the marine aquaculture production and producing in 2006 a total export revenue of US$ 2207 millones (fob).

Commercial salmon farming commenced in Chile with the importation of eggs from the northern hemisphere but in recent times the production of eggs and genetic selection stocks for Chilean conditions have been developed. In recent years, the use of innovative technologies, particularly for Atlantic salmon culture, e.g. photoperiod and temperature manipulation, have permitted the transfer of fish to sea at different times of the year and harvesting throughout the year, reducing the need to import eggs, and consequently, reducing the risks of introducing exotic parasites and diseases. However, several environmental issues remain unstudied or unregulated (Buschmann et al., 2006a) resulting in pressure on the producers and the government from environmental groups. Environmental impacts of the salmon aquaculture industry prior to 1996 were reviewed by Buschmann et al. (1996a) who concluded that at the time there were no significant impacts. However, after over 10 years of significant expansion

scientific evidence indicates that significant nutrient and benthic impacts have occurred in some licensed aquaculture areas, causing changes to the physico-chemical properties of the sediments, and significant losses of benthic biodiversity (Soto and Norambuena, 2004; Buschmann & Fortt, 2005; Buschmann et al., 2006b). However, the literature also indicate that the above-mentioned environmental effects, are not well studied in Chile (Buschmann et al., 2006a).

Nutrient inputs from salmon aquaculture in Chile

Soto and Norambuena (2004) did not detect increased water column nitrogen concentrations near salmon farms compared with control sites. However, in a bay channel in southern Chile used for intensive salmon production, significantly higher concentrations of ammonium (a salmon excretory product) was found near the cages in comparison to amounts in a control site located ~3 km from the cages (Buschmann et al., 2006b). The bay/channel region in southern Chile offers a complex topography, with poorly understood hydrodynamics and currents, where tidal currents are the major driver of water flows. Tidal currents reverse directions every 12 h. As a result, nutrient impacts of salmon farms can be greater downstream than in other latitudes (Figure 1). This can be especially true in a high density farming areas such as farms crowded along the shorelines of Chiloé Island in southern Chile (Figure 2), where the addition of nutrients of one farm will interact with the waste flows of other farms. For this reason farm specific regulations will not enough to control environmental impacts of salmon aquaculture. Carrying capacity of the aquaculture areas and modelling the nutrients flows needs to be implemented to produce sound management practices in areas with high densities of aquaculture practices such these in southern Chile.

Seaweeds can detect excess nitrogen inputs, even when traditional analytical methods cannot (Troell et al., 1997). Seaweeds showed increased tissue nitrogen concentrations and enhanced growth rates when cultivated near salmon pens (Troell et al., 1997). Macroalgae responded strongly when cultured in nitrogen rich salmon effluents (Buschmann et al., 1994; Buschmann et al., 1996b). Unicellular algae have a higher capacity than seaweeds to capture nitrogen because of their higher surface/volume ratio and for this reason it can be expected that they are also an efficient user of salmon farm nutrients.

Salmon aquaculture and harmful algal blooms (HABs) in Chile

Different algal species have been reported to cause HABs in Chile causing damage to the salmon aquaculture industry, fisheries, and coastal communities (Table 1). An expansion of the toxic algae *Alexandrium catenella* into the northwest Patagonian region of southern Chile has occurred and been found to be due to surface water drift by wind forcing as well as due to the unique circulation features of these inland seas (Molinet et al., 2003). These responses can be modified in euthophic waters. An environmental issue of major concern in Chile is the induction of HABs through the input of nitrogen into the water by salmon aquaculture. Laboratory studies indicated that salmon excretion products had no significant effect on toxic *Alexandrium* species (Arzul et al., 2001); however, Buschmann et al. (2006b) found dinoflagellate population growth in 1,500 L tanks was enhanced when using effluents from fish tanks. A field study showed that in the presence of salmon pens significant increases in dinoflagellate densities occurred in pulses (Vergara, 2001). Salmon farm wastes can lead to the development of

high ammonium concentrations in channels and fjords of southern Chile that could be an important risk factor of the induction of HABs (Buschmann et al., 2006b).

Therefore, increased nutrient loads in poorly flushed areas with high densities of farms, as well as the modification of water column nitrogen/phosphorus ratios by intensive salmon farming could enhance the risks of HABs. Nutrient loading from salmon farming together with other environmental factors (e.g. winds, depth) interact and they need to be considered in its complexity when documenting increases of HABs in the channels and fjords of southern Chile. This approach has also been suggested for other regions (Halleagraeff, 1993; Smayda, 1990), but the issue remains controversial (Sellner et al., 2003). This type of research requires urgent attention in Chile. The hydrodynamics of the coastal environment of the Chile and the interactions with salmon aquaculture is almost unstudied; its unique fjords, channels and bays offer a unique experiment that requires urgent scientific attention.

Concluding remarks

Marine environmental research associated with salmon aquaculture requires urgent attention in Chile, especially since the salmon industry plans to continue expanding south, toward one of the few remaining pristine, biologically unique, and poorly studied coasts of the world (Försterra and Häussermann, 2004; Buschmann et al., 2006b). By using the ISI Web of Knowledge it is possible to obtain 540 references with the key words of "salmon environmental effects). When the word of Chile is added as a keyword during the search, this number is reduced to only 12 references. In other words, Chile produced only ~2% of the aquaculture-environment studies. This scientific database is inadequate to manage and help plot the future sustainability for a country that is now the western world's largest mariculture nation. Multidisciplinary research approaches, including oceanographic and ecological studies, together with ecosystem modeling are urgently needed.

It has been suggested that the dispersal of salmon farm by proper site location with adequate flushing will minimize the effects and prevent harmful environmental changes. However, salmon aquaculture is a highly concentrated activity in Chile; as a result the wastes from different farm sites interact. With further concentration of farms, and an uncertain governance and regulatory structure, these synergies will become the norm, and could alter marine ecosystem energy, organic and inorganic material flows on a larger scale, compromising complex environmental systems. Recent R&D projects conducted to reduce some negative environmental impacts of fed aquaculture using ecological engineering approaches have been carried out in Chile. The recycling of wastes in recirculating systems, and the increased production of co-cultured extractive species (*e.g.* shellfish and seaweeds) to increase overall productivity of marine resources of feed, water and fossil energy are part of the solution (Bardach, 1997; Buschmann et al., 1996b; 2001; Chopin et al., 2001; Costa-Pierce, 2002a,b, 2003; Neori et al., 2004; 2007; Stickney and McVey, 2002; Troell et al., 2003). Nevertheless, a balanced coastal ecosystem requires not only an ecologically integrated aquaculture approach introducing ecological engineering (Troell et al. 1999), but also from modern regulations. Better codes of practices help to make these changes, but independent and public scrutiny should also be part of a governance system.

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Figure 1. Current speed and direction at 3 m depth Punta Cai-caén, Calbuco, X Region in Chile during a 12 h period. North above x-axis South under x-axis.

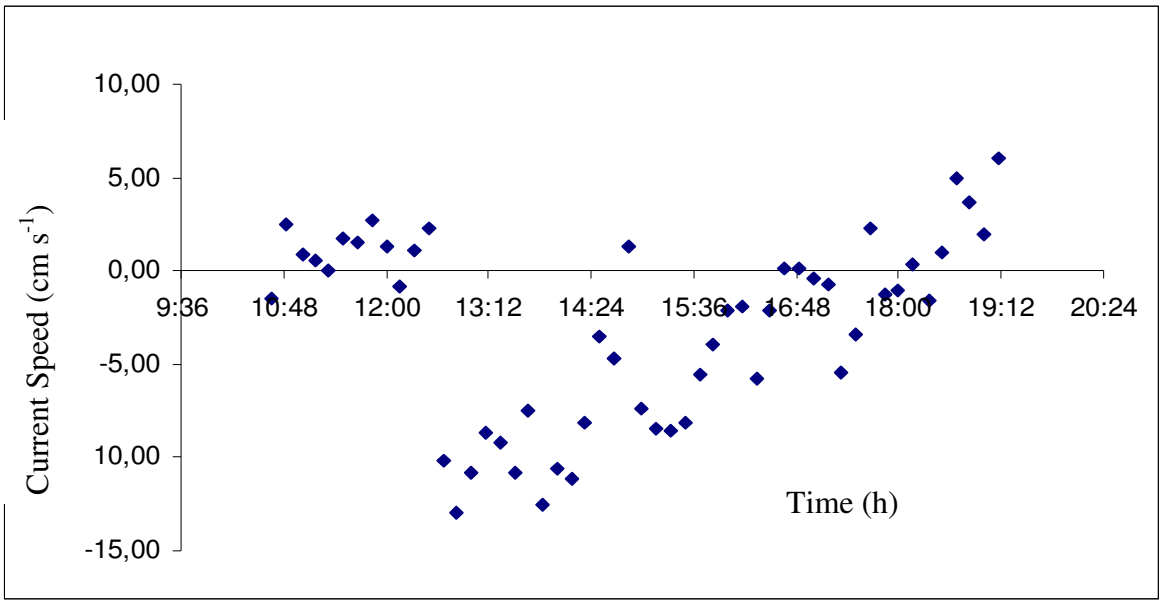

Figure 2. Photograph showing high salmon farm densities in Chiloé Island in southern Chile.

Table 1: Harmful algae species in Chile, year and region of the event recorded and toxins produced during the last three decades (after Buschmann et al., 2006a).

Species	Years of events	Areas affected [a]	Effects
Alexandrium catenella	1972, 1981 y 1989, 1991, 1994, and since 1995 to 2002	42º S to 55º S	Toxic, source of PSP [b]
Dinophysis acuta	1970, 1979, 1986, 1991, 1993, 1994	41º S to 46º S	Toxic, source of DSP [b]
Prorocentrum micans	1983	41º S to 43º S	Fish mortality
Gymnodinium cf. clorophorum	1989, 2003 y 2005	41º S to 43º S	Loss of appetite in aquaculture fish
Gymnodinium spp	1999	42º S to 54º S	Benthic and pelagic resources mortality
Potential harmful species present in Chile: *Alexandrium ostenfeldii, Dinophysis acuminata, Dinophysis fortii, Dinophysis rotunda, Dinophysis tripo, Gonyaulax poyhedra, Gymnodinium catenatum, Gymnodinium splendens, Prorocentrum gracile, Ceratium tripo, Ceratium furca, Scrippsiella trochoidea, Noctiluca scintillans*			
Pseudo-nitzschia	1993, 1997, 1999, 2000	27º S to 30º S and 41º S to 43º S	Toxic, source of ASP [b]
Leptocylindrus minimus	1989, 1993 y 1998	41º S to 43º S	Behaviour change and mortality in aquaculture fish
Chaetoceros convulutus	1991 y 1995	41º S to 43º S	Fish mortality
Chatonella	2004	41º S to 43º S	Fish mortality
Potential harmful species present in Chile: [C] *Skeletonema costatum*			
Heterosigma akashivo	1988	41º S to 43º S	Salmonids mortality
Dictyocha speculum	1995	41º S to 43º S	Salmonids mortality

[a] Regions affected approximated.
[b] Shellfish Poisons, PSP: Paralytic; DSP: Diarrhetic; ASP: Amnesic.
[c] Species present in Chile recognized as harmful in other part of the world.[a] Regions affected approximated.
[b] Shellfish Poisons, PSP: Paralytic; DSP: Diarrhetic; ASP: Amnesic.
[c] Species present in Chile recognized as harmful in other part of the world

CHAPTER 4: Salmon aquaculture and harmful algal blooms (HABs)

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Introduction

Nutrient stimulations of the pelagic ecosystems with organic wastes from salmon farm facilities have been implicated in the development of harmful algal blooms (HABs). This chapter provides a summary of the concerns related to HABs; a review of the scientific evidence that considers the processes that relate to HAB development as a result of salmon farm nutrient loading; implications of these data to farm carrying capacity; and future research needs related to this issue.

HABs can cause widespread mortality in natural populations of invertebrates and fishes, as well as to those species grown in aquaculture facilities (salmon farms). The effects of these blooms are most often associated with their impacts to shellfish resources, from which they present illnesses such as Amnesic Shellfish poisoning (ASP), Diarrhetic Shellfish Poisoning (DSP), and Paralytic Shellfish poisoning PSP). The build-up of HAB-related toxins in shellfish that cause these illnesses result in fishery closures, and the associated loss of commercial opportunities (economic loss), a compromise to human health (through seafood safety threats), and a concern regarding their effects on overall environmental quality.

Intense phytoplankton bloom (*Noctiluca* sp.) observed along the central coast of British Columbia, Canada.
(2002 photo by S.F. Cross, University of Victoria, Canada)

The Intergovernmental Oceanographic Commission (IOC) of UNESCO maintains a database of harmful algal bloom information, including taxonomic nomenclature status, taxon type data, pertinent scientific references, and a summary of the harmful effects associated with these taxa. Table 1 provides a compilation of the HAB taxa that have been documented by this organization, indicating a total of 98 species from around the world. The table is reduced in size by summarizing these groups by genera, with an indication of the global diversity of the harmful phytoplankton species in the adjacent column.

Table 1 also summarizes the harmful (toxic) effects associated with these species groups, illustrating the range of impacts from production of toxins responsible for diarrhetic (DSP), amnesic (ASP), and paralytic (PSP) shellfish poisoning, and hence those that can compromise human health and safety, to those effects causing significant fish, shellfish, macroinvertebrate mortalities (with implications to both wild and cultured populations).

Table 1. Harmful Algal Bloom genera, number of species, and noted harmful effect(s) reported (extracted and compiled from IOC-UNESCO database; www.ioc-unesco.org/hab)

	Harmful Algal Genera	Number of HAB Species	Harmful Effect(s) Associated with Species
Diatoms	Amphora	1	Domoic acid
	Nitzschia	1	Domoic acid
	Pseudo-nitzschia	10	Domoic acid
Dinoflagellates	Dinophysis	11	DSP taxons
	Alexandrium	11	PSP toxins
	Coolia	1	cooliatoxin
	Gambierdiscus	5	ciguatoxin- and maitotoxin-like toxins
	Ostreopsis	4	palytoxin analogues
	Protoceratium	1	yessotoxin
	Pyrodinium	1	PSP toxins
	Heterocapsa	1	mass mortality of shellfish
	Pfiesteria	2	fish kills
	Protoperidinium	1	azaspiracid; NSP
	Prorocentrum	13	ichthyotoxic; okadaic acid - DSP
	Amphidinium	3	Haemolysins
	Cochlodinium	1	fish kills - toxin unknown
	Gymnodinium	1	brevetoxins, NSP
	Gyrodinium	1	PSP toxins
	Karenia	10	brevetoxins, NSP
	Karlodinium	2	fish and invertebrate kills
	Takayama	1	fish and invertebrate kills
Haptophytes	Chrysochromulina	2	fish, benthos and plankton mortality
	Phaeocystis	2	hemolysin? Toxic to fish
	Prymnesium	5	fish and invertebrate mortality
Raphidophyceans	Chattonella	5	fish kills by gill damage
	Fibrocapsa	1	fish mortality
	Heterosigma	1	fish mortality

Contribution of salmon farms to HAB development and/or persistence

A recent document, produced by the Scottish Executive Environment Group (SEEG, 2006) provides a comprehensive review of the harmful algal bloom communities as they relate to fish farming in the coastal waters of Scotland. This work was based upon a substantial science citation list, comprised of approximately 650 papers from refereed journals, and extends beyond that of the Scottish experience with HABs to include regional comparisons within the review. This review does not intend to reiterate this work but provides a brief summary of some of the key findings as they relate to the issue of salmon farm nutrient release and its impact with respect to harmful algal bloom stimulation and/or persistence (www.scotland.gov.uk/Publications/2006/02/03095327/2.).

The SEEG (2006) harmful algal bloom review provides 59 specific summary comments and recommendations related to the situation of fish (and shellfish) farming, and their respective nutrient inputs to Scottish coastal waters. These statements/conclusions provide valuable consideration to the situations in other regions that currently support a fish farming industry. The focus of this review, based on the documented scientific experience across these jurisdictions, reflects the negative impacts of HABs on these aquaculture industry sectors.

With support from studies presented in the primary scientific literature, the SEEG (2006) review found that in general, and with the available scientific information, that there was little indication that harmful algal blooms were developed, or sustained, by the nutrient inputs associated with salmon aquaculture facilities. The review also clearly indicates that the waste composition, water quality and oceanographic conditions required to initiate and sustain a harmful algal bloom are very complex and very much species-specific. Examples of this inherent complexity in phytoplankton physiology, and thus in the processes that could determine the development or stimulation of harmful algal blooms resulting from fish farm nutrient loads, are provided as follows.

Nutrient forms and uptake variability - experimental results

The nature of the organic waste stream released from a salmon farm, discussed in Chapters 2 and 3, will comprise a chemically diverse pool of dissolved organic nitrogen that will become available, in a variety of forms, to the phytoplankton species assemblage that occurs within this receiving environment. Laboratory studies that have exposed various toxic phytoplankton to farm excreta have shown that there is considerable difference in response among species. Arzul et.al. (2001) reported that PSP-forming species, *Alexandrium catenella* and *A. minutum,* were unaffected by these nitrogenous wastes, including the ammonia and urea components that are readily utilized by many species. Furthermore, this study showed that the Raphidophycean species *Heterosigma akishiwo* was inhibited by Atlantic salmon wastes – a surprising result given that this species has been responsible for devastating fish kills at farm sites and has been implicated as a bloom that may be stimulated by salmon farm wastes.

In addition to urea and ammonia, precursors within this catabolism pathway (including those of purines such as adenine and guanine) will also be available to phytoplankton upon release to the environment within the overall nutrient pool. Experimental work (e.g., Allison and Syrett, 1987) has shown that these breakdown products serve as good, sole N sources for phytoplankton. However, this literature has also shown that the capacity to assimilate these breakdown components varies significantly among species and that both stimulation and inhibition of growth will occur (Oliveira and Huynh, 1990). These authors also showed that the ichthyotoxic flagellate species *Heterosigma akashiwo* and *Prymnesium parvum* differed greatly in their ability to use these compounds as a N source. While the latter could use two of the purine breakdown products (hypoxanthine and xanthine) as a sole N source, *H. akishiwo* could assimilate none – in fact, it could only take up urea if nickel (Ni^{2+}) was present in the medium.

Experiments conducted with red tide species (Iwasaki, 1984; Gentein, 1998) hypothesized that exogenous polyamines could stimulate and regulate blooms. The release of polyamines from decaying diatomaceaous blooms and from spoiled fish (cadaverine, putrecine, spermidine) have been shown to stimulate growth of *Chyrsochromulata leadbeateri* in culture (concentrations < 110 uM), but depressed growth at higher (1,100 um) concentrations (Legrand et.al., 2001). Experimental studies have also suggested that n addition to their potential as phytostimulants, polyamines appear to be co-factors that enhance the ichthyotoxicity of toxins (Shilo, 1967; Legrand et al., 2001).

These experimental data, alone, can not be used to infer that such processes are involved in selecting, or triggering individual phytoplankton species during the initiation of a bloom event, but rather demonstrates the species-specific nature of nutrient uptake and the inherent complexity associated with the processes involved in the development of algal blooms (including HABs). The experimental nature of these studies make extrapolation to the field situation difficult, and as a result no confirmatory studies have been completed to support such laboratory observations.

Nutrient forms and uptake capability – links to field observations

Buschmann et.al (2006) states, that in addition to a variety of dinoflagellate and diatomaceous blooms that have occurred in Chilean waters over the past 3 decades, Chile has experienced a number of novel HAB events since salmon farming began within their southern waters. Concerns that salmon nutrient loading from these sites were expressed in this review paper. As a result, farm effluent was used to demonstrate that dinoflagellates were stimulated under the presence of these nitrogenous wastes while diatom populations become depressed in tank experiments. Limited field sampling at one farm site showed that dinoflagellate density became elevated within a few weeks after installation of the farm, as compared with two adjacent control stations. It was suggested that nutrient pulses could explain the localized impact to these naturally occurring phytoplankton populations.

Iriarte et al (2005) attempted to link field observations of HAB activity, derived from satellite imagery and *in situ* biomass and chlorophyll measurements, with an analytical approach that assessed the glutamine-synthetase (GS) enzymatic activity in the bloom-forming dinoflagellate species, *Gymnodinium cf. chlorophorum*. They suggest that since this enzyme correlates with the use of ammonium as an external nitrogen source it may be a good indicator for ammonium utilization when such single-species blooms occur. A reference to the potential use of this approach for salmon farm interactions with bloom development was also suggested, given the concentrations of ammonium nitrogen released from these facilities. No subsequent testing of this approach has yet been conducted.

Ongoing field observations of and bloom events in eastern Canada (Martin and LeGresley, 1999) can be related to annual levels across a long history of phytoplankton species monitoring in a salmon growing region that currently supports approximately 80-90 farms in a relatively small geographical area. However, early phytoplankton

records from the 1960's suggest that the introduction and subsequent increase in salmon farming have neither increased nor intensified blooms of these HAB species. In fact, HAB outbreaks of PSP-toxins (*Alexandrium fundyense)* were reportedly the largest in 1976 and 1979, prior to salmon farm development, and at that time were responsible for extensive herring mortality within this coastal area (Martin and LeGresley, 1999).

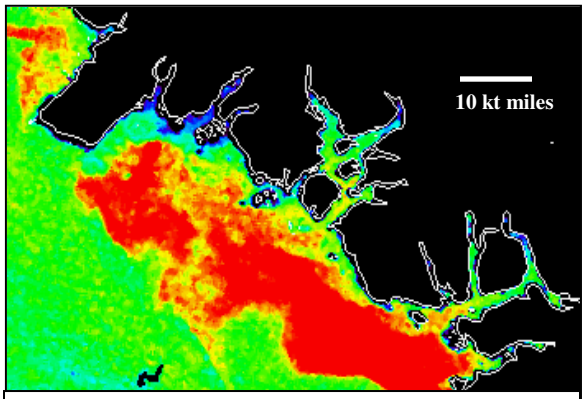
Although the species that produces domoic acid in the Bay of Fundy (Canada), *Pseudo-nitzschia pseudodelicatissima*, is present year round in the water column, concentrations have increased and exceeded one million cells per litre, resulting in unsafe levels of domoic acid in local shellfish. These events occurred in areas supporting salmon aquculture, but only in 1988 and 1995. No relationship to levels of farm production were shown to be associated with these blooms, yet continued concern over the potential role of these farms in stimulating or intensifying these events.

The ecophysiology of this species group, and in particular the production of domoic acid (the ASP-producing amino acid), provides one example suggesting that fish farm nutrient loading can not be directly responsible for its bloom dynamics. The excretion of ammonium (NH_4^+) from a farm represents a major component of the nutrient waste stream, the component known to be preferentially utilized by phytoplankton over that of nitrate (NO_3^-). However, the production of domoic acid can not occur in the absence of NO_3^-, and in fact is inhibited with increasing levels of NH_4^+ (Bates et.al. 1991). As nitrate is a *new* form of nitrogen, introduced via terrestrial inputs and oceanographic processes, the occurrence of ASP-producing HAB's will not develop not be sustained by the nutrient loads of a salmon farm.

Broad scale regional factors affecting bloom development

The regional development of algal blooms can occur on a regular, almost predictable manner in areas with well-defined processes that contribute to the basic requirements of bloom stimulation. Seasonal development of appropriate temperature conditions, nutrient concentrations and irradiance levels can initiate these bloom events. Local oceanographic processes can stimulate oceanic nutrient upwelling or seasonal rainfall periods can introduce terrestrial sources of nitrogen. Regions in which meteorological conditions are conducive to the development of optimal conditions will also, as a result, support resting (cyst) stages of certain HAB species – referred to as coastal seed areas.

The development and subsequent movement of HAB's from their originating seed areas, via advective processes, has been well documented (for a variety of species), in Norway (Dahl and Tangen, 1993), Sweden (Lindahl, 1993), the southern Gulf Stream (Tester et al., 1991), the Indo-Pacific (Hallegraeff and McLean, 1989), and along the Irish coast (O'Boyle et al., 2001) to name but a few. The advection of HAB's into areas of



Satellite image (chlorophyl) of offshore *Heterosigma akishiwo* bloom (red) off coastal British Columbia, Canada (black). Advection of the ichthyotoxic bloom into the inlet waters (offshore-inshore) is shown along the nearshore edge of the bloom. (Image produced from MERIS oribital platform sensor array).

salmon farming has represented the most significant concern in terms of risk to the aquaculture facility, and considerable effort has been placed on monitoring regional bloom movements to predict when such conflicts might development.

Heterosigma akashiwo provides a good example of a significant ichthyotoxic bloom species that has resulted in significant economic losses to the salmon aquaculture industry in western Canada (Whyte, 1999). The adjacent image shows the spatial extent of an intensive *Heterosigma* bloom developed from an offshore seed area. The bloom routinely starts to develop in late August, intensifies and is advected into the inshore waters via tidal currents and summer wind patterns. Salmon farm sites within the adjacent inlets can experience severe concentrations of this ichthyotoxic species with devastating consequences to farm stock.

Understanding the environmental conditions responsible for the regional, presumably natural development of phytoplankton blooms (harmful or otherwise) will allow a proper evaluation of the risks of nutrient loading from salmon aquaculture facilities. However, this can not be achieved in the absence of knowledge on the many other anthropogenic influences – in particular, other sources of nutrient inputs, the risks associated with species transplant (e.g., bilge water discharge impacts), global warming and its effects on broad-scale pattern changes, etc.

Summary

Much of the science related to harmful algal blooms has occurred outside of the areas directly influenced by salmon farms. A focus on the blooms themselves, through *in situ* monitoring (e.g., analytical approaches, detailed biomonitoring of species biomass/composition) within the initial dilution zone of farm facilities, and with concurrent and comparative assessments of these dynamics, could provide useful insight into how or if these nutrient inputs will have a stimulatory or inhibitory affect on phytoplankton blooms. A move to assessing the complex relationship among the *in situ* physical and chemical conditions affecting bloom development and persistence, the temporal and spatial fluctuations of nutrient flux (natural and farm-derived), and an understanding of the normal, successional change in species composition that would determine what species might be '*triggered*' to bloom is critical to considering and developing appropriate mitigation plans. Identifying which species are most susceptible to nutrient loading, in terms of bloom development, requires a further understanding of species-specific physiological differences, and lab-based assessments such as those conducted on a number of the HAB species will continue to provide a valuable linkage (input) to our understanding of these complex field observations.

Many HAB events can be clearly attributed to regional processes that occur well outside of the direct (near-field) influences of salmon farms. Seed areas for harmful algal species can produce intensive and extensive bloom events, and the transport of these blooms through oceanographic advective processes to distant farming areas can result in significant impacts to farm operations (fish stress/mortality through toxicity, dissolved oxygen depression, etc.).

However, from a scientific perspective while the nutrient loading of farm might not (alone) be sufficient to initiate and sustain HABs, the question remains as to whether the nutrient conditions within farming areas will promote the establishment of new phytoplankton seed areas, given conditions that may be conducive to the population dynamics of particular species.

Research needs

In terms of the nutrient loading effects of salmon aquaculture facilities on harmful algal bloom (HAB) development, re-occurrence (frequency), and regional/localized persistence, there remains a clear need to address the question of linkage with a focus on field studies. While laboratory and mesocosm-based research has provided valuable evidence of the potential for species-specific nutrient effects under controlled conditions, it is imperative to demonstrate whether lab hypotheses are valid under the complexity of field conditions – in essence, "*can harmful algal bloom development be related directly to the release of nutrients from salmon farms*?". Individually and as interactive co-variables affecting such processes, questions that require address under such *field* conditions include:

- What are the *in situ* concentrations of the various nutrient components of fish farm wastes over a production cycle, their release rates, and the variation of these fluxes over time (diurnal, seasonal change)? How do these relate to the population dynamics of the various HAB species?
- How does phytoplankton community structure, inter-specific competition and uptake preferences for available nutrients affect 'triggers' for algal bloom development?
- How do natural nutrient fluctuations interact with salmon farm nutrient pulses in determining algal bloom development, intensity and/or persistence?
- How does farm site physiography and oceanography affect nutrient component phytoavailability?
- At what farm production level, and under what receiving environment conditions, will a measurable nutrient impact be realized?
- Can predictive models be used to provide reasonable certainty (risk) regarding carrying capacity for specific, defined bodies of water?
- What ongoing mitigation measures can be employed to further reduce the risk of nutrient enrichment effects in and around salmon farms?

Recommendations for mitigating the potential for farm-related HAB development

While there is some laboratory-based evidence to support the position that the nutrient inputs from salmon aquaculture facilities can elicit a response within the harmful algal bloom community (SEEG, 2006), it remains unclear from the current scientific literature and available regional biomonitoring initiatives whether these sources of nutrients actually contribute to the natural and typically unpredictable nature of these bloom events. As many of the HABs comprise ichthyotoxic species, and hence have a direct and negative effect on the fish farms themselves, it would follow that a goal of reducing

nutrient waste discharges is inherently in the best interest of industry. The economic losses associated with such blooms have been significant (Whyte, 1999).

As presented in Chapter 2, the ongoing effort to improve feed quality will result in a continued reduction in farm nutrient flux. In Chapter 3, the siting of farms (i.e., number, size, proximity, oceanographic and physiographic considerations, etc.) is discussed in terms of the potential cumulative nutrient loading effects and hence carrying capacity issues. Both of these ongoing activities will minimize the flux and resulting *in situ* concentrations of farm-derived nutrients, and thus ensure that the natural assimilative capacity of the water column is neither exceeded nor significantly burdened.

Despite the current absence of scientific evidence to link fish farm nutrient loading to Harmful Algal Bloom development and/or persistence there will always, intuitively, be a concern that these, coupled with other anthropogenic nutrient loads to coastal waters, will have some future, unforeseen cumulative impact on ecosystem function. In addition to the incremental improvements in farm operations that will realize a gradual reduction in nutrient losses, other avenues of research and development that would result in further, and perhaps a more substantial removal of the nutrient loads from fish farms, is encouraged.

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CHAPTER 5: Nutrient impacts of salmon aquaculture on Chilean lakes

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Introduction

The southern region of Chile (40 – 55ºS) has seen an enormous growth of salmon aquaculture and now accounts for 90% of national aquaculture. Currently, salmon farming (80% of which is Atlantic salmon) is expanding to the southern fjord areas of Chile. There is still a lack of knowledge regarding how to manage farming operations to control the impact of salmon farming on marine and freshwater ecosystems (Soto & Norambuena, 2004; Buschmann et al 2006; Mulsow et al 2006). Salmon farming in southern Chile has increased to take advantage of favourable environmental features of pristine areas of inner seas such as fjords, embayments, estuaries, channels, as well as lakes and rivers of the southern region of Chile (Soto 2002). Salmon cage in southern region of Chile (the Inner Sea of Chiloé and fjords) can release large amount of organic matter and nutrients to the pelagic and benthic systems (Soto & Norambuena, 2004; Mulsow et al 2006). These nutrients could be recycled and utilized by pelagic and benthic food webs. Finally, a mayor comprehensive survey of salmon production within Chile`s freshwater southern lakes focused on the history, tendencies and environmental impacts was done by León et al (2007).

The study area considered in this review is focused in lakes of southern Chile (38 – 43ºS). The physical, chemical, and biological features of the water column and sediments have been studied to address the potential impacts of salmon culture. Specifically, several studies on carrying capacity have been done for lakes of Chiloé (Campos 1995, 1997a, b, c, d, e ; Soto 2002); antibacterial resistance from freshwater salmon farms (Miranda & Zemelman, 2002); salmon threats in freshwater system in southern Chile (Soto et al 2006); and studies on the bioindicators of salmon farming eutrophication (Soto & Mena 1999).

Phosphorus plays an important role as "limiting nutrient" for algal growth in lakes (Hecky & Kilham 1988). Steinhart et al (2002) working in 28 lakes of southern Chile found C:P and N:P ratios greater than the Redfield ratio suggesting P may be the primary limiting nutrients in southern Chilean lakes. Nitrogen forms (nitrate and ammonia) were also of particular interest due to their excretion as waste products by fish, as well as the ability of nitrogen to stimulate algal biomass in some aquatic systems (Glibert & Terlizzi 1999).

The main objective of this chapter is to evaluate the status of inorganic nutrients loading of salmon aquaculture in the lake systems of southern Chile. Inorganic nutrients such as nitrate, ammonia, orthophosphate, total phosphorus and total nitrogen through the water column at sites below salmon farms and sites surrounding the cages were sampled between 1997 – 2005 by different studies, and published in peer reviewed journals as government technical reports.

Description of the Chilean lake areas

Two distinct groups of lakes emerged based on literature nomenclature: North-patagonian lakes including Lakes Llanquihue, Rupanco, Puyehue, Yelcho. These lakes are considered oligotrophic, large and deep basins and several human activities around and within the lakes such as agriculture and salmon farming, tourism and recreation (sport fishing). The lakes are urbanized (Soto 2002; Soto et al. 2006). On the other hand, Chiloé lakes (also called humic lakes: Villalobos et al., 2003) corresponded to Lakes Natri, Huillinco, Tarahuin. These lakes are of small area, classified as eutrophic-hypertrophic lakes, had brown color waters and used mainly for smolt production. Most of their basins (near 70%) are covered by a mixed mature or regrown native forest (Villalobos et al 2003). Historically, the first stages of salmon farming in Chile (from ova to smolt) have relied on estuaries and freshwater (lakes and rivers) systems. Smolt production accounts for more than 50% of total activity in the Lake District, which represent a potentially large nutrient input to water column as well as sediment habitats.

Impacts on water column nutrients

Comparisons of water quality variables between Patagonian and Chiloé lakes revealed the importance of sitting salmon cages in areas of large lakes with deep basins and high water exchange rates (Table 1). Salmon farming strongly affected inorganic nutrients in the small, shallow lakes. On average, high concentrations of ammonium, nitrate and orthophosphate were found in surface waters around the cages compared to the control sites, mainly in Chiloé lakes (Natri, Huillinco, Tarahuin) (Figure 1). However, effects of inorganic nutrients on primary productivity and algal biomass were not observed around the cages (autotrophic biomass measured as chlorophyll *a*). The lack of effect may be attributed to an overall effect on the whole lake since carrying capacity evaluations for these lakes revealed that salmon cages have exceeded the lake's carrying capacity for nutrient inputs. In many of these lakes salmon farming has been shown to be the main nutrient input (eg. Natri, Tarahuin, Popetan). Similar results were obtained that showed increased nutrient values in Chiloé lakes (Table 2).

Most of the Chiloé lakes showed high concentrations of total nitrogen (annual mean: 200 – 3000 $\mu g\ L^{-1}$) and total phosphorus (annual mean: 20 – 500 $\mu g\ L^{-1}$) (Villalobos et al., 2003). At these lakes water exchange rates are apparently insufficient to reduce nutrient impacts through the dispersion or biological assimilation. Lake Natri (with a renewal time of water = 3.5 years; Villalobos et al 2003) has seen a major impact of salmon farming on nutrients. In summary, salmon cages cannot be sustainably operated in small Chiloé lakes and small embaynments of large Patagonian lakes without increasing overall lake levels of total phosphorus and total nitrogen. Similar patterns have been indicated for Canadian lakes suggesting that total phosphorus will be critical if farms follow historical procedures (Yan, 2005). Additional key information presented by León et al (2007) indicated (1) a positive smolt production trends (smolt abundance/surface lake) over the 1998 to 2005 period in several lakes of southern Chile, and (2) 10 salmon farms in lakes showed stated of anoxia, wich represents 20% operating in lakes during the 2003 to 2005 period. Thus, it is evident that the impact of salmon farming in lake systems of southern Chile shows no sign of declining.

On the other hand, Patagonian lakes (Llanquihue, Rupanco, Puyehue, Yelcho) no significant differences between lakes having salmon cages and control sites were detected for total phosphorus (3.2 – 11.2 µg L^{-1}), orthophosphate (2.1 – 4.1 ug L^{-1}), dissolved inorganic nitrogen (DIN: 12.4 – 31.2 µg L^{-1}), as well as chlorophyll biomass (0.7 – 2.1 µg L^{-1}) (Soto, 2002). However, another study showed higher nutrient concentrations in two bays having salmon aquaculture in Lake Llanquihue (Table 2; Figure 3). This study also demonstrated that in these bays, phytoplankton cell densities showed significant increases (Figure 2, Table 3). Cell densities of diatoms decreased, and dinoflagellate cell densities increased near salmon farms in comparison with control areas (Figure 2). Therefore, increased nutrients from salmon aquaculture in poorly flushed, oligotrophic lakes with long water residence times showed significant impacts on water column nutrient levels and phytoplankton. To mitigate these, an ecosystems approach can be incorporated which, for example, could include enhanced sport fishing by increasing fishing pressure around cages, by using polycultures (Soto and Mena, 1999), or by implementing habitat modification devices (Soto and Jara, 2007). It is important to note that the status of southern chilean lakes depends on several others productive activities such as agricultural, livestock grazing, industrial, urban waste and land use change, which are sources of contamination and must be included in future environmental impact analyses.

Water quality implications

Results compiled from several studies published to 2002 indicate that Chiloé lakes were heavily impacted by salmon cages probably due their small size, shallow depth and low water exchange rates, among other variables (farming practices, volume of water). Concentrations of total phosphorus, total nitrogen, dissolved inorganic nitrogen, and orthophosphate were most affected due to salmon farming in these lakes. In lake systems these conditions lead to oxygen depletion (Cornel & Whoriskey, 1993; Temporetti & Pedrozo, 2000; Veenstra et al., 2003) due to enhancement of respiration by fishes and bacteria-zooplankton. Impacts on the relative abundance/biomass of phytoplankton and zooplankton components may also be expected (Stirling & Dey, 1990). In contrast, Patagonian lakes (with higher number of farms compared with Chiloé Lake system), had more localized and short term impacts on the pelagic ecosystem due to their larger volumes and higher water exchange rates.

Research needs

Long-term water quality data from Chiloé and Patagonian lakes influenced by salmon farms in should be collected in order to test, at a whole-lake level: (i) enhancement of autotrophic biomass and carbon availability to microbial components (bacteria and microzooplankton), (ii) oxygen depletion in the water column by different biological processes such as respiration by fish, microbial respiration, and nitrification; and (iii) changes in the relative abundance of higher trophic levels including zooplankton and native fishes.

For those lakes that no longer in use for salmon cage farming, remediation research should be conducted to follow the absorption of nutrients and improvement in pelagic and benthic ecosystems.

Management needs

Studies of carrying capacity of Chilean lakes (Fisheries Research Fund from the Fisheries Undersecretariat, Campos et al 1997a, b, c, d, e; Villalobos et al 2003) show that salmon farming has exceeded the carrying capacity of these ecosystems, especially for lakes on Chiloe Island, and these lakes have developed eutrophic conditions. Better management of siting of salmon cages in the lakes would avoid their location in small and shallow lakes, and restrict the size of the farms (in terms of density/biomass production). One example is given by Leon et al (2007), which recommended the need for a shift to closed-containment recirculation systems than the traditional flow-through system because the first eliminate many of the environmental impacts.

For larger lakes which may still hold the promise of sustainable salmon farming it is important to develop an ecosystem approach to aquaculture. A permanent monitoring program should be in place with indicators which can be connected to salmon farming management. Monitoring should include potential links between nutrient levels, morphometrics-hydrological site-specific features, farm-related production variables (biomass production), and operational procedures.

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Table 1. Two examples of Chiloé (Natri and Tarahuin) and North-patagonian (Llanquihue and Rupanco) Chilean lakes. Morphometric parameters, salmon production and soluble Phosphorus and Nitrogen (*) loaded to lake water column.

Variables	Natri	Tarahuin	Llanquihue	Rupanco
Surface Area (Km2)	7.8	7.7	870	235
Catchment Area (Km2)	46.5	38.1		9994
Mean Depth (m)	35	22	182	163
Land Use	>50% mixed native forest	>50% native forest	>50% agriculture	>50% mixed native forest
Salmon Production (Tons)	480		2600	520
P soluble (of total waste from salmoniculture origen) **	1300 (22%)	32 (30%)	9 (30%)	8 (9.7%)
N soluble (of total waste from salmoniculture origen) **	33000 (80%)	120 (60%)	72 (60%)	75 (15.5%)

* Soto (2000); Campos (1997a, b); Campos (1995)

** Estimated by traditional P and N mass balance models (Vollenweider 1968, 1976; Dillon & Rigler, 1974).

Table 2. Concentration of macronutrients (Phosphate PO_4); Total Nitrogen (N = Nitrate + Nitrite + Ammonium); all in µg L^{-1}) in Lake Llanquihue (Puerto Fonck and Ensenada) and Chiloé. (A) Data from Soto (2002) and (B) Buschmann, unpublished results.

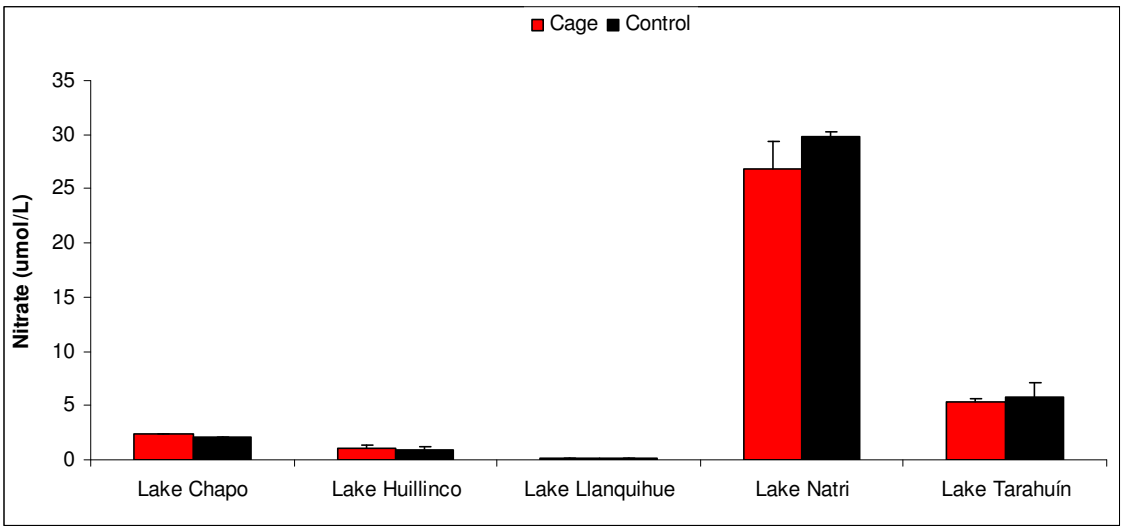
	A: Soto (2002)		B: Puerto Fonck		Ensenada		Chiloé[1)]	
	PO_4	N	PO_4	N	PO_4	N	PO_4	N
Controls	1.5	17.4	----	----	----	----	----	----
Bays with salmon	2.26	23.57	ND[2)]	ND[2)]	9.0	66.0	553.3	424.0
Under salmon cages	----	----	10.0	65.0	15.0	35.6	286.0	414.0
Interstitial waters	----	----	1666.3	----	953.3	----	4703.3	----

[1)]Average values for Lake Natri and Huillinco; [2)]ND = values under the detection limit

TABLE 3. Nested factorial ANOVA testing the response of cell density (cell numbers mL^{-1}) of (A) total phytoplankton; (B) diatoms; (C) dinoflagellates; (D) other phytoplankton cells in the water column (data in Figure 2) . The analysis considered different control and salmon farming sites in Patagonian lakes (Rupanco and Llanquihue) and Chiloé Island lakes (Huillinco and Natri). d.f. = degree of freedom of the ANOVA.

TREATMENTS	A: TOTAL PHYTOPLNAKTON (d.f.= 1,30)	
	F-Value	Probability
Patagonian vs. Chiloé lakes (L)	0.963	0.004
Farming vs. Control sites (C)	5.954	0.021
L x C	2.048	0.163
Sites Variability	23.06	<0.001
	B: DIATOMS (d.f. = 1, 30)	
Patagonian vs. Chiloé lakes (L)	11.69	0.002
Farming vs. Control sites (C)	7.971	0.008
L x C	2.724	0.109
Site Variability	31.525	<0.001
	C: DINOFLAGELLATES (d.f. = 1, 30)	
Patagonian vs. Chiloé lakes (L)	0.914	0.347
Farming vs. Control sites (C)	0.060	0.809
L x C	1.251	0.272
Site Variability	0.152	0.699
	D: OTHER PHYTOPLANTON (d.f. = 1, 30)	
Continental vs. Chiloé lakes (L)	0.141	0.709
Farming vs. Control sites (C)	0.298	0.589
L x C	0.018	0.893
Site Variability	1.420	0.243

Fig. 1a. Nitrate and orthophosphate concentrations in water column measured in salmon farming cages at Patagonian (lakes Chapo and Llanquihue) and Chiloé lakes (Huillinco, Natri and Tarahuin).



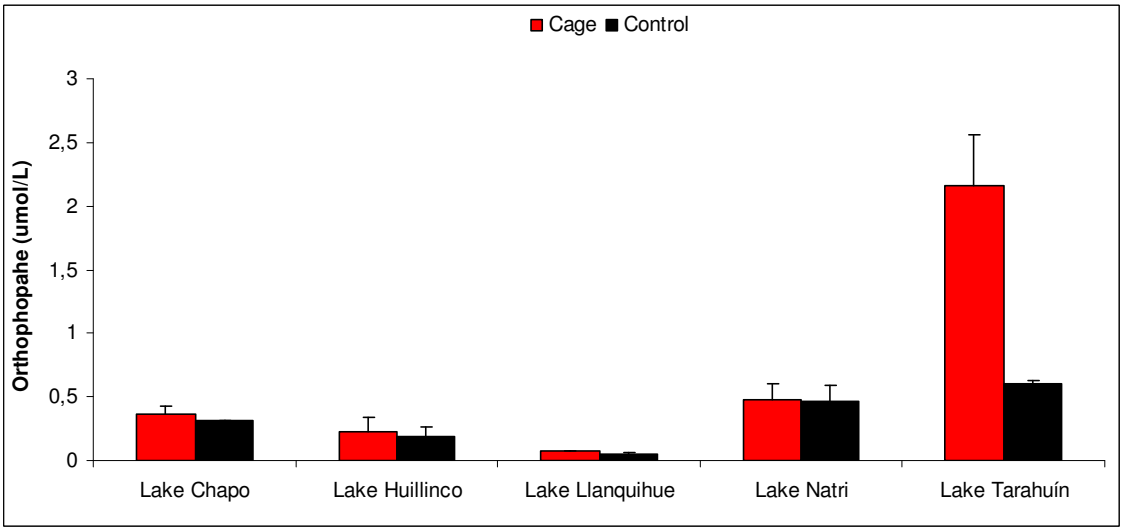
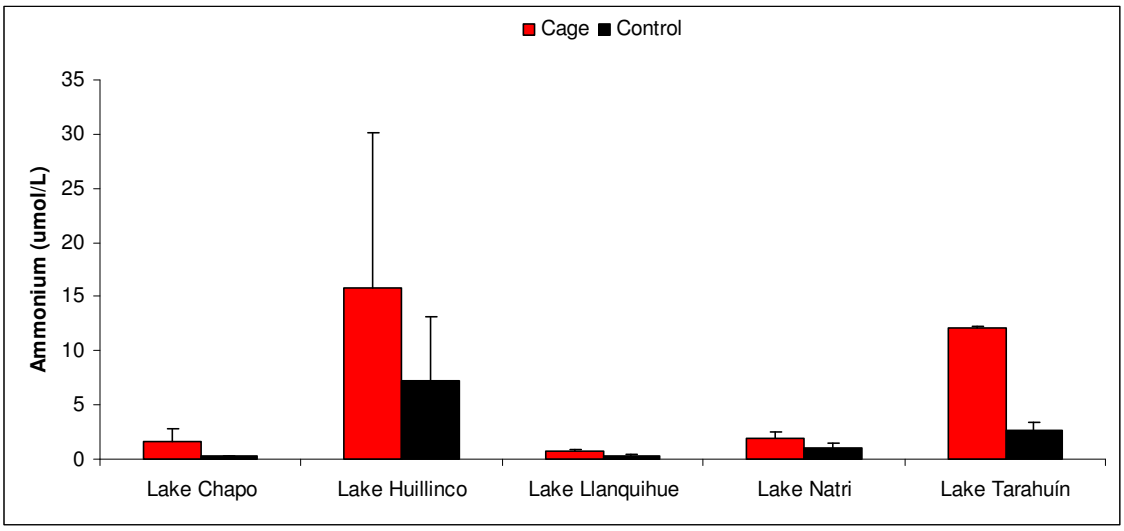


Fig. 1b. Ammonium concentrations and chlorophyll *a* biomass in water column measured in salmon farming cages at Patagonian (Chapo and Llanquihue) and Chiloé (Huillinco, Natri and Tarahuin) lakes.



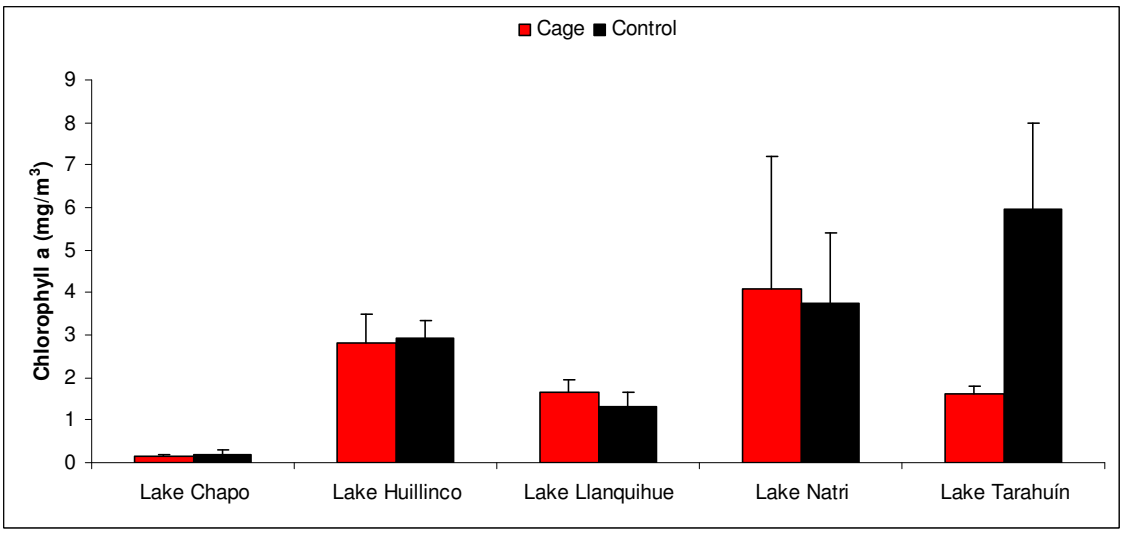


Figure 2. Cell densities of phytoplankton in salmon aquaculture (cage) and control areas (control) in Patagonian (Continental) and Chiloe lakes. Statistical analysis of the data in Table 3.

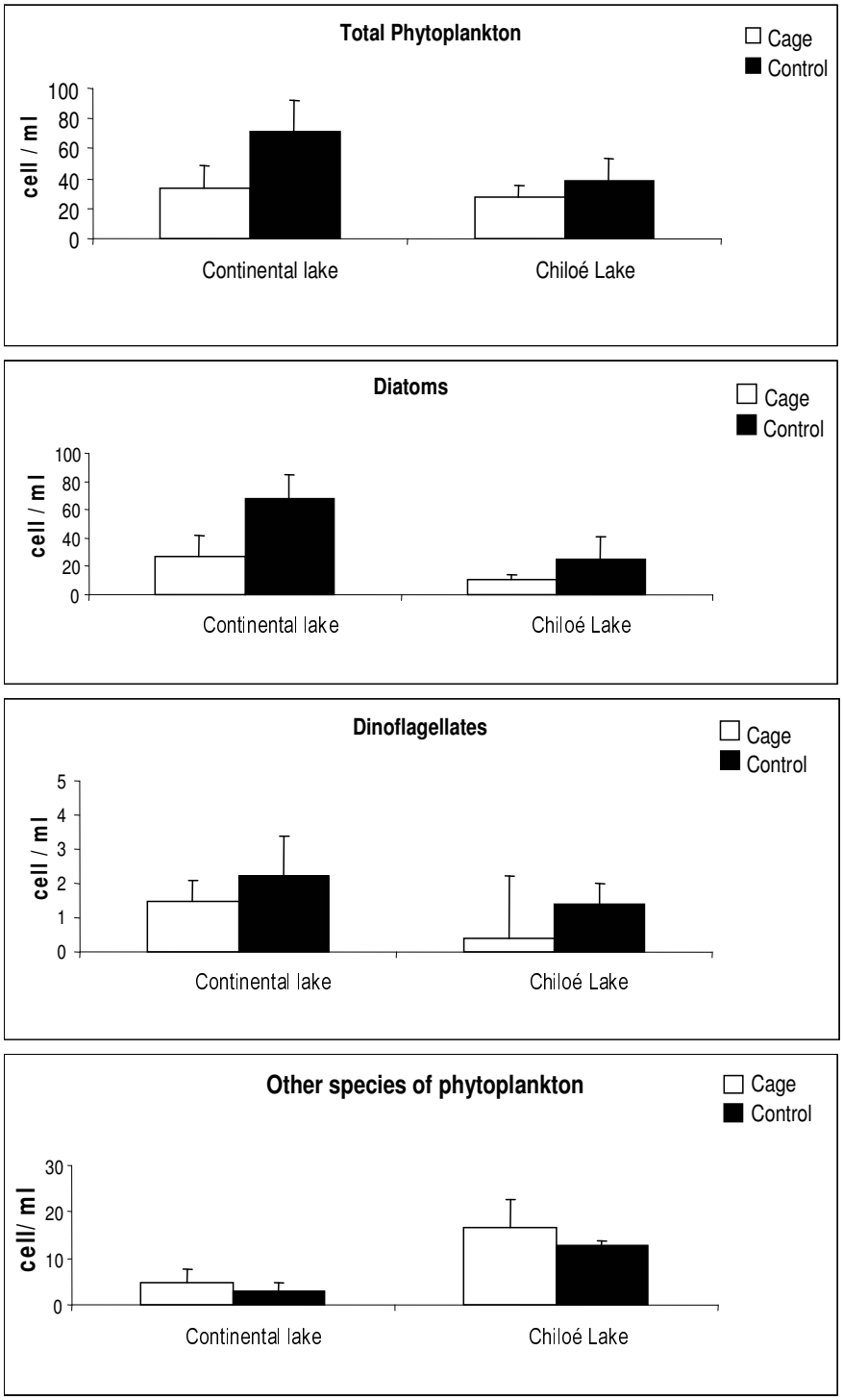


Figure 3. Nitrogen and Phosphorus budget for salmon farming into oligotrophic lake Llanquihue. Original figure based on information in Soto (2000).