Seafood Watch
Seafood Report

MONTEREY BAY AQUARIUM®

Farmed Salmon
Atlantic salmon (*Salmo salar*)

Image © Monterey Bay Aquarium

Robert Mazurek
Fisheries Research Analyst
Monterey Bay Aquarium

&

Matthew Elliott
Independent Consultant

Final Report
April 27, 2004

About Seafood Watch® and the Seafood Reports

Monterey Bay Aquarium's Seafood Watch® program evaluates the ecological sustainability of wild-caught and farmed seafood commonly found in the United States marketplace. Seafood Watch® defines sustainable seafood as originating from sources, whether wild-caught or farmed, which can maintain or increase production in the long-term without jeopardizing the structure or function of affected ecosystems. Seafood Watch® makes its science-based recommendations available to the public in the form of regional pocket guides that can be downloaded from the Internet (seafoodwatch.org) or obtained from the Seafood Watch® program by emailing seafoodwatch@mbayaq.org. The program's goals are to raise awareness of important ocean conservation issues and empower seafood consumers and businesses to make choices for healthy oceans.

Each sustainability recommendation on the regional pocket guides is supported by a Seafood Report. Each report synthesizes and analyzes the most current ecological, fisheries and ecosystem science on a species, then evaluates this information against the program's conservation ethic to arrive at a recommendation of "Best Choices", "Good Alternatives" or "Avoid." The detailed evaluation methodology is available upon request. In producing the Seafood Reports, Seafood Watch® seeks out research published in academic, peer-reviewed journals whenever possible. Other sources of information include government technical publications, fishery management plans and supporting documents, and other scientific reviews of ecological sustainability. Seafood Watch® Fisheries Research Analysts also communicate regularly with ecologists, fisheries and aquaculture scientists, and members of industry and conservation organizations when evaluating fisheries and aquaculture practices. Capture fisheries and aquaculture practices are highly dynamic; as the scientific information on each species changes, Seafood Watch's sustainability recommendations and the underlying Seafood Reports will be updated to reflect these changes.

Parties interested in capture fisheries, aquaculture practices and the sustainability of ocean ecosystems are welcome to use Seafood Reports in any way they find useful. For more information about Seafood Watch® and Seafood Reports, please contact the Seafood Watch® program at Monterey Bay Aquarium by calling 1-877-229-9990.

Disclaimer
Seafood Watch® strives to have all Seafood Reports reviewed for accuracy and completeness by external scientists with expertise in ecology, fisheries science and aquaculture. Scientific review, however, does not constitute an endorsement of the Seafood Watch® program or its recommendations on the part of the reviewing scientists. Seafood Watch® is solely responsible for the conclusions reached in this report.

Seafood Watch® and Seafood Reports are made possible through a grant from the David and Lucile Packard Foundation.

Executive Summary

Salmon are an important component of the global aquaculture industry, and are farmed worldwide. Farmed salmon available in the U.S. seafood market are primarily Atlantic salmon (*Salmo salar*) imported from Chile and Canada; a smaller amount of Atlantic salmon is raised domestically.

Environmental concerns over salmon farming primarily stem from the fact that farmed salmon are raised in marine net pens, where they are in direct contact with the surrounding marine environment. As a consequence of being farmed in open systems, farmed salmon can escape during storms and routine handling events. There is a growing body of evidence that when salmon farmed within their native range escape they can interbreed with wild conspecific salmon and reduce the fitness of endangered wild salmon stocks. Risk also exists that escaped farmed salmon may become reproductive and establish populations in areas in which they are not native, such as the Pacific.

In addition to the relatively high incidence of escaped fish, open salmon farming systems also allow the free-flow of wastes into the surrounding marine environment. Such wastes include biological "wastes" such as diseases and parasites, organic wastes such as feces and uneaten aquafeed, and chemical wastes such as unprocessed antibiotics, pesticides, and anesthetics. These wastes can negatively affect the marine environment in the following ways:

- Salmon farming operations can serve as a vector for diseases and ectoparasites, notably sea lice, which can negatively affect wild salmon. While the literature on disease transfer to wild fish remains somewhat inconclusive, there is significant evidence that sea lice from salmon farms are harming wild salmonid populations, particularly in Europe.

- Organic wastes from feces and uneaten aquafeed can accumulate on sediments and affect the benthic species distribution within the immediate vicinity of salmon net pens. Infaunal species diversity is typically lower beneath and down current from net pens with low to moderate flushing rates, though it may be higher in areas with good flushing. Nutrients from salmon operations can also be a contributor to larger regional problems of eutrophication.

- Chemical wastes, such as pesticide baths applied to treat sea lice, may impact non-target species such as lobsters and shrimps. To control the effects of applying pesticides in an open environment, a number of regulations exist to minimize environmental impacts.

Apart from these direct effects, salmon farming also places an indirect stress on the marine environment by utilizing significant quantities of wild fish used in processed aquafeed. Wild fish that are caught for "reduction" to fish meal and fish oil for aquafeeds

typically originate off the coasts of South America and the United States, where they represent important components of their surrounding marine ecosystems.

Management of salmon farming varies substantially worldwide. However, given the recent scrutiny of the environmental effects of the farmed salmon industry, management practices are generally becoming more rigid in an effort to improve the sustainability of salmon farming.

A separate Seafood Watch Report and ranking exists for U.S. farmed freshwater coho salmon grown in land-based tanks. This report is available at www.seafoodwatch.org.

Table of Sustainability Ranks

	Conservation Concern			
Sustainability Criteria	**Low**	**Moderate**	**High**	**CRITICAL**
Risk of Escaped Fish to Wild Stocks				√
Risk of Disease Transfer to Wild Stocks			√	
Use of Marine Resources			√	
Risk of Pollution & Habitat Effects			√	
Effectiveness of the Management Regime		√		

Overall Seafood Recommendation:

Best Choice Good Alternative **Avoid**

Introduction

Background

For more than one hundred years juvenile salmon have been cultured, raised in captivity, and released into the wild to enhance or create fisheries. However, it wasn't until the late 1960's that the first attempts were made to raise salmon in captivity to adulthood for commercial sale (Sylvia, Anderson et al. 2000).

