# Impacts of Salmon Aquaculture on the Coastal Environment: A Review

Inka Milewski
Conservation Council of New Brunswick, 180 St. John Street, Fredericton, New Brunswick, Canada, E1N 4S5, Tel (506) 622-2460; Fax (506) 622-2438; E-mail: milewski@nbnet.nb.ca

**Abstract**

By the end of this decade, world-wide production of farmed salmon is estimated to reach 2,000,000 mt and almost all farmed salmon production takes place in sheltered areas of the coastal zone. This paper reviews the main activities associated with the marine phase of salmon aquaculture production, the pathways to the environment of the various activities and the potential effects on the coastal environment. The review is based on a extensive survey of the last ten years of published scientific research. It concludes there are large gaps in our knowledge of the impacts salmon aquaculture has on the marine environment. At the same time, the review reveals that salmon aquaculture: 1) contributes to coastal nutrient pollution, exacerbating existing problems from agricultural runoff, sewage discharges and atmospheric deposition; 2) releases toxic compounds, exacerbating existing pollution of coastal ecosystems; and 3) interferes with the performance of existing wild salmonid stocks, exacerbating the continuing decline in wild Atlantic salmon stocks. Given the large gaps in our knowledge and the universally acknowledged poor state of health of estuaries and coastal waters, it is recommended that regulatory agencies and policy-makers apply the precautionary principle to decisions concerning expansion of salmon, as well as other finfish, aquaculture in coastal waters and to maximizing mitigative measures (e.g., closed containment systems, restrictions on the use of pesticide and acoustic deterrent devices, moratoriums, and comprehensive environmental assessments) on existing operations.

## Introduction

The production of farmed Atlantic salmon (*Salmo salar*) has risen dramatically in the past decade. In 1990, world-wide production was 225,492 metric tonnes (mt) and the projected production for 2000 is estimated at over 700,000 mt (FAO 1998). By the year 2010, world-wide production of farmed salmon is estimated to reach almost 2,000,000 mt (IntraFish 1999). Not only has production increased, but the intensity of salmon aquaculture has also increased. In the 1970's and 1980's, salmon farms were raising tens of thousands of fish per farm and farms were generally scattered over a large geographic area. Today, a single salmon farm can cover many hectares of coastal area and raise hundreds of thousands of fish per farm site. World-wide production has also increased due to the introduction of various salmon species to countries (e.g., Australia and Chile) and regions of countries (e.g., west coast of Canada and the United States) where the species did not exist naturally ( Thomson and McKinnell 1997; Reilly et al. 1999; Winkler et al. 1999).

Almost all farmed salmon production takes place in sheltered areas of the coastal zone. These areas provide protection from heavy seas, suitable year-round temperature and, depending on the location, some tidal flushing (Saunders 1995). Coastal sites also provide salmon growers with convenient and inexpensive access to their grow-out sites. New technologies and production techniques have allowed the salmon aquaculture industry to expand into previously undeveloped sites such as offshore and more wave-exposed areas (Rosenthal et al. 1995a). Space limitations and environmental problems such as disease outbreaks have forced some producers into new areas that may be marginal for salmon farming, ecologically sensitive, or in conflict with traditional uses of the area (Millar and Aiken 1995; Cripps and Kelly 1996; Muir 1996).

Along with the rise in salmon production, there has been an increase in public and scientific concern about the environmental impact of salmon aquaculture. This concern has led to increased research which in turn has led industry to make improvements in feed quality, feeding control and husbandry practices. Food conversion ratios (the weight of food fed: biomass of fish produced) have dropped, the dietary levels of nitrogen and phosphorus levels have decreased, and the use of antibiotics has dropped 90% per unit weight (Beveridge et al. 1997). The benefits gained from these improvements may have been offset by the overall increases in the number of fish farms and fish production. For example, the waste discharges from individual farms may have decreased but the number of farms and the number of fish per farm has increased. The result is a net increase in waste discharges. The ability to improve feeding efficiencies and food conversion ratios may have peaked and there is considerably less room for reduction of waste outputs in the future (Beveridge et al. 1997; Burd 1997).

The number of scientific reports and environmental assessments on the impact of waste discharges from salmon farms is extensive (Ackefors and Enell 1990; Bergheim et al. 1991; Braaten 1991; Folke et al. 1994; Gowen et al. 1994; Hansen 1994; Findlay et al. 1995; Rosenthal et al. 1995b; Bergheim and Åsgård 1996; GESAMP 1996; Burd 1997; Findlay and Watling 1997; ICES 1999; Dudley et al. 2000; Mazzola et al. 2000; Morrisey et al. 2000; Pohle et al. 2001). Despite the volume of research conducted to date, the full range of environmental issues has not been adequately examined. For example, there are no studies which examine the impact of waste discharges from farm sites on the structure and function of coastal habitat (Costa-Pierce 1996). This type of research would examine the impact of fragmenting benthic habitat by waste deposition on ecological processes like competition, predation and energy flow. There are also very few published studies on the impact of aquaculture on biodiversity at larger spatial and ecological scales (Beveridge et al. 1997)

This paper was one of a series of discussion documents prepared for a conference, Marine Aquaculture and the Environment: A meeting for stakeholders in the Northeast. Its purpose was to provide background information to participants and to stimulate discussion on the research, conservation, resource management and sustainability issues posed by aquaculture development. This paper offers only a brief review of the potential impacts of salmon aquaculture, specifically the marine phase of production, on the marine environment and its associated wildlife and covers only the last ten years of published scientific literature.

**Pathways of Interactions with the Marine Environment and Potential Effects**

The production of farmed Atlantic salmon can be viewed as a two-phase activity. The first is a freshwater phase which involves the production of juveniles (smolt) from eggs. This process can be entirely land-based with eggs raised in hatcheries and, once hatched, transferred to large outdoor tanks. Grow-out of smolts in lake cages does occur (e.g., Scotland, Norway, Chile and British Columbia) (Saunders 1995). Eggs can be obtained from an on-farm or local commercial hatchery operation. They can also be imported from hatcheries from other regions of a country or, depending on import regulations, foreign sources. The second phase is the marine grow-out phase. Smolt are transferred to net pens or sea cages anchored in nearshore coastal waters where they are fed and grown to harvestable weight. The number of salmon per net pen will depend on the size of the salmon, the size of the net pen, depth of the water beneath the net pen and general water quality conditions. Stocking density (kilograms of fish per cubic metre) may be regulated by government agencies.

Salmon aquaculture takes place mainly in sheltered areas of the coastal zone which include habitats such as estuaries, salt marshes and mud flats (Beveridge et al. 1997). Estuaries, where many salmon aquaculture operations are sited in North America, rank as some of the most biologically productive and important ecosystems in the world (Thorne-Miller and Catena 1991; Norse 1993). Estuaries provide temporary or permanent homes for a large number of commercially important animal species such as clams, oysters, lobsters, scallops, salmon, pollock, flounder, herring, and haddock, as well as plants such as kelp and rockweed. Seventy-five percent of the United States commercial fishery landing are estuarine-dependent species (Chambers 1992). Estuaries are also areas of high biological productivity and provide the ecological foundation for many other non-commercial species such as birds, invertebrates (including plankton) and marine mammals.

Table 1 identifies the main activities associated with the marine phase of salmon aquaculture production, the pathways or connections to the environment of the various activities and the potential effects of these activities on the environment and its associated wildlife. (A similar table can be prepared for the freshwater phase of salmon aquaculture). The table identifies potential interactions only and makes no assumptions about the degree or magnitude of the impacts to the environment. The magnitude of an impact will depend on many factors such as the scale and duration of the activity, the biological and oceanographic setting in which the activity takes place, and the combined effect of other past, existing and imminent activities in the area. Ultimately, the determination as to whether environmental impacts will occur can only be addressed through some type of comprehensive environmental impact assessment process. This review will focus on some of the key pathways associated with the marine component of salmon aquaculture operations.

***Effects of Net Pen Structures***

A single net pen or sea cage occupies a vertical and horizontal space in the water column. Net pens range in size from 900 $m^3$ to 32,000 $m^3$ and they are laid out in double rows of 8, 12 or 20 pens (Saunders 1995). The number of fish produced per farm varies depending on the depth of water and current speed at the site, the size of the site, number of net pens and, in some countries, guidelines established by regulatory agencies. For example, guidelines in New Brunswick (Canada) calculate the theoretical Estimated Site Potential (ESP) for a site with a water depth of 20.0 - 24.99 m and a minimum area of 12.03 hectares to be 240,000 fish (Rosenthal et al. 1995b). In New Brunswick, many farms raise between 200,000 - 300,000 fish. The distance separating individual salmon farms is variable and may be prescribed by government regulations. In New Brunswick, the minimum separation distance between salmon farms is 300 m and there is no scientific basis for this distance (Rosenthal et al. 1995b). Norway, Scotland, Ireland and British Columbia suggest 1 km as a minimum separation distance between farm sites (Stewart 1998). Chile has set 2.4 km as the mandatory distance between farms.

The simple presence of net pens in the water serves to attract and deter wildlife. Fish in the pens and excess or uneaten feed provide food for seals, birds, other fishes and invertebrates. The physical structures of the net pens may provide shelter for some benthic animals as well as present a physical or olfactory barrier to other species. According to a 1987 survey conducted in British Columbia, factors which influenced the magnitude and degree of interaction between salmon net pens and wildlife include: farm size, age and net pen structure; size and species of salmon raised; proximity to colonies or concentrations of wildlife; site management practices and the size and colour of mesh used in predator nets (Rueggegerg and Booth 1989).

There are very few studies and only a handful of reports on the direct impact of net pen structures on wildlife. For example, drowning of birds by entanglement in net-cages does occur (Iwama et al. 1997). (The subject of bird and aquaculture interactions is covered by the discussion paper prepared by Thurman Booth.) The potentially large physical barrier created by net pens could affect the migratory behaviour of pelagic fishes, birds or marine mammals. Herring fishermen in New Brunswick believe that salmon cages may alter or block normal migration routes taken by herring, thus interfering with the fixed gear weir fishery (Milewski et al. 1997). Stephenson (1990) notes that herring weirs in close proximity to major salmon farm sites have been observed to perform poorly. No studies and scientific research have been done to support or refute these observations.

***Noise Effects from Acoustic Harassment Devices***

The fact that net pens attract wildlife and can cause direct losses in farmed fish production has led salmon farmers to use a variety of methods (e.g., underwater predator nets and curtains, top nets for bird exclusion, underwater acoustic devices, emetics, seal bombs, trapping, dogs, guns) to reduce or eliminate wildlife interactions (Iwama et al. 1997). The use of underwater noise to deter or repel marine mammals, particularly seals, has been used by salmon farmers since the mid 1980's. Two basic types of underwater devices can be used: 1) low-powered devices called acoustic deterrent devices (ADDs) used to temporarily displace marine mammals from potential danger such as fishing gear; and 2) high-powered acoustic harassment devices (AHDs) designed to cause pain and used to prevent marine mammal predation on fish (Johnson and Woodley 1998; Reeves et al. 1996). Low-powered ADDs have proven to be ineffective in deterring seals as they seem to habituate to the sound (Iwama et al. 1997). Although the principle target of ADDs and AHDs is seals, other wildlife (e.g., fish, invertebrates, and cetaceans) can respond to underwater noise effects (Popper and Fay 1993; Richardson et al. 1995; Hartline et al. 1996; Wiese 1996).

Water is an efficient medium through which sound can travel long distances and the ability of an animal to detect sound depends an animal's hearing process (Davis et al. 1998). For example, some fish like herring have very good auditory capabilities whereas other species, like cod, Atlantic salmon, pollock and haddock are less sensitive to sound (Enger 1967; Olsen 1969; Fay 1988; Popper and Fay 1993; Mann et al 1997). Many invertebrates have vibration sensors and, while they do not "hear", they do sense the associated particle motion created by the sound (Budelmann 1996).

Cetaceans largely sense their environment and communicate using sound. Human-generated noise is of particular significance to these animals (Ketten 1991). Noise can potentially affect cetaceans in several ways. These include: permanent deafness; temporary threshold shifts (reduced sensitivity to sounds for a time); stress; psychological effects; behavioural responses (such as orientation away from the sound or cessation of feeding); and masking of other sounds important to the animals which could be from prey, predators, members of the same species or other parts of their environment (Richardson et al. 1995; Gordon and Moscrop 1996) .

In underwater acoustics, sound is expressed as sound pressure level (Pa - Pascals) and a source level is usually expressed as function of the sound pressure level at 1 m from the source (Davis et al. 1998). For example, the source level for a commonly used AHD is expressed as 194 decibels (dB) re 1 Pa at 1 m (Iwama et al 1997). Baleen whales often show behavioural reactions to noise at an sound pressure levels of about 120dB re 1 Pa at 1m (Richardson et al. 1995). A recent study found American shad (*Alosa sapidissima*), a clupeid, had two regions of sensitivity: one at low frequencies (1- 8 kHz) which is commonly found among fishes, and one at high frequencies (25-180 kHz), at which most fish have not previously been tested (Mann et al. 1997). The hearing threshold for herring at high frequencies (50 - 1200 kHz) has been reported as 75-80 dB re 1 Pa (Enger 1967). The sound received by an animal will depend upon how much propagation loss occurs between the source and the receiver and there are many factors (e.g., water depth and temperature) that affect the propagation of sound in water (Davis et al. 1998).

There is a considerable body of scientific literature on the effect of underwater noise on wildlife, particularly from off-shore oil and gas operations on cetaceans. Direct research on the potential effects on wildlife of AHDs used on salmon farms has been slow to emerge. There are a few exceptions. A field study done in British Columbia found that the abundance of harbour porpoise (*Phocoena phocoena*) dropped precipitously in the study area when an AHD was activated. The impact of the AHD was suggested to extend beyond the 3.5 km sighting range of the field study (Olesiuk et al. 1995). The results of two independent studies that monitored the occurrence of killer whales (*Orcinus orca*) between 1984 through 1998 in two areas northeast of Vancouver Island (British Columbia) concluded that the use of AHDs was the primary cause of the whales' avoidance of traditional travel routes (Morton and Symonds 2000). The decline in traditional abundance of killer whales in the Broughton Archipelago and Johnstone Straits areas was statistically correlated to the onset of ADH used by salmon farms in the study areas. Morton (2000) also found that Pacific white-sided dolphin (*Lagenorhyncus obliquidens*) declined in the Broughton Archipelago after AHDs were introduced.

Strong et al. (1995) and Johnston and Woodley (1998) surveyed the use of AHDs in the Bay of Fundy (New Brunswick). Strong et al. (1995) found a high proportion (40 - 60%) of salmon farms using AHDs to ward off seals. Johnston and Woodley (1998) reported 46% of aquaculture sites in the Quoddy region and 22% of sites in the Grand Manan areas used AHDs. They believe their figures may be an underestimate as their initial survey was done during daylight hours. A subsequent evening survey of four sites in the Quoddy area revealed that one AHD was activated only during evening hours (Johnston and Woodley 1998). Both surveys concluded that AHDs could negatively impact harbour porpoise (*Phocoena phocoena*) populations by displacing them from their traditional feeding areas.

Virtually no studies have been done on the effects of underwater noise on seabirds and very few studies have been done on fishes or invertebrates. There are no direct studies done to date on the effects of AHDs use by salmon farms on sound-sensitive fish species like herring (*Clupea harengus*) or baleen whales such as the Atlantic Right (*Eubalaena glacialis*), Minke (*Balaenoptera acutorostrata*), Fin (*Balaenoptera physalus*) and Humpback (*Megaptera novaeangliae*) whales. Research done on the use of low-powered (133-145 dB re 1 Pa) ADDs to mitigate harbour porpoise by-catch in gill nets present conflicting results on their impact on herring catchability (Kraus et al. 1997; Trippel et al. 1999; Culik et al. 2001).

### *Escapement of Farmed Fish*

Atlantic salmon juveniles and adults escape from net pens as a result of operator error, storm damage, predation by seals, or vandalism. The release of farmed fish into the wild means financial losses to salmon farmers and, depending on the scale and frequency of escapements, it can mean ecological losses. There is now a general recognition that one of the most damaging environmental consequences of aquaculture is the escapement and establishment of self-sustaining introduced species or the alteration of indigenous (native) gene pools (Arthington and Blühdorn 1997).

Lassuy (1995) reports that the introduction of non-native fish from aquaculture facilities is believed to be a factor in the decline of seven fish species listed as endangered or threatened under the U.S. Federal Endangered Species Act. The brown trout (*Salmo trutta* L), introduced to Australia in the late 1800's, has been implicated in the decline in numbers of four endangered species and four vulnerable species (Welcomme 1988). Rainbow trout (*Oncorhynchus myskiss* (Walbaum)) has been implicated in the decline of indigenous fishes in Peru, Columbia, Chile, Yugoslavia, Himalayan rivers, South Africa, and New Zealand (Welcomme 1988). The impacts of non-native species on the native biota are usually irreversible (Arthington and Blühdorn 1997).

The potential effects of escaped aquaculture organisms have been summarized in four categories: 1) alteration to the host environment (e.g., direct effects on physical habitat, water quality and biological resources); 2) disruption of the host community (principally through predation and competition); 3) genetic degradation of wild stocks; and 4) introduction of parasites and diseases (Beveridge and Phillips 1993). Some or all of these effects may occur depending in part on whether the species is introduced (released into an environment outside its natural range) or whether the farmed species is within its native range and the population status (e.g., abundance, reproductive success, recruitment, etc.) of the native species.

Research on the potential impacts of escaped farmed salmon on wild salmon has accelerated over the past 10 years. With 94% of all adult Atlantic salmon located in aquaculture operations and the populations of wild Atlantic salmon continuing to decline, questions about the evolutionary fate of wild Atlantic salmon have been raised (Crozier 1993; Heggberget et al. 1993; Fleming et al. 1996; Gross 1998; DFO 1999; Norris et al. 1999; Fleming et al. 2000). It has been suggested that as a result of 'domestication,' farmed Atlantic salmon now represents a new biological entity, *Salmo domesticus*, which exhibits many genetic and developmental differences from the wild species (Gross 1998). If, as has been reported, farmed salmon can reproduce in natural waters (Carr et al.1997; DFO 1999; Fleming et al. 2000) and outside their native range (Volpe et al. 2000), farmed Atlantic salmon have the potential to be very successful invaders in areas outside, as well as inside their native range. The potential ecological effect of their invasion ranges from competition for food and space and predation on early life stages, to complete displacement of wild species and impoverishment of biodiversity (NRC 1997; Gross 1998). (The subject of farmed and wild salmon interactions is covered by the discussion paper prepared by Kjetil Hindar). There is no published scientific literature on the ecological effects of escaped farmed Atlantic salmon on other wild non-salmonid species.

In addition to ecological and genetic impacts, escaped farmed fish can transmit pathogens (e.g., viruses, bacteria, parasites, etc.) to wild fish. Wild fish can also transmit pathogens to farmed fish and there is considerable discussion and debate as to whether wild salmon pose a greater disease threat to farmed salmon than escaped farmed salmon pose to wild fish. A literature survey by Bakke and Harris (1998) reveals that 225 species of infectious agents have been reported from wild and domesticated Atlantic salmon in marine and freshwater habitats.

The presence of a pathogen within an organism does not imply a disease condition will develop. The development of an overt disease is the result of a complex interaction between the host fish, the pathogen and the environment (Kent 1994). A healthy fish living under good to excellent habitat conditions will usually resist infection by pathogens (Stewart 1998). Stephen and Iwama (1997) explain the higher frequency and prevalence of diseases in cultured species compared to wild fish in part by the fact that the density of fish within the net pen is high and a pathogen is likely to find a new susceptible host. Stress caused by adverse temperature and salinity levels, low oxygen or high carbon dioxide levels, poor diet, overcrowding, presence of predators, transportation, or high suspended solids will predispose salmonids to disease by raising blood cortisol concentration which compromises the function of the immune system (Schreck et al. 1993; Barton and Iwama 1991).

According to Bakke and Harris (1998), very few pathogens have had significant impacts on wild salmon populations. Although many pathogens are found in both wild and farmed fish, disease outbreaks in wild salmon resulting from the spread of disease from farm salmon remains an exceptional phenomenon. With so few wild salmon left, however, any disease outbreak in the wild population can be significant. Conspicuous epidemics in wild salmon populations have been cause by a few bacteria (*e.g., Aeromonas salmonicida* responsible for furunculosis, *Renibacterium samoninarium* responsible for bacterial kidney disease) and a monogean parasite, *Gyrodactylus salaris* (Bakke and Harris 1998). More recently, sea lice (parasitic copepods) outbreaks have been reported in wild salmonids (Birkeland 1996; Johnson et al. 1996 ). The virus causing infectious salmon anemia (ISA) has been reported in wild salmon (Whorisky 2000).

Depending on the infectious agent and the infectious load at the farm site, pathogens from farmed salmon can be transmitted to invertebrates, birds, other fishes, plankton, sediments, and carried on various fish wastes which, in turn, can serve as reservoirs for the pathogen. Nese and Enger (1993) isolated *A. salmonicida* in marine plankton and sea lice which has also been identified as a vector for transmitting *A. salmonicida* and ISA (Nylund et al. 1993). Bjoershol et al. (1999) examined the risk of disease transmission between scallops and Atlantic salmon in Norway. In a laboratory experiment, they demonstrated that scallops could accumulate and excrete the bacteria, *A. salmonicida,* responsible for furunculosis for 14 days after initial exposure. Salmon exposed to infected scallops exhibited an increased mortality rate; the scallops appeared unaffected by the pathogen. When the scallops were challenged with ISA-virus, the virus was not detected in the scallops, nor was it possible to transmit ISA-virus from scallops to salmon in the experiment (Bjoershol et al. 1999). In laboratory experiments, Totland et al. (1996) demonstrated that skin mucus, faeces, urine and blood could transmit the ISA-virus and cause disease conditions with variable efficiency in healthy Atlantic salmon. Bruno and Stone (1990) showed that the sea louse, *Lepeophtherirus salmonis,* could transfer from farmed salmon to pollock and from pollock to salmon. The length of time plankton, sea lice, other invertebrates, sediments or skin mucus can be carriers or reservoirs of viable pathogens varies from a few hours to years depending on the pathogen. The potential also exists for a pathogen reservoir to be viable long after a salmon farm ceases operation. Husevåg (1994) found that *A. salmonicida* and *Vibrio salmonicida* (responsible for Hitra Disease) were able to survive for 18 and 70 months, respectively, in marine sediments.

It is very difficult to study the incidence of disease in wild species. The pathogenicity of an infectious agent may be so great that infected fishes die and disappear before the pathogen can be detected and identified (Bakke and Harris 1998). To date, research regarding disease transmission between farmed salmon and wild fish has focused primarily on salmonids. As discussed earlier, pathogens associated with farmed salmon have been found in other marine biota. There is virtually no research on the pathogenicity of these infectious agents in the wild host.

***Release of Uneaten Feed and Faeces***

The quantity and composition of uneaten food and faeces generated from fish farms depends on a number of factors including the type of feed (moist versus dry), number of fish per cage, the health of the fish (sick fish tend to have reduced appetites), frequency of feeding, type of feeding method (automatic versus hand feeding), and feed conversion ratios. Unlike terrestrial livestock operations, salmon farms are not required to contain or manage salmon wastes. In salmon (or other marine finfish) aquaculture operations, the farm boundary is defined by an open-mesh net. Wastes discharged from the farm are deposited directly into the surrounding environment. The magnitude of the ecological impact of these wastes on the environment will depend on: 1) size of farm operation (number of net pens per operation); 2) density of fish per pen; 3) duration of farm operation on a particular site; 4) physical and oceanographic conditions associated with farm site; 5) natural biota of the region; and 6) assimilative capacity of environment.

Estimates for the amount of fish feed that enters the marine environment uneaten are between 15 and 20% for dry feed and more than 20% for moist feed (Burd 1997). As for faeces, it is estimated that the production of one kg of Atlantic salmon will generate 162 g of faeces (Bergheim and Åsgård 1996). Table 2 provides an estimate of the total amount of solid waste (uneaten food and faeces) entering the marine environment from salmon aquaculture production in British Columbia and New Brunswick based on a low estimate of feed wastage (15%).

Accurate figures for the amount of fish feed used in New Brunswick salmon farms were unavailable but production estimates for New Brunswick in 1995 are known. Using an averaged feed conversion ratio, the amount of fish feed used in New Brunswick can be estimated. Approximately the same values for total tonnes of uneaten feed and faeces discharged into the marine environment (11,762 mt for British Columbia and 5,332 mt for New Brunswick) can be obtained by using the conversion factor (for dry feed, 1 mt of fish produces approximately 0.368 mt of waste) proposed by Bergheim et al. (1991). The conversion factor will be higher (1.08 mt of waste for 1 mt of fish produced) for farms using moist feed. While dry feed is preferred by fish farmers, fish tend to prefer moist feed as it is more like the texture of their natural foods.

The fate and impact of solid and dissolved wastes released from salmon farms is the subject of extensive modeling (Hargrave et al. 1993; Kelly et al. 1994; Strain et al. 1995; Kelly et al. 1996; McDonald et al. 1996; Silvert and Sowles 1996; Ervik et al. 1997; Findlay and Watling 1997; Gillibrand and Turrell 1997; Dudley et al. 2000; Morrisey et al. 2000; Hansen et al. 2001). These models principally examine the quantities of waste generated and their dispersion (or sedimentation) after release. The development of models that predict the ecological response of the benthic community (e.g. changes in population densities, species number, a functional response of the biological community) are still in their infancy and tend to be highly site-specific (GESAMP 1996; ICES 1999). It has been pointed out that at larger ecological scales, the error in model predictions becomes more significant and can result in predictions of no impact when impacts will in fact occur (Type II statistical error) (GESAMP 1996). (The subject of assessing habitat impacts from finfish aquaculture using models is covered more fully by discussion papers prepared by Bill Silvert and Chris Heinig)

The accumulation of solid waste (sediment) from fish farms can be restricted to just below the sea cage or up to 1.2 km from a farm site (Homer 1991). Sediment accumulation beneath net pens appears to be less of a problem in erosional areas where the current velocity is high and aggregates formed by natural flocculation processes tend not to accumulate on the bottom (Hansen 1994; Hargrave et al. 1997). Areas of low current velocity or depositional areas can make for poor aquaculture sites as the natural flocculation and depositional equilibrium tends to become unbalanced and leads to increased deposition of particulate material (Milligan and Loring 1997; Loring et al. 1998).

The ecological impacts of solid waste discharges are most often measured and reported as a function of changes in bacterial and/or macrofaunal biomass and species richness (number of taxa). The community structure beneath the net pen can become more simplified and microbial metabolism can shift from aerobic to anaerobic respiration (Burd 1997; Costa-Pierce 1996). In high impact areas, out-gassing of carbon dioxide, hydrogen sulphide and methane from sediments can occur beneath net pens (Black et al. 1996; Chang and Thonney 1992). Species diversity under net pens is often reduced to two taxa, the polychaete *Capitella capitata* sp. complex and certain nematodes (Levings 1994; Findlay et al. 1995; Duplisea and Hargrave 1996; Pohle and Frost 1997; Mazzola et al. 2000). According to Burd (1997), this combination of taxa seems to occur without fail under organic enrichment conditions at salmon farms worldwide. The estimated time for the benthos to recover its species abundance, richness and biomass after fish farming ceases has been reported from a few months to five years, depending on the scale and duration of the fish farming activity and the biophysical geography of the area (Burd 1997; Mazzola et al 2000; McGhie et al 2000; Pohle et al 2001).

To date, research on the ecological effects of solid waste impacts from salmon farms has focused mainly at small spatial scales (around a particular cage or farm site) and relatively short temporal (one to three years) scales. There are very few published research papers on the ecological effects of waste discharges from fish farms across larger spatial or longer temporal scales. Pohle et al. (2001), in the longest (1994-1999) study to date, found significant regional loss of benthic species diversity and significant increases in nutrient pollution in the L'Etang Inlet in the Bay of Fundy. The L'Etang Inlet, an area of approximately 31 $km^2$, has the highest number of salmon farms in Atlantic Canada and produces the greatest proportion of farmed salmon in the region. In 1998, the Inlet was cleared of farmed salmon due to an outbreak of infectious salmon anemia (ISA). Despite cessation of farming in the Inlet for approximately a year, the benthic community did not recover (Pohle et al. 2001).

There is virtually no published research on the impact of fragmenting benthic habitat on biological communities and ecosystems functions, such as predator-prey relations and energy flows. Habitat fragmentation at different spatial scales can have direct and indirect effects on species, community and ecosystem-level composition, structure and function (Thrush 1991; Ray 1991; Russell et al. 1992; Bell et al. 1995; Irlandi et al. 1995; Simenstad and Fresh 1995; Kneib 1997; Snover and Commito 1998; Frost et al. 1999; Irlandi et al. 1999; Lawrie and McQuaid 2001). Furthermore, no direct research has been done on the ecological impacts of multiple stressors (e.g, pulp mill effluent, sewage discharges, and aquaculture) on biological communities or ecosystems. Research on the loss of foraging, spawning, and/or nursery habitat for wild species as a result of fish farms is also scarce. Lawton and Robichaud (1991) reported a population of lobsters were displaced away from their historic seasonal spawning site with the introduction of salmon farms to the same site.

An emerging ecological issue related to fish feed is the inter-ecosystem cost of aquaculture (Fischer et al. 1997; Folke et al. 1998; Naylor et al. 1998). Specifically, concerns are being raised about the potential ecological impacts of transferring organic matter (forage fishes transformed into fish meal) from offshore oceanic systems to terrestrial and coastal ecosystems. Forage fishes such as herring, anchovy and capelin play a key role in marine food webs as they are the primary food source for top predators such as cod, tuna, whales and seabirds. Small pelagic fish such as anchovy, jack mackerel, pilchard, capelin, menhaden, herring and sardine are also the primary species harvested for fish meal and fish oil (Tacon 1994). The United Nations Food and Agriculture Organization (FAO) estimates that 27 percent (31,000,000 mt) of the total catch of pelagic fish is reduced to animal feeds (FAO 1997). Fifteen percent of this total is used in aquaculture production, with finfish such as salmon consuming the most fish. In the late 1980's, it was estimated that 5.3 kg of wild fish were required to produce 1 kg of farmed salmon (Folke and Kautsky 1989). Ten years later, this figure has dropped to approximately 3 kg of wild fish to produced 1 kg of farmed salmon (Naylor et al. 1998).

There is considerable research on replacing fish protein with plant protein (Gabrielsen and Austreng 1998; Thodesen and Storebakken 1998; Carter and Hauler 2000; Lein and Roem 2000; Refstie et al. 2001). What percentage of fish meal can be replaced by plant protein remains a question. The digestibility and palatability of plant protein by carnivorous fish, like Atlantic salmon, varies with the species and type and amount of plant protein used in the fish meal formulation (Burel et al. 2000; Elangovan and Shim 2000; Kissil et al. 2000; Sveier et al 2000; Refstie et al. 2001). While plant protein may constitute a portion of fishfood formulation, protein derived from wild fish will likely remain the principal source of dietary protein for farmed salmon and other farmed marine finfish (Tacon 1994).

In the past fifty years, the population of wild Atlantic salmon in the northern hemisphere has not exceeded 25,000 - 35,000 mt (Gross 1998). Today, approximately 600,000 mt of farmed salmon have a food requirement far in excess of any historic wild salmon population. To meet this high demand, more and more forage fishes will need to be caught, potentially resulting in a depletion of nutrients and an alteration in the food chain in one area and the equivalent accumulation of nutrient and alteration in food webs in other systems (Fischer et al. 1997). With worldwide farmed salmon production expected to reach 2,000,000 mt by 2010, the harvest pressure on forage fishes may become greater.

***Release of Nitrogen and Phosphorus***

In addition to the solid component of wastes discharges from salmon farm operation, there are dissolved components in the form of nitrogen (N) and phosphorus (P). Most of the total nitrogen in the wastes is in the dissolved fraction, while the majority of the total phosphorus is in the particulate fraction (Costa-Pierce 1996). Anthropogenic nitrogen loading in marine waters is acknowledged as the principal cause of degradation and alteration to coastal ecosystems worldwide (Bell and Elmetri 1995; Paerl 1997; Howarth 1998; Seitzinger and Sanders 1999; Wu 1999). Nitrogen and phosphorus loading into marine (and other) waters can initiate a biological process (eutrophication) that, depending on the volume and duration of nutrient loading and the assimilative capacity of the receiving waters, can culminate in a fundamental shift in the food web structure of an area and lead to ecological simplification (McClelland and Valiella 1998; Ingrid et al. 1999; Worm et al. 1999; Worm and Lotze 2000 Worm et al. 2000). The Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP 1990) outlined the following biological and ecological changes that take place as eutrophication progresses: increased primary production; changes in plant species composition; very dense, often toxic, algal blooms; conditions of hypoxia (low oxygen concentration) or anoxia (no oxygen); adverse effects on fishes and invertebrates; and 6) changes in structure of benthic communities.

It has been pointed out that N and P discharges from aquaculture operations represent a very small percentage of total N and P loads on a national scale (Ackefors and Enell 1990). Local loading of N and P from fish farms can be very significant and, in fact, can represent the largest source of N and P in a given area. Table 3 compares the C, N, P outputs from salmon aquaculture operations in the L'Etang Inlet in New Brunswick with several other sources in the vicinity of the farms. For the L'Etang Inlet, aquaculture operations are the largest anthropogenic source of nutrient inputs.

There are differing views regarding the contribution of nutrient releases (N and P) from net pen operations to the occurrence of harmful algal blooms (HABs) in coastal waters (Burd 1997; Berry 1996). A number of reports document the occurrence and abundance of HABs in the vicinity of net pens (Wildish et al. 1990; Martin et al. 1999; Whyte et al. 1999), but none of these monitoring programs were experimentally or statistically designed to answer the question of whether salmonoid aquaculture influence blooms of HABs.

One of the difficulties in studying the impacts of N and P discharges from salmon farms is that, often, nutrients from net pens are not the only source of discharges. Models that estimate the relative contributions of nitrogen from different sources and their loading rates have been developed and applied to field conditions (Hinga et al. 1991; Weiskel and Howes 1991; Valiela et al. 1997). In many cases, these models have been developed with a view to providing better tools for decision-making in matters of coastal zoning for whole watersheds (Valiela et al. 1997). Most management decisions concerning development in the coastal zone, however, are still made on a project by project or farm by farm basis. This approach to decision-making tends to ignore synergistic interactions among two or more human influences (Myers 1996; Worm and Lotze 2000). Whole watershed management will require whole watershed information and to date this information is not available where most salmon farming occurs.

***Antibiotics***

A broad range of antibiotics (e.g., oxytetracycline, erythromycin, amoxycillin, chloramphenicol, oxolinic acid, etc.) are used in salmon aquaculture to treat a variety of bacterial infections (e.g., bacterial kidney disease, furunculosis, bacterial septicaemias). Antibiotics are applied as a bath, injected, or mixed with the feed. Data on the volume of antibiotics used in fish farming is lacking for most countries except Norway (GESAMP 1997). Antibiotic use in Norway has dropped from 48,000 kg per year in 1987 and 680 kg per year in 1998 (ICES 1999). Salmon production for the same period increased from 60,000 mt to 400,000 mt. The Norwegian decline is frequently cited as an example of the trend in antibiotic use in the salmon aquaculture industry (Fossbakk 2000). Data on the amount of antibiotic use in North American salmon farming is not readily available. By the early 1990's, usage in Canada was down to 200 g/mt compared to Norway's 165 g/mt (Stewart 1994). Although the trend in antibiotic use in Norway shows a decline, this dramatic decline is not necessarily reflected in North America. In 1996, B.C. salmon farmers used an average of 165 g of active antibiotic ingredients to produce 1 mt of salmon (Dodd 2000). For 1996, this use translated to approximately 6.6 mt of antiobiotics used in B.C. on total farmed salmon production of 40,500 mt. Figures for Norway show that in 1996, 1.03 mt of antibiotics were used on total production of close to 300,000 mt (ICES 1999).

Many antibiotics mixed with feed tend not to be absorbed by the fish and are excreted unchanged in an active form in the faeces. Depending on the antibiotic used, between 60% to 85% of the drug can be excreted through the faeces unchanged (Alderman et al.1994; Samuelsen 1994; Weston 1996). In addition, sick fish tend to have reduced appetites and a great deal of the treated feed falls uneaten to the bottom. As a result, a considerable amount of antibiotics can accumulate in the sediments and be made available to fish and invertebrates attracted to the net pen sites to feed. Antibiotics vary in their persistence in sediments, which can range from a day to 1.5 years. The most commonly used antibiotics, oxytetracycline and oxolinic acid, can persist in sediments for 10 - 6 months respectively (Weston 1996). Wild fish and invertebrates can accumulate antibiotics in their tissues to levels which would be considered unacceptable for human consumption (Capone et al. 1996). Samuelson et al. (1992) reported oxolinic acid residues in wild saithe, mackerel, cod, pollock, wrasse, salmon, flounder, cancrid crabs and mussels persisting for 1-2 weeks after treatment of salmon in net pen farms. Ervik et al. (1994) reported oxolinc acid or flumequine residues in 84% of the 189 saithe tested. Coyne et al. (1997) reported the uptake of oxytetracycline by blue mussels in the vicinity of salmon farms after treatment of fish. In a study of the toxic effects of antibacterial agents on algae, Holten Lutzhøft et al. (2000) reported algae, particularly cyanobacteria, have a higher sensitivity toward antibacterial agents compared to crustaceans and fish. The authors recommend that an environmental risk assessment of antibacterial agents should include a cyanobacteria.

One outcome of wide-spread antibiotic use, whether in animal or human populations, is the potential for the development of drug resistance among target pathogens. Drug resistence has been identified for strains of *A. salmonicida*, the bacteria responsible for furunculosis (Barnes et al. 1994; Hawkins et al. 1997). Drug resistence has also been reported in natural sediment bacteria from antibiotics that have accumulated below net pens (Husevåg et al. 1991; Nygaard et al. 1992; Husevåg and Lunestad 1995; Capone et al. 1996; Kerry et al. 1996). The ecological impacts (e.g., changes to sedimentary microbial abundance or biogeochemical process) of antibiotic use in fish farming are virtually unexamined ( Weston 1996; GESAMP 1997 ICES 1999).

***Pesticide Use***

Sea lice (*Lepeoptherius* sp. and *Caligus* sp.) are naturally occurring external parasites which rarely have had a significant effect on wild fish (Roberts and Shepard 1986), until recently (Birkeland 1996; Johnson et al. 1996). The crowded and stressed conditions of salmon farms, as well as the constraints on swimming speed imposed by their confinement, provide good breeding conditions for sea lice ( Nagasawa et al.1993). Infestations of sea lice are a serious problem for most salmon farms and have cost the industry millions of dollars in lost salmon and reduced market value for salvaged fish.

Roth (2000) reports that eleven compounds representing five pesticide types are currently being used on salmon farms for sea lice control. These include: two organophosphates (dichlorvos and azamethiphos); three pyrethrin/pyrethroid compounds (pyrethrum, cypermethrin, deltamethrin); one oxidizing agent (hydrogen peroxide); three avermectins (ivermectin, emamectin and doramectin) and two benzoylphenyl ureas (teflubenzuron and diflubenzuron). With the exception of hydrogen peroxide, all the compounds used to control sea lice were first developed for terrestrial agriculture and all of the compounds are labeled by regulatory agencies as toxic or extremely toxic to aquatic invertebrates and/or fish. Five of the compounds (ivermectin, emamectin, doramectin, teflubenzuron and diflubenzuron) are mixed with feed and the remaining compounds are applied in bath treatments. In these bath treatments, tarpaulins are used to enclose the nets of a pen. The nets are drawn towards the water surface, thereby reducing the water volume requiring treatment. Oxygen is pumped into the remaining water in order to keep the enclosed salmon alive. Oxygenation also aids in mixing the pesticides applied to the cage. Once the nets have been drawn up, the volume of the remaining water is calculated. It is important that this volume be calculated as accurately as possible: a major miscalculation could mean the difference between a treatment dose or a toxic dose of a given pesticide. When the treatment is completed, the used bathing solution is released into the environment. Repeated applications are necessary to prevent re-establishment of lice on the host fish.

As with antibiotics, data on the amount of pesticide use are not available except for Norway. In 1989, 6.78 mt of organophosphates were used in Norway (ICES 1999). The use of these and other pesticides administered in bath treatments declined to approximately 200 kg in 1998. This decline in organophosphates does not reflect a decrease in sea lice infestation but rather a shift from pesticides applied by bath treatment to the use of pesticides mixed with feed. In 1998, 1.76 mt of benzoylphenyl ureas were mixed with fish feed versus zero in 1996 and 770 kg in 1997 (ICES 1999). The use of two organophosphates, trichlorofon and dichlorvos, were discontinued in 1997 and 1998, respectively, in Norway (ICES 1999). According to Roth (2000), the number of compounds registered for use in aquaculture in any one country is highly variable, ranging from 9 (Norway) to 6 (Chile, United Kingdom) to 4 (Ireland, Faeroes, Canada) to 2 (United States).

Pesticides mixed with feed tend to fall uneaten to the bottom and accumulate in sediments. Pesticides can also pass through a fish largely unabsorbed. Unlike antibiotics, pesticides used in bath treatments release significant quantities of toxic material directly into surrounding waters (GESAMP 1997). There is a small body of published research and data on the lethal and sublethal effects on non-target aquatic organisms of various pesticide compounds used in aquaculture (Burridge and Haya 1993; McHenery et al. 1996; Thain et al. 1997; Pahl and Opitz 1999; Abgrall et al. 2000, Burridge et al. 2000). General conclusions that can be drawn from these studies are: 1) crustaceans are the non-target organisms most sensitive to the pesticides; and 2) early life stages of non-target organisms are more sensitive than later life stages. The ecological implication of these conclusions remain largely unexamined. Very little scientific, field-generated data exists on the long-term sequential use of pesticides in salmon aquaculture on non-target species and their subsequent population- or community-level impacts.

In addition to knowledge gaps on the impact of active ingredients in these pesticides, there is also a lack of toxicology data on the so-called “inert” ingredients which typically comprise a significant percentage (by volume) of a given pesticide. Inert compounds act as solvents or carriers for the active ingredient in pesticide formulations that are sprayed or used in bath treatments. These compounds can be toxic (Burridge and Haya 1995) or act as endocrine disruptors (Fairchild et al. 1999) and, in some instances, they can be of greater environmental concern than the active compound itself. Burridge and Haya (1995) found that the pesticide formulation used to treat sea lice, Aquagard®, which consists of the solvent di-n-butylphthalate, is more toxic to juvenile Atlantic salmon than the active ingredient dichlorvos (an organophosphate) alone. Di-n-butylphthalate (DBP) belongs to a class of compounds called phthalate acid esters (PAE). PAEs are endocrine disrupting compounds and are on the priority list of pollutants in Canada and the United States. It has been estimated that approximately 8 tonnes of DBP are being released into the marine environment through aquaculture use (Roth et al. 1993). Virtually no research has been published on the impact of solvents or carriers associated with pesticide used in salmon aquaculture.

**Conclusion**

Based on this survey of the published scientific literature, there are large gaps in research on, and subsequently knowledge of, the impacts salmon aquaculture on the marine environment and associated wildlife (Table 4). The research to date is largely focused on single-level (species) observation, small spatial scale and short temporal scales. The conclusions that can be drawn about environmental impacts from this type of research or monitoring are very limited (Underwood and Peterson 1988; Noss 1990; Myers 1996; Rojo and Alvarez-Cobelas 2000; Somerfield and Gage; 2000; Verdonschot 2000;). For example, species-level observation provide very little information on changes to the trophic structure of a community or about future sizes of natural populations (Underwood and Peterson 1988). Furthermore, attempts to model the impact of aquaculture or some other industrial development are often undertaken well after the development activity is established. By that time, the economic commitment by the private and public sectors is too great to substantially change the path of development if monitoring results demonstrate adverse environmental effects. If the tools of scientific modelling are to be used meaningfully, they must be used prior to development.

Questions are being raised about the sustainability of salmon (and other finfish) aquaculture (Ellis 1996; Fischer et al. 1997; Goldburg and Triplett 1997; Naylor et al. 2000). With the production of farmed salmon expected to double in the next decade and new marine finfish species being added to the global production of farmed fish, there is an urgent need to review and address the gaps in the state of our knowledge of the impacts of salmon aquaculture on the coastal environment. The information provided by such a review would both direct research efforts to areas where our understanding of salmon aquaculture impacts are weak and incomplete, and provide regulatory agencies with more up-to-date information on which to define and set ecologically meaningful environmental standards, guidelines and objectives.

Until such a review is undertaken, it would be appropriate for regulatory agencies to apply the precautionary principle to decision-making concerning expansion of finfish aquaculture in coastal waters and to mitigative measures on existing operations. This principle states that “where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation” (Environment Canada 1996). Recognition of the gap in scientific information and data has led to the increased acceptance of the precautionary approach as a decision-making principle. The principle essentially favours erring on the side of human health and environmental protection rather than short-term economic growth and it is becoming an important element of international environmental law.

The first significant application of the precautionary principle in international environmental law took place in 1987 at the signing of the *Montreal Protocol on Substances That Deplete the Ozone Layer*, an international treaty restricting the use of certain chemicals that damage the ozone layer (Cameron and Abouchar 1996). The signatories, including Canada, decided to move ahead with international controls in the absence of conclusive proof of environmental damage. At the time, uncertainty existed about the role of CFCs in creating the ozone hole over Antarctica and there were no comprehensive estimates of measured global ozone loss or detectable increases in the UV radiation reaching the earth (French 1997). Signatories agreed that the lack of complete scientific certainty was insufficient to delay an international policy response since such a delay might result in serious or irreversible damage. The principle has since been incorporated into a number of other global conventions. They include the 1992 Rio Declaration on environment and development and the 1996 United Nations Convention on Straddling Fish Stocks and Highly Migratory Fish Stocks.

It is universally acknowledged that marine estuaries and coastal waters are seriously degraded. The prospect of more finfish aquaculture in coastal waters cannot be viewed as a positive step for the recovery of degraded marine ecosystems. Given that the state of knowledge of the acute, chronic, and cumulative effects of marine finfish aquaculture on marine life and their habitat is incomplete, and that the environmental impact of the industry may be greater than currently observed or predicted, regulatory agencies and policy-makers need to implement the precautionary principle in managing aquaculture development. Adopting this approach would mean that, with respect to all substances and activities associated with marine fish farming that are suspected of posing a serious threat to the marine environment, the absence of adequate scientific information would not be used as a reason for postponing or failing to take maximum mitigation measures. This could include 1) a shift to closed containment systems; 2) restrictions on the use of pesticides; 3) restrictions on the use of acoustic deterrent devices; 4) use of moratoria; and 5) institution of comprehensive environmental assessments.

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**Table 1**. Major activities associated with the marine phase of salmon aquaculture and their potential effect on the environment and its wildlife.

| Activity | Pathway | Potential Effect |
|---|---|---|
| net pens | - physical structure | - direct mortality through entanglement<br>- behavioural changes in coastal pelagic fishes, birds and marine mammals (e.g., avoidance)<br>- loss of habitat for pelagic species |
| | - lights | - shifts in plankton communities in response to photoperiod changes<br>- behavioural changes in fishes, birds and marine mammals |
| | - predator control using firearms | - direct mortality |
| | - noise generated by acoustic harassment devices (AHDs) | - behavioural changes in invertebrates, fishes, birds, and marine mammals (e.g., avoidance)<br>- loss of habitat created by acoustic exclusion zones<br>- interference with communication signals<br>- temporary hearing loss or permanent hearing damage |
| | - fish escapement | - disease transmission to other species<br>- genetic interactions with wild salmon<br>- displacement of wild salmon and other fishes from natural habitat (e.g., through competition, predation) |
| fish feed | - release of uneaten food and faeces | - suffocation and displacement of benthic organisms<br>- loss of foraging, spawning and/or nursery habitat for wild species<br>- loss of biodiversity<br>- fragmentation of benthic habitat<br>- inter-ecosystem costs (e.g., forage fishery) |
| | - release of nitrogen and phosphorus | - change in water quality<br>- mortality of plankton (including fish and invertebrate egg and larvae)<br>- increased primary productivity<br>- shift in plankton community composition<br>- increase in harmful algal blooms<br>- alteration of coastal food webs |
| | - antibiotics | - tainting of wild species<br>- changes in benthic bacterial community |
| therapeutants and chemicals | - pesticides | - direct mortality and sublethal effects<br>- tainting of wild species<br>- behavioural changes in mobile invertebrates and fishes |
| | - disinfectants and anti-foulants | - direct mortality and sublethal effects<br>- tainting of wild species<br>- behavioural changes |

**Table 2.** Estimate of the total solid waste entering the marine environment from marine aquaculture production in New Brunswick and British Columbia, Canada in 1995.

| Province | Tonnes of Fish Produced | Tonnes of Feed Used | Tonnes of Faeces Produced | Tonnes of Uneaten Fish Feed Entering the Marine Environment (based on 15% Feed Wastage) | Total Tonnes of Waste (Uneaten Feed plus Faeces) Entering the Marine Environment |
|---|---|---|---|---|---|
| British Columbia | 31,964[1] | 42,936[2] | 5,178[3] | 6,440 | 11,618 |
| New Brunswick | 14,490[4] | 18,837[5] | 2,347[3] | 2,825 | 5,172 |

[1] Value obtained from Ellis 1996, page 91.

[2] Value obtained from Burd 1997, page 17.

[3] Calculated using conversion (1 kg of salmon produced will generate 162 gm of faeces) cited in Bergheim and Åsgård 1996.

[4] Actual value obtained from New Brunswick Department of Fisheries and Aquaculture. Aquafacts. 1996

[5] The Food Conversion Ratio (FCR) is a ratio of the total amount of food fed and the amount of biomass produced during a particular time interval. The British Columbia (B.C.) Ministry of Agriculture, Fisheries and Food (MAFF) uses a FCR ratio of 1.5 in their waste discharge models. The Department of Fisheries and Oceans (Canada) used a 1.15 FCR value in their submission to the B.C. Salmon Aquaculture Review. The average of these two values is 1.3.

**Table 3.** Annual Estimated Input of Carbon, Nitrogen, and Phosphorus to the L'Etang Inlet, Bay of Fundy, New Brunswick, 1992

| Source | Carbon (tonnes) | Nitrogen (tonnes) | Phosphorus (tonnes) |
|---|---|---|---|
| Pulp Mill | 110 | 3.1 | N/A |
| Sewage Treatment[1] | 41 | 3.8 | 0.7 |
| Back Bay Fish Cannery | 46 | 8 | 1.11 |
| Run-off | 300 | 10.8 | 0.66 |
| Precipitation | 0 | 17 | 0.45 |
| Black's Harbour Fish Plant [2] | 340 (880) | 61.0 (220.0) | 8.4 (30) |
| Aquaculture[3] (22 salmon farms) | 850 | 290 | 45 |

**Source**: Strain et al. 1995.

[1] From sewage treatment plant serving the town of Blacks Harbour (population 1200)

[2] Since 1991, stickwater (the black liquor produced from cooking fish and the most highly concentrated waste stream produced in the plant) has not been discharged from the plant. The numbers in brackets reflect pre-1991 discharge levels which included stickwater.

[3] In 1992, there were 22 fish farms in the L'Etang Inlet with a licence capacity of 2.2 million fish (approximately 8,000 mt). The actual production figures for the entire New Brunswick Bay of Fundy salmon aquaculture industry in 1992 ( the year of the study) was 8,836 mt representing an estimated 2.43 million fish. (New Brunswick Department of Fisheries and Aquaculture).

**Table 4.** Summary of the gaps in knowledge and research on the impacts of salmon aquaculture on the coastal environment.

| What is known about impacts | What impacts need to be researched |
|---|---|
| **Net Pens** | |
| - direct mortality of wildlife occur through entanglement of nets | - impacts of net pens structures on the behaviour of migratory species (e.g., fishes and marine mammals) |
| - direct mortality of wildlife occur as a result of firearms used for predator control | - long-term impact of ADHs on hearing loss or permanent hearing damage in marine mammals |
| - behavioural changes in marine mammals occur due to AHD use | - impacts of AHDs on the behaviour of seabirds, fishes or invertebrate |
| - transmission of infectious agents occur from farmed to wild salmonid and to non-salmonid fish species and invertebrates | - impact of acoustic exclusions zones created by AHDs on marine mammals and fishes (e.g., displacement from traditional feeding, nursery, or refuge areas) |
| - transmission of infectious agents occur from wild to farmed salmonids | - ecological (e.g., competition, predation) impacts of escaped farmed Atlantic salmon on other wild, non-salmonid species |
| - genetic interactions occur between farmed and wild salmon | - pathogenicity of infectious agents transmitted from farmed salmon to wild non-salmonid fishes or invertebrates |
| **Fish Feed** | |
| - suffocation and displacement of benthic organisms occur as a result of accumulated food and faeces | - landscape-level effects of benthic habitat fragmentation on ecological processes (e.g., competition, predation, energy flow) |
| - changes in benthic bacterial community occur | - impact on biodiversity at larger spatial scales |
| - changes in water and sediment quality occur | - ecological impact of multiple stressors on biological communities or ecosystems |
| | - inter-ecosystem cost of aquaculture |
| | - ecological impact of the loss of foraging, spawning and/or nursery habitat for wild species as a result of waste accumulation |
| | - toxic effect of N and P release on zooplankton mortality |
| | - impact of N and P loading from aquaculture on harmful algal blooms (HABs) or phytoplankton community composition |
| **Therapeutants and Chemicals** | |
| - antibiotic tainting of wild species occur | - ecological impacts (e.g., changes to sedimentary microbial abundance, geochemical processes) of antibiotic use sub-lethal effects of pesticides on non-target species |
| - direct mortality and tainting of wild species occur as a result of pesticide use | - impacts of the long-term sequential use of pesticides on non-target species and subsequent population- or community-level impacts |
| | - sub-lethal and acute impacts of active ingredients ("inerts") in pesticides on target and non-target species |