After more than three decades of gradual improvements, farmed salmon producers have developed aquaculture methods that result in the cost-effective rearing of salmon from eggs, through adulthood, to harvest. These operations and techniques can be broken down into the following four major steps:

1. Eggs are harvested from broodstock, followed by artificial spawning, incubation, and hatching at land-based hatchery facilities.
2. Juveniles are reared to the smolt stage in freshwater, either in hatcheries or in lake-based net-cage sites.
3. Salmon are "grown out" in marine-based, coastal net pens. Net pens are generally placed in areas of relatively cold, clean water, and are stocked with fish at high densities. Fish are grown to size on high-protein diets.
4. Fish are harvested after one to two years, processed, and sold. (Tyedmers 2000)

During the late 1960's and throughout the 1970's farmed salmon production was relatively small. The beginning of the 1980's, however, witnessed the start of a rapid increase in the production of farmed salmon, particularly in Norway, which continues today (FAO 2002). In 1980, just 5,000 metric tons (mt) of farmed salmon was grown, harvested, and sold worldwide. By 1990, production reached 210,000 mt/year, and by the year 2000 farmed salmon production reached over 850,000 mt. Today salmon farming is a major aquaculture industry, dominated by multinational corporations that produce more salmon than all wild salmon fisheries combined (Forster 2002).

The steep rise in the production of farmed salmon over the past two decades has stemmed from a combination of factors, including an increased demand for inexpensive salmon (particularly in the United States), more efficient farms, the stocking of fish at higher densities within these farms, and the expansion of the industry to new regions and locations (Pike and Barlow 2001). Salmon farming has transitioned into large-scale, intensive production.

Farmed Salmon Species

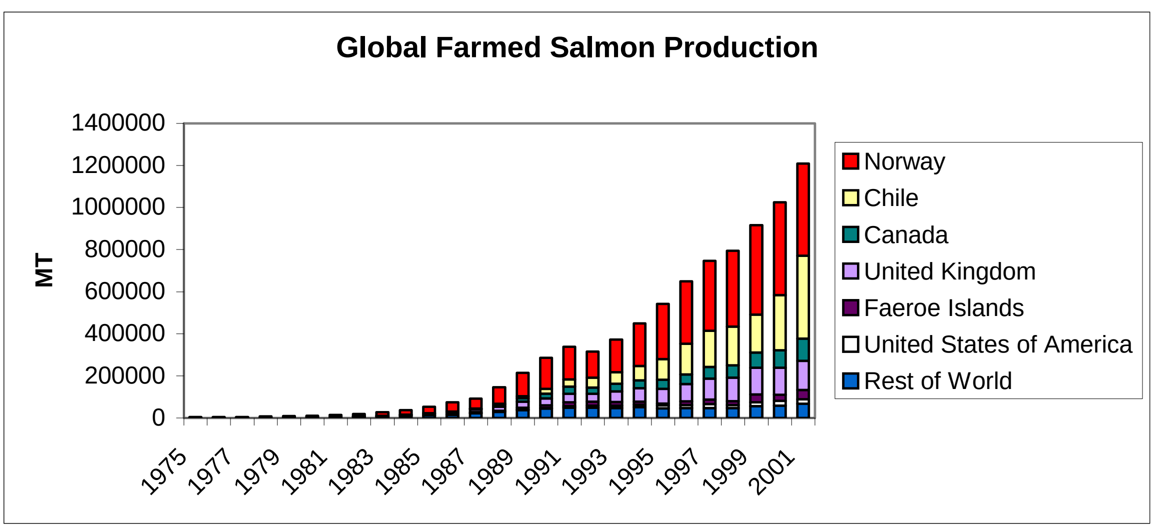
The vast majority of salmon farmed today are Atlantic salmon (*Salmo salar*); in 2002, over one million tons of Atlantic salmon was farmed worldwide. In addition, a much smaller quantity of Pacific salmon—chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*)—are cultured, along with steelhead (*Salmo trutta*) and Arctic char (*Salvelinus alpinus*), a related salmonid. Annual production of farmed Pacific salmon was approximately 174,700 mt in 2001, less than 15% of total farmed salmon production (FAO 2002).

In comparison, the species distribution of wild-caught salmon is essentially the inverse of farmed species. Commercial wild Atlantic salmon harvests are trivial. Devastated by extensive habitat loss and overfishing, wild Atlantic salmon landings are only about 5,000 mt annually, and are scattered across Northern Europe (2001 landings: Norway, 1,125 mt; Finland 817 mt; Ireland 688 mt; Greenland 434 mt). Wild Atlantic salmon landings represent less than half of one percent of total Atlantic salmon consumption (FAO 2002). In contrast to Atlantic salmon, the vast majority of Pacific salmon on the global market comes from wild fisheries. Over the last decade, annual harvests of Pacific salmon averaged just over 800,000 mt. This dichotomy makes for a relatively straightforward rule of thumb: Atlantic salmon is predominantly farmed and Pacific salmon is predominantly wild-caught.

In summary, this decade has witnessed the ascendancy of farmed Atlantic salmon from a niche commodity to one of mass-market status (Forster 2002). Today, slightly more than half of the salmon on the global market is farmed Atlantic salmon; the remainder is primarily wild-caught Pacific salmon, with minor contributions from farmed Pacific salmon and wild Atlantic salmon. Farmed salmon production exceeded wild salmon harvests for the first time in 2000. Forecasts predict that farmed salmon will continue to out produce wild harvests by increasing margins into the future.

Geographic Distribution of Production

Salmon farming is a relatively global industry; more than two dozen nations practice intensive salmon aquaculture. However, four countries currently dominate the global salmon production market; Norway, Chile, the United Kingdom, and Canada account for over 85% of the farmed salmon produced worldwide (FAO 2002). These four nations share access to the cold, clean, marine waters and protected shorelines of the North Atlantic essential to salmon farms (Forster 2002). As a consequence, their collective production dwarfs the remaining 15% of farmed salmon from more than twenty other nations (FAO 2002).



Data source: (FAO 2002).

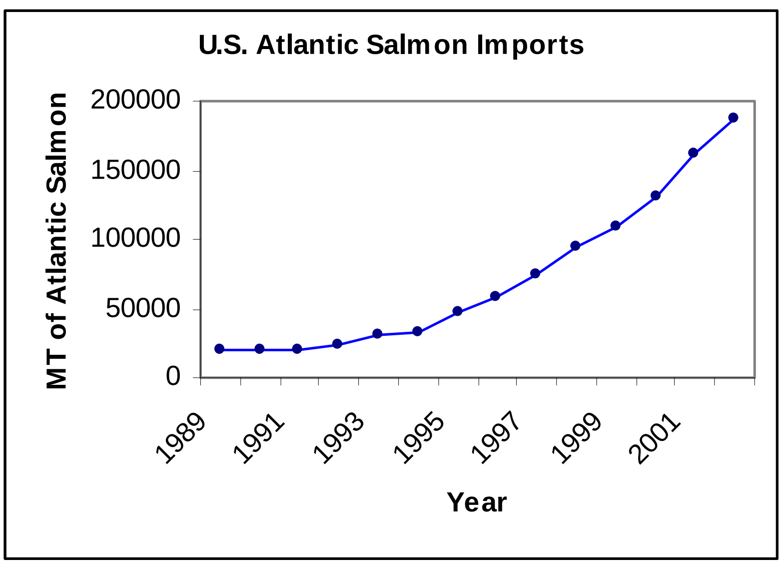
United States Farmed Salmon Market

The United States market has been responsible for driving much of the growth of the global salmon industry. Currently, the U.S. is the world's largest single importer of farmed salmon; the U.S. consumes nearly one-third of global farmed salmon. As a result, farmed salmon is one of the most ubiquitous products on the U.S. seafood market. Salmon is now available year-round, and can be found whole or as fillets, and may be fresh or frozen, smoked or dried, processed or unprocessed. When used for sushi or sashimi, farmed salmon is commonly sold as *sake*; farmed salmon roe is commonly sold as *ikura*.

U.S. Imports of Farmed Salmon

Over 90% of the farmed salmon consumed in the United States is imported from farms abroad (NMFS 2003). In 2002, the United States imported a record-high 213,000 mt of salmon from over thirty-five countries. Salmon imports consisted of a variety of product forms (whole, fresh, frozen, fillets, etc.) and species of salmon, both wild-caught and farmed. Despite this variety, at least 90% of salmon imports (more than 192,000 mt) were of farmed origin.

The trajectory of imported farmed salmon in the United States has followed a pattern similar to worldwide production, rising steadily over the past decade. As a proxy for farmed salmon imports, U.S. imports of Atlantic salmon are graphically presented below. Atlantic salmon imports grew at a rate of 23% per year between 1992 and 2002 (NMFS 2003).



Source: (NMFS 2003).

While close to two-dozen nations export farmed salmon to the United States, over 90% of the farmed salmon imported in the United States originates at farms in only two countries, Chile and Canada. The remainder is mostly comprised of fish shipped from Norway and the United Kingdom, with both nations exporting over 4,000 mt of farmed Atlantic salmon to the U.S. in 2002.

Nation	Exports to USA	% US Imports
Chile	98,694 mt	51.4%
Canada	78,332 mt	40.8%
Norway	7,261 mt	3.8%
UK	6,049 mt	3.2%
Others	1,550 mt	0.8%
Total	192,000 mt	100.0%

The vast majority of farmed salmon imported in the U.S. are Atlantic salmon. Only relatively small numbers of farmed chinook and coho salmon are imported in the U.S. from Canada, Chile, and New Zealand. Collectively, these non-Atlantic species represent approximately 3% of U.S. farmed salmon imports (NMFS 2003).

Domestic Production

In addition to imports, some farmed Atlantic salmon is raised in the United States, in the states of Maine and Washington. According to a 1998 U.S. Department of Agriculture (USDA) aquacultural census, twenty-eight fish farms in the United States produced adult salmonids for commercial sale (USDA 1998; Nash, Brooks et al. 2001).[1] A dozen farms in Maine accounted for approximately three-quarters of U.S. farmed salmon in 1998; the other 25% were primarily raised on nine farms in the State of Washington.

Though small, U.S. farmed salmon production has also grown significantly over the past decade. Between 1989 and 1998, U.S. farmed salmon production more than quadrupled (FAO 2002). In 2001, U.S. aquaculturists reared just under 21,000 mt of Atlantic salmon (NMFS 2002). Of that 21,000 mt production, nearly 4,000 mt were exported to Canada (NMFS), leaving 17,000 mt of domestically-farmed salmon for U.S. consumption.

Including both imported and domestically-raised salmon, the countries of origin for the U.S. supply of farmed salmon in 2002 were:

Nation	% U.S. Imports
Chile	47.3%
Canada	37.5%
U.S.	8.1%
Norway	3.5%
UK	2.9%
Others	0.7%
Total	100.0%

[1] Excludes Alaskan salmon ranching operations – marine finfish farming is illegal in Alaska.

Domestic production of farmed salmon appears to be about 8% of national consumption. However, these figures exaggerate the market share of domestically farmed salmon, insofar as U.S. production figures are recorded in live weight (whole fish), whereas almost two-thirds of imported farmed salmon is already filleted (NMFS 2003). Given that a salmon fillet represents only up to 60% of the whole body mass of an adult salmon (Forster 2002), the U.S. imports the *equivalent* of 270,000 mt of whole salmon. Hence, domestic supply is closer to roughly 6% of national consumption.

Environmental Concerns: The Availability of Science

As farmed salmon production has increased, concern has grown over potential and actual adverse environmental impacts associated with the marine grow-out phase of salmon farming (Folke, Kautsky et al. 1994; Lassuy 1995; Findlay and Watling 1997; Naylor, Goldburg et al. 1998; Naylor, Goldburg et al. 2000; Volpe, Taylor et al. 2000; Naylor, Williams et al. 2001; Gaudet 2002). The most frequently cited environmental effects associated with salmon aquaculture, which will be discussed in this report, include: salmon escapes and associated impacts; the potential for disease and parasite transfer from farmed fish to wild fish; release of nutrient and chemical wastes; and the use of wild fish in salmon feed. These concerns primarily stem from two factors:

1. As salmon are grown out in net pens located in the ocean, waste materials (both organic and chemical) cannot easily be collected. Instead, wastes generally flow into the surrounding waters where they are diluted, but may still affect surrounding ecosystems. Net pens also permit marine animals to escape more frequently than land-based systems. Escaped animals can potentially interact with wild animals, often negatively (e.g., outcompeting, interbreeding, spreading disease, etc.).

2. Salmon are carnivorous, and thus naturally have a higher dietary protein requirement than, for example, herbivorous fish. To meet this demand cost-effectively, commercial feed formulations typically contain fish meal and fish oil derived from wild fish. Some critics (e.g., Naylor, Goldburg et al 1998) have raised concerns about the net loss of protein involved in this process, and the concomitant demands that aquaculture and other users of fish meal and fish oil are placing on distant marine ecosystems.

Applying generalizations about the salmon farming industry to specific farms is not always warranted, however. First, there is considerable variation not only between individual farms, but also between farming practices in different nations. Second, salmon farming is a young industry, and one that has made considerable improvements over the past two decades. The industry has taken several steps to improve husbandry practices, such as reducing the amount of fish meal in salmon feeds, decreasing antibiotic and pesticide use, and building stronger net pens to prevent escapes. In many cases, however, the progress that has been made to reduce environmental impacts has largely been offset by the industry's rapid expansion.

The availability of scientific evidence on the environmental impacts of salmon farming is mixed. Some effects, such as the tendency for farming practices to affect the areas beneath and directly around salmon farms, are well documented. Other effects, such as regional or long term impacts of salmon farming are poorly understood and poorly documented (Milewski 2002).

For other environmental impacts, such as the effect of escaped farmed salmon on wild salmon populations, or the potential for disease transfer, the nature and size of effects are more difficult to determine. In some cases, there has been an absence of documented detrimental effects to date. This may be due to several reasons; negative effects may never occur, they may not have occurred yet, or they may have occurred and not been documented because the information is unknown, unpublished, or proprietary.

To make an overall assessment of the environmental effects of salmon farming, the following analysis presents both documented evidence of environmental impacts from salmon farming, as well as scientific assessments of the risks posed by current farming practices. Whenever possible, research from Canada and Chile—the main sources of farmed salmon consumed in the U.S.—is presented. However, much of the considerable body of peer-reviewed literature that exists on salmon farming is European owing in part to the region's longer farming history. In addition, findings and statistics have been supplemented by several governmental and intergovernmental reports and reviews.

A separate Seafood Watch Report and ranking exists for U.S. farmed freshwater coho salmon grown in land-based tanks. This report is available at www.seafoodwatch.org.

Analysis & Evaluation of Seafood Watch® Sustainability Criteria

Criterion 1: Risk of Escaped Fish to Wild Stocks

Guiding Principle: Sustainable aquaculture operations pose no substantial risk of deleterious effects on wild fish stocks through the escape of farmed fish.

One path through which aquaculture directly affects the environment is through farmed fish that escape into surrounding waters. Escaped fish can prey on native species, spread disease, breed with native fish or other escaped fish, compete for food and territory, or be fed upon by other animals. Each of these fates represents an alteration of the existing trophic web. If escaped fish are able to successfully reproduce, any alteration in the trophic web can be perpetuated to subsequent generations and intensified by increased populations of the escaped fish.

Research on the potential impacts of escaped farmed salmon entering coastal ecosystems has intensified in the last decade. Most of this research has focused on the capacity of farmed salmon to change the existing ecology of areas in which they are released. Specifically, researchers have examined the effects of escaped farmed species mating with their wild counterparts and altering natural genetic strains (Arthington and Bluhdorn 1996; Hutchinson 1997), and the effects of escaped farmed salmon competing for territory and food with other salmon species (Fleming, Jonsson et al. 1996; EAO 1997; Gross 1998; Fleming, Hindar et al. 2000).

In areas where the farmed species is native—such as Atlantic salmon farmed in much of Europe, Maine, and the East Coast of Canada—concern has been raised that escaped farmed salmon could contribute to the eventual extinction of some strains of wild Atlantic salmon, which have already been reduced by habitat loss, pollution, and overfishing (Anderson, Whoriskey et al. 2000; Garant, Fleming et al. 2003; McGinnity, Prodohl et al. 2003; NRC 2004). In areas where the farmed species is not yet established, such as Atlantic salmon cultured in Chile, British Columbia, and Washington State, research has centered on the potential for escaped fish to establish self-sustaining populations, and the subsequent effects these populations can have on native species (Volpe, Taylor et al. 2000).

Frequency of Escapes
Because salmon are typically raised in marine net pens only partially sheltered from storms, large-scale escapes can occur when the containment systems are damaged. In addition to large-scale escapes, smaller but perhaps more regular “chronic” releases of fish can occur during routine handling (Bridger and Garber 2002). While global records have not been kept, significant escapes have been documented throughout all of the main areas that salmon is farmed:

- In Chile, escapes are concentrated during the winter months of June and July, when strong storms cause containment failure (Soto, Jara et al. 2001). Between 1994 and 1995 salmon farms in Southern Chile reportedly lost several million coho salmon, Atlantic salmon, and steelhead trout (Soto, Jara et al. 2001). As a result of such failures, escaped farmed salmon have become an important species to artisanal fishermen (Soto, Jara et al. 2001). The escaped farmed fish caught off the Chilean coast are primarily coho salmon, but include Atlantic salmon as well as steelhead trout.

- On the Western Coast of North America, escapes have not been accurately recorded but are believed to be substantial (Volpe, Taylor et al. 2000). In July 1997, for example, over 350,000 Atlantic salmon escaped in Puget Sound from a single farm (Gross 1998). U.S. records indicate that 600,000 farmed salmon escaped in the Pacific Northwest between 1996 and 1999, and over a million fish escaped between 1990 and 2000 (Nash, Brooks et al. 2001). Up to 2% of farmed fish may escape in British Columbia each year (Alverson and Ruggerone 1997). As off the Chilean coast, farmed fish are regularly caught by commercial fishermen on the West Coast of North America as far north as Alaska.

- In the North Atlantic up to two million salmon are believed to escape annually (Schiermeier 2003). These escapes were recently highlighted when the loss of some 100,000 fish in the Orkney Islands attracted local recreational fishermen in large numbers (McDowell 2002). As in the other major farming regions, escaped Atlantic salmon are subsequently caught in the wild in the waters of the North Atlantic. In some years 30-40% of Atlantic salmon caught in Norway have originated from fish farms (Hansen, Reddin et al. 1997; Naylor, Williams et al. 2001).

Due to the paucity of systematic data, determining whether the total volume of escaped salmon is increasing or decreasing is problematic. On one hand, the technology used to design marine net pens continues to improve, resulting in more sturdy containment systems. Similarly, most nations have developed or are developing management practices to help reduce the occurrence of escapes. On the other hand, the total number of salmon grown in farms continues to increase. According to one industry analyst, “Some fish will always escape from fish cages, although the number of them can be greatly reduced by good management” (Forster 2002).

As a result of escapes, salmon originating from aquaculture facilities can be found in the ocean throughout much of the native range of wild salmon species worldwide as well as in areas where those species of salmon are not native. Characterizing the effects of these escapes depends largely on the environment into which they escape. In particular, concern over the impacts of escaped salmon is likely to focus on whether they are indigenous or non-indigenous to the waters into which they escape.

Impacts of Escaped Non-Indigenous Salmon

Salmon that escape into areas in which they are not native are an example of the larger phenomenon of invasive species. Invasive species are animals that have been transported to parts of the world where they are not originally native, and which, once transported, can have devastating impacts on an ecosystem. The International Convention on Biological Diversity has identified invasive species as one of the fundamental threats to biodiversity. Globally, it has been estimated that invasive species are second only to habitat destruction in causing the loss of biodiversity (Vitousek, Mooney et al. 1997). In marine waters, the introduction of invasive species has resulted in “fundamental impacts on fisheries resources, industrial development and infrastructure, human welfare, and ecosystem resources and services” (Carlton 2001). Because of its permanence, the introduction of invasive species is one of the most lasting ways in which humans are affecting the global environment.

The ability of a nonnative species to become invasive, such that its introduction can result in severe changes to an ecosystem, depends largely on whether or not it can successfully survive and reproduce in its new environment. If unable to become established in a new environment, a nonnative organism is unlikely to spread or cause significant ecological change. With respect to introduced salmon, most debate has focused on characterizing the likelihood that escaped Atlantic salmon will become established, and invasive, in Pacific waters. Some researchers have argued that the risk of establishment is substantial enough to warrant measures being taken against escapes (Volpe, Taylor et al. 2000; Soto, Jara et al. 2001; Gajard and Laikre 2003). Most notably, the first documented case of escaped farmed Atlantic salmon successfully spawning in British Columbia has raised serious concern. A dozen juvenile Atlantic salmon of two year-classes were recently captured in the Tsitika River (Volpe, Taylor et al. 2000). These juveniles were the natural offspring of escaped farmed salmon, indicating that escaped adults have spawned in Pacific rivers on multiple occasions. Similarly, reproduction by intentionally introduced Atlantic salmon was previously observed subsequent to introduction in Chile and Australia, though these introductions failed to create self-sustaining populations (Nash, Brooks et al. 2001). The effects of an established Atlantic salmon population in the Pacific are difficult to predict. If Atlantic salmon are able to become fully established, populations of Atlantic salmon could conceivably compete with Pacific salmon populations (some of which are in poor health), prey on native fish species, increase predator densities, or otherwise change the marine ecosystem in ways we cannot currently predict.

While acknowledging the limited reproduction of Atlantic salmon in British Columbia, other reviewers have characterized the risks of establishment and subsequent ecological effects as insignificant (Nash, Brooks et al. 2001; Waknitz, Tynan et al. 2002). Despite the few observations of Atlantic salmon reproducing outside their native range, there is no evidence to date of wild-born Atlantic salmon reaching maturity and subsequently reproducing (Nash, Brooks et al. 2001; Soto, Jara et al. 2001). Though a few of the millions of escaped adult Atlantic salmon have reproduced, no naturally-born Atlantic salmon have been observed to reach maturity. Several factors indicate farmed Atlantic salmon are unlikely to become established in the Pacific in the future:

- Intentional stocking efforts of Atlantic salmon have repeatedly failed. Over the past century, there have been several hundred attempts to establish Atlantic salmon outside their native range for recreational fisheries. With the exception of two landlocked populations, all such introductions have failed (Waknitz, Tynan et al. 2002). More specifically, deliberate releases of Atlantic salmon have been made repeatedly over the past century in both the Pacific Northwest and Chile to establish viable fisheries. "Although routine monitoring programs occasionally find naturally-produced juveniles, naturally-produced adults have yet to be observed" (Nash, Brooks et al. 2001). Similar releases have been made on multiple occasions in Chile, and no established populations of Atlantic salmon have been observed (Soto, Jara et al. 2001).

- Atlantic salmon populations are struggling even in their native habitat. Restocking programs in native rivers have also been relatively unsuccessful, indicating that the species is not easily introduced even into areas where it is well-adapted (Nash, Brooks et al. 2001).

- Farmed Atlantic salmon appear to feed poorly once released into the wild. In Chile, analyses of stomach contents indicate that escaped Atlantic salmon are worse natural feeders and slower growing than escaped Pacific salmon (Soto, Jara et al. 2001). In the Pacific Northwest, "Few prey items of any sort have been found in the stomach contents of escaped Atlantic salmon which have been recaptured. As survival in the wild is extremely low for escaped farm fish, it is assumed that their domestic upbringing makes them poor at foraging successfully for themselves" (Nash, Brooks et al. 2001).

- The domesticated nature of farmed fish may make them easier victims for predators such as marine mammals (Nash, Brooks et al. 2001).

In light of the repeated empirical evidence, the likelihood of Atlantic salmon becoming established in the Pacific has been characterized as "remote" by some authors (Nash, Brooks et al. 2001) based on the observation that Atlantic salmon have not established themselves as readily as other salmonid species.

However, previous failures to become established are no guarantee that future introductions will also fail, particularly given the changing and dynamic nature of marine ecosystems at this time (Simberloff and Von Holle 1999; Carlton 2001). Given the permanent nature of the ecological impacts of invasive species there are reasons to be especially cautious about escaped fish. The observed reproduction of Atlantic salmon in British Columbia, Chile, and Australia indicates that the species is physically capable of reproducing in the Pacific. Determining with certainty that Atlantic salmon will not become established in a dynamic environment would require greater knowledge of the ecological system than currently exists. As one review of the risks of Chilean salmon escapes comments, "Biological sustainability entails spatial and temporal dimensions and requires knowledge of the dynamics of the ecosystem, which in turn requires appropriate time scales and horizons. It is difficult to predict the behavior of an ecosystem without knowledge of the entire system's components. Regretfully, Chile lacks this information" (Gajard and Laikre 2003). Their current lack of knowledge suggests the need for more research on these topics.

It is also important to note that escaped nonnative salmon are capable of affecting ecosystems prior to or without actually becoming established. In effect, the continual escape of salmon is the equivalent of a small reproducing population. This population can alter existing food webs in freshwater and marine environments. For example, concern has been raised that through their feeding habits, Atlantic salmon released into Chilean lakes may be affecting native fish species. One review of salmon farming speculates that "Chile could be approaching this critical period of decline for several native species without realizing it or taking measures to stop it because of the lack of baseline data and a strategy to monitor the effects of introduced exotic species" (Gajard and Laikre 2003). In Chilean marine environments, escaped salmon are the top predator in many areas. As a result, the density of escaped salmon found in the wild is negatively correlated with the abundance of native fish, most likely due to predation of salmon on native fish (Soto, Jara et al. 2001). In the Pacific Northwest, the effects of Atlantic salmon escapes are likely to be smaller for several reasons, including the much larger population of native Pacific salmon, sizeable public salmon hatchery programs, and higher abundance of piscivorous marine mammals (Nash, Brooks et al. 2001).

Impacts of Escaped Indigenous Salmon

Concern over escapes in areas in which the farmed salmon species is native—such as Atlantic salmon raised in Europe, Eastern Canada, and Maine—has primarily focused on the effect of escaped fish on wild Atlantic salmon populations. According to the intergovernmental North Atlantic Salmon Conservation Organization, concerns about salmon farming center on the risk of disease and parasite transmission, particularly sea lice, to wild stocks, and effects on the genetic composition of wild stocks caused by interbreeding with escaped farmed salmon. Interbreeding can disrupt the transmission of adaptive traits important for the survival and reproduction of wild fish, thereby depressing population fitness. "The latest scientific research suggests that such interbreeding and poorly planned stocking practices could have serious consequences for the wild salmon which are adapted to the conditions in each river" (NASCO 2003). These interbreeding concerns have been exacerbated by the generally poor health of wild Atlantic salmon stocks; throughout much of the species' southern distribution in Europe and North America, Atlantic salmon stocks are depressed, endangered, or have already been extirpated. In 2000, a series of poor wild salmon returns led the U.S. Fish and Wildlife Service (FWS) and National Marine Fisheries Service (NMFS) to officially list Atlantic salmon populations in Maine as endangered. The status assessment noted interactions with farmed Atlantic salmon as one of several credible threats to the remaining wild fish population (FWS 1999; NRC 2004). In addition to interbreeding and disease transfer, escaped fish can compete with wild fish for food or territory.

While a variety of interactions between farmed and wild salmon exist, the scientific consensus is that, "As a general rule, interactions (between introduced and wild Atlantic salmon) are likely to be negative in their effect on the viability of wild populations" (Youngson and Verspoor 1998). Such interactions are often indirect, such as through competition and displacement. For example, researchers have shown that escaped farmed fish can alter the natural stream environment of wild salmon by elevating densities and increasing overall levels of competition for food and habitat (Einum and Fleming 1997; McGinnity, Stone et al. 1997). In addition, escaped farmed salmon arrive later than wild salmon at spawning grounds. While the timing of spawning varies considerably, if farmed salmon spawn later they can dig up the gravel that contains the nests of wild females and replace the wild-salmon eggs with their own (Webb, Hay et al. 1991). As a consequence of these various interactions, the survival and reproduction rate of wild Atlantic salmon is likely to be depressed.

More importantly, escaped salmon can affect wild populations through interbreeding. As a result of selective breeding programs, domesticated Atlantic salmon strains are now genotypically and phenotypically distinct from wild populations. Unlike hatchery-released salmon, which use eggs obtained from spawning wild fish (or returning hatchery fish), salmon that escape from farms originate from selectively-bred genetic strains, which are multiple generations removed from wild strains (Arthington and Bluhdorn 1996; Hutchinson 1997; Fleming, Hindar et al. 2000). This is not to imply that there are no issues associated with the genetic integrity of hatchery-raised fish. However, such differences are not as large as those from intentional selective breeding programs. The resulting farmed strains outgrow their wild counterparts in farm settings; in salt water, farmed strains grow roughly three times faster than their wild counterparts, and have significantly higher pituitary growth hormone levels (Fleming, Hindar et al. 2000). Farmed strains are also more efficient at converting feed into body mass under optimum conditions, though they are less well adapted to transition from freshwater to saltwater environments (Handeland, Bjornsson et al. 2003). Some researchers have argued that the genetic strain of farmed Atlantic salmon differs substantially enough from its wild counterpart to merit a new species name: *Salmo domesticus* (Gross 1998).

In recent years there has been mounting evidence that male wild Atlantic salmon are mating with escaped farmed Atlantic female salmon, and a shift in the gene pool of the species is occurring (Crozier 1993; Carr, Anderson et al. 1997; Fleming and Einum 1997; Skaala and Hindar 1997; Gross 1998; Youngson and Verspoor 1998; Fleming, Hindar et al. 2000). For example, Skaala and Hindar (1997) found that escaped farmed fish contributed about 44% of the total genes of Atlantic salmon in Norway's River Vasso. A more recent study compared the reproductive success of wild and farmed male Atlantic salmon that mature precociously in freshwater (parr). It found that farmed parr have two to four times higher breeding and fertilization success than wild or hybrid parr. The authors concluded that "Early maturing farm and hybrid males may perpetuate significant gene flow in the second and subsequent generations of invasion by farm fish into native populations, hastening the threat to their genetic integrity" (Garant, Fleming et al. 2003).

Gene flow from farmed to wild fish can harm wild salmon populations in at least two ways. First, hybrid farmed-wild salmon can outcompete wild fish in the freshwater environment. Hybrid Atlantic salmon grow faster and tend to be larger than their wild counterparts (Ferguson, McGinnity et al. 1997; Fleming, Hindar et al. 2000). Empirical evidence indicates that the faster-growing farmed and hybrid juveniles subsequently displace wild juveniles in rivers through competition. Second, despite the growth advantages of farmed strains in laboratory and freshwater settings, research shows farmed genetic strains to be less fit than wild stocks in the wild marine environment (Oekland, Heggberget et al. 1995; Fleming, Jonsson et al. 1996; Fleming, Hindar et al. 2000). Farmed and hybrid strains appear to be less able to compete successfully for food, territory, and mates by a substantial margin. The poor survival of farmed and hybrid salmon in marine environments can lead to a net reduction in the number of returning adults. A recent multi-cohort study determined that farmed salmon have an estimated lifetime reproductive success of just 2% of native wild salmon. Hybrid salmon demonstrated a lifetime reproductive success of 27% to 89% of wild salmon. Moreover, as the result of outbreeding depression, 70% of the embryos of second generation hybrids died, thereby compounding their poor lifetime reproductive success (McGinnity, Prodohl et al. 2003). This combined effect of competition as juveniles and poorer survival rates as adults is highly detrimental. As the authors of the study concluded:

> The combined impact of hybridization and competition means that, when a large number of farm salmon spawn in a river, the number of adult salmon returning to the river and the potential offspring production in the next generation are reduced. The degree of the impact will depend on various factors including relative numbers of wild and farm salmon, and

> juvenile habitat availability. As repeated escapes are now a common occurrence in some areas, a cumulative effect is produced generation upon generation, which could lead to extinction of endangered wild populations as a result of this 'extinction vortex'. (McGinnity, Prodohl et al. 2003)

In contrast to Atlantic salmon, less research has been done on the genetic effects of the few escaped farmed Pacific salmon mating with wild conspecifics. In most regions, effects of these escapes at current levels are likely to be dwarfed by Pacific salmon stocking and ranching efforts. However, there would be an increased potential for genetic effects if the West Coast salmon industry switched to farming Pacific salmon, given that the farmed fish may be considerably more domesticated than those used in hatchery operations.

Evaluation of Factors

Primary Factors to Evaluate

Evidence that farmed fish regularly escape to the surrounding environment:
- Regularly and often in open systems

Status of escaping farmed fish to the surrounding environment:
- Non-native (including genetically modified salmon) but not yet fully established OR native and genetically distinct from wild stocks

Secondary Factors to Evaluate

Where escaping fish are non-native: evidence of the establishment of self-sustaining feral stocks.
- Establishment is probable on theoretical grounds or unknown

Where escaping fish are native: evidence of genetic introgression through successful crossbreeding.
- Empirical and theoretical evidence of introgression

Evidence of spawning disruption of wild fish:
- Empirical and theoretical evidence of spawning disruption

Evidence of competition with wild fish for critical food resources or habitats:
- Empirical and theoretical evidence of competition

Stock status of affected wild fish:
- Substantially below B_{MSY} (e.g., < 50%) OR overfished OR “endangered”, “threatened” or “protected” under state, federal or international law

Evaluation Guidelines

- A "Minor Risk" occurs when a species:
  - Rarely or never escapes AND is native and genetically similar to native populations OR
  - Infrequently or regularly escapes AND survival is known to be negligible

- A "Moderate Risk" occurs when the species:
  - Infrequently escapes AND is non-native but not yet fully established AND there is no evidence to date of negative interactions;
  - Is non-native but historically widely established OR
  - Infrequently escapes AND is native but genetically dissimilar to native populations

- A "Severe Risk" occurs when the species:
  - Frequently escapes AND is non-native and shows the potential to establish feral populations AND shows the potential for negative interactions with native populations OR
  - Frequently escapes AND is native but genetically dissimilar to native populations AND shows the potential for negative interactions and breeding with native fish

- A "Critical Risk" occurs, and the species is given the recommendation "**Avoid"** regardless of other criteria, when the species:
  - Ranks a "severe risk" AND the status of the affected wild fish ranks red.

Risk of Escaped Fish to Wild Stocks Rank:

Low Moderate Severe **Critical**

Criterion 2: Risk of Disease and Parasite Transfer to Wild Stocks

Guiding Principle: Sustainable aquaculture operations pose no substantial risk of deleterious effects on wild fish stocks through the amplification, retransmission or introduction of disease or parasites.

Wild and farmed salmon frequently carry many of the same disease agents such as viruses, bacteria, and parasites. As such, a secondary pathway through which salmon farming can affect wild salmon is through the introduction or transmission of diseases and parasites to wild salmon. The science of disease interaction between wild and farmed fish remains contentious, however, and the aquaculture industry and wild salmon biologists have debated over several years whether wild salmon, which often carry disease pathogens without showing any symptoms of being sick, pose a greater disease risk to farmed salmon than escaped farmed salmon pose to wild fish (Milewski 2002). In most cases healthy fish (wild or farmed) can keep pathogens from developing into debilitating infections (Kent 1994). When debilitating infection does occur, sick fish are likely to fall victim to predators. In contrast, environmentally stressed fish can be susceptible to hundreds of infectious agents (Bakke and Harris 1998). Research shows that the prevalence of disease in cultured species tends to be significantly higher than in wild species (Stephen and Iwama 1997). This phenomenon presumably occurs in part because farmed salmon experience more physiological stress, in part due to unnaturally high salmon density in net pens.

To limit the effects of disease on salmon farms, aquaculturists can control outbreaks through several techniques, including management techniques such as lowering stocking densities, separating age classes, and leaving sites fallow, and treatment techniques such as the application of antibiotics (Weston 1996), pesticides (Roth 2000) and vaccines (Forster 2002). In particular, the development and application of vaccines over the past decade has substantially reduced the incidence of certain diseases and the industry's dependence on antibiotics (Forster 2002).

Despite numerous efforts to control disease at salmon farms, outbreaks continue to occur. The spread of infectious salmon anemia (ISA), for example, which attacks the kidneys and circulatory system of fish, led to the intentional destruction of millions of farmed fish throughout Europe, Canada, and the United States. In 2001, the state of Maine ordered over 900,000 diseased farmed salmon killed in Cobscook Bay in an attempt to prevent further spread of the disease to nearby farmed or wild salmon. In addition to ISA, farmed and hatchery salmon are affected by numerous diseases and parasites such as sea lice (*Gryodactylus salaries;* Bakke and Harris 1998) (Butler 2002; Revie, Gettinby et al. 2002; Heuch, Revie et al. 2003), infectious hematopoietic necrosis (IHN) (Naylor, Eagle et al. 2003), furunculosis, bacterial coldwater disease (Flagg, Berejikian et al. 2000), bacterial kidney disease (BKD) (Olafsen and Roberts 1993), salmon swimbladder sarcoma virus (SSSV), amoebic gill disease (Douglas-Helders, Dawson et al. 2002), and infectious pancreatic necrosis virus (Bowden, Small et al. 2002.). Each of these diseases can have substantial effects on farm productivity.

While it is clear that disease presents a husbandry problem for aquaculturists, it is less clear what effects disease outbreaks in farmed salmon pose to wild salmon populations. Unfortunately, there is only a small body of science available on the topic of disease transfer between farmed and wild salmon and vice versa, as it is difficult to determine the extent of transmission of diseases from farmed to wild fish, or the impacts of such transmissions (FWS 1999; Flagg, Berejikian et al. 2000; LaPatra 2003). As a consequence, the significance of the release of aquatic animal pathogens remains largely speculative.

Disease outbreaks in wild salmon resulting from the spread of disease from farmed salmon have been rarely documented, in large part due to the inherent difficulties of assessing the prevalence of disease in wild fish. It may also be due to a lack of such outbreaks in wild salmon populations. However, certain parasites and pathogens from farmed salmon have a demonstrated potential to infect wild salmon (Brackett 1991; Hjeltnes, Bergh et al. 1995; Bakke and Harris 1998). Several accounts have suspected that outbreaks of the following diseases may have originated at salmon farms and infected wild salmon populations: furunculosis (Bakke and Harris 1998); monogean parasites (Bakke and Harris 1998); sea lice (Birkeland 1996; Johnson, Blaylock et al. 1996); and the virus that causes infectious salmon anemia (Whoriskey 2000). This risk of disease from farms generally falls into two categories:

1. Aquaculture can serve as a vector to *introduce* a disease into new waters. The importation of infected eggs or live fish can lead to the exposure of wild salmon populations to foreign diseases and parasites. Once released in a new region, pathogens can negatively impact wild stocks, which may lack natural defenses to such introduced organisms. There have been only a few documented cases of introduced diseases. The monogean parasite *Gryodactylus salaries*, for instance, was accidentally introduced to Norwegian waters in the mid-1970s, and led to the extinction of several wild salmon runs. While the result of the introduction of exotic diseases can be extremely serious, stricter biosafety controls are now generally exercised by importing nations and farms to protect the industry from exposure to identified pathogens.

2. Farming operations may create a reservoir for an existing disease or parasite, thereby altering the pattern of exposure to wild fish. Sea lice, for example, are among the most easily identifiable, and perhaps most problematic of these wide spread, native parasites (NASCO 2003). Sea lice are parasitic copepods that feed on the mucous, skin, and blood of salmon. Infestations of these ectoparasites reduce the fitness of salmon and, on highly infested individuals, can be fatal (Wagner, McKinley et al. 2003; Glover, Hamre et al. in press). Various species of sea lice are endemic to Europe, North America, and South America; however pre-aquaculture observations of sea lice epizootics on wild fish are virtually non-existent. The development of salmon aquaculture may have increased the incidence of sea lice epizootics, however there is no baseline for comprehensive comparison (Butler 2002; Naylor, Eagle et al. 2003).

Due to the high density of farmed salmon relative to wild populations, sea lice outbreaks are relatively commonplace on many salmon farms. The concentration of salmon farms in areas where wild salmon live or migrate can create an important vector for infecting wild fish, particularly migrating salmon postsmolts that are forced to travel through waters with abnormally high concentrations of sea lice. A review of salmon farming by the Scottish Executive reports that, "The results from a co-operative research project between the Institute of Marine Research, Bergen, Norway and the University of Bergen indicate that more than 86% of the wild postsmolts of Atlantic salmon migrating out of the Sognefjord, and between 48.5% and 81.5% of the postsmolts from the Nordfjord were killed as a direct consequence of sea lice infections during the spring of 1999" (CRU 2002). The sea lice in question were believed to have originated at nearby aquaculture operations. According to a second recent review, "Studies in Norway, Ireland, and

Scotland estimate that in salmon-farming areas the majority of larval lice are produced from farm salmon, due to the far greater numbers of farm hosts relative to wild hosts. Consequently, in Norway and Ireland declines in wild salmonid stocks in farming areas have been linked to elevated louse infestations emanating from salmon farms" (Butler 2002). There have been fewer studies or reports of sea lice in North America, though the parasites are problematic there as well. Sea lice from salmon farms were listed by the U.S. Fish and Wildlife Service as one of the threats to Maine's wild salmon populations (FWS 1999). These concerns have been further fueled by the deteriorating health of wild Atlantic salmon stocks throughout much of the North Atlantic.

In Pacific waters, there has been less focus on the effects of sea lice, though heightened sea lice densities around farms may affect other species of wild fish. Anecdotal evidence from Canada's western shores indicates that sea lice originating at aquaculture facilities may have impacted juvenile pink salmon (Naylor, Eagle et al. 2003). Any ecological effects of sea lice in Chile remain undetermined (Marin, Sepulveda et al. 2002; Gonzalez and Carvajal 2003; Sepulveda, Marin et al. In Press).

Evaluation of Factors

Primary Factors to Evaluate

Risk of amplification and retransmission of disease or parasites to wild stocks:
- Empirical and theoretical evidence of amplification or retransmission

Risk of species introductions or translocations of novel disease/parasites to wild stocks:
- Likely risk of introductions or translocations on theoretical grounds or unknown

Secondary Factors to Evaluate

Bio-safety risks inherent in operations:
- High risk: Open systems

Stock status of potentially affected wild fish:
- Substantially below B_{MSY} (e.g., < 50%) OR "overfished" OR "endangered", "threatened" or "protected" under state, federal or international law

Evaluation Guidelines

- Risk of disease transfer is deemed "Minor" if neither primary factor ranks red AND both secondary factors rank green.
- Risk of disease transfer is deemed to be "Moderate" when the ranks of the primary AND secondary factors "average" to yellow.

- Risk of disease transfer is deemed to be "Severe" if:
    - Either primary factor ranks red AND bio-safety risks are low or moderate OR
    - Both primary factors rank yellow AND bio-safety risks are high AND stock status of the wild fish does not rank green.

- Risk of disease transfer is deemed "**Critical",** and the species given the recommendation "**Avoid**" regardless of other criteria, if:
    - Both primary factors rank red AND stock status of the wild fish ranks red.

Risk of Disease Transfer to Wild Stocks Rank:

Low Moderate **Severe** Critical

Criterion 3: Use of Marine Resources

Guiding Principle: Sustainable aquaculture operations use less wild caught fish (in the form of fish meal and fish oil) than they produce in the form of edible marine fish protein, and thus provide net protein gains for society.

Background

Aquaculture indirectly affects the marine environment through the use of wild marine life in feed for farm-raised fish. Fish meal, fish oil, crustacean meal, and other marine-derived feed ingredients are commonly used as feedstuffs in aquaculture as well as in the poultry and livestock industries. Fish meal and fish oil are produced from wild pelagic fish, such as anchovies and menhaden, which have been processed to remove water and separate out high-protein meals and concentrated oils. One ton of pelagic fish is likely to yield around 180 kilograms of fish meal and 60 kilograms of fish oil, although yield rates (particularly of fish oil) can vary widely (Hardy 2003). The practice of turning wild fish into feedstuffs is widespread; roughly a third of global fisheries landings are converted into fish meal and fish oil annually (FAO 2002). These ingredients have proven to be cost-effective and thus typically form around half the feed for farmed salmon.

Several recent reviews have been critical of aquaculture's use of wild fish for both practical and ethical reasons (Naylor, Goldburg et al. 1998; Naylor, Goldburg et al. 2000; Tidwell and Allan 2001). Practically, general concern has centered over the ecosystem consequences of removing wild fish for use as poultry, livestock and aquaculture feeds (Naylor, Goldburg et al. 1998; Naylor, Goldburg et al. 2000; Franklin 2001; Dayton, Thrush et al. 2002). The removal of forage fish leaves less prey available for wild predators such as seabirds, marine mammals, and predatory fish. The removal can also have top-down effects on ecosystems, potentially encouraging the growth of plankton and zooplankton (Franklin 2001; Dayton, Thrush et al. 2002). In addition, some recent studies have raised health concerns over the concentration of PCBs in farmed salmon, originating from contaminated fish meals and fish oils (Easton, Luszniak et al. 2002; Jacobs, Covaci et al. 2002; Hites, Foran et al. 2004).

Ethically, some have objected to the fact that farming carnivorous animals results in a net loss of protein (Naylor, Goldburg et al. 1998). Critics draw reference to the fact that, other than specialty products such as mink and alligators, no terrestrial carnivores are commercially farmed. These reviews have urged the aquaculture industry to transition away from farming carnivorous animals such as salmon and shrimp, and instead focus on herbivorous and omnivorous fish with lower fish meal and fish oil requirements such as catfish, tilapia, and carp (Naylor, Goldburg et al. 1998; Goldburg, Elliott et al. 2001).

Farmed Salmon Feed Use

Atlantic, chinook, and coho salmon are carnivorous fish (Halver and Hardy 2002); in the wild, juvenile salmon feed on a range of animals including crustaceans, insects, mollusks, and other fish; adults at sea typically eat squid, shrimp, and other fish (Froese and Pauly 2003). Aquacultural nutritionists necessarily formulate diets that match the nutritional requirements of specific farmed animals. As such, salmon are generally fed diets with relatively high concentrations of fish meal and fish oil.

The total quantity of wild fish used by the global salmon industry depends essentially on three factors: the average percentage of wild fish used in salmon feeds (in the form of fish meal and fish oil), or “inclusion rates”; the average efficiency with which salmon convert feed into body weight, or “feed conversion ratios”; and the total amount of salmon produced worldwide.

Inclusion Rates

The typical salmon diet contains fish meal and fish oil, high-protein plant and animal material, grain-derived products for binding the aquafeed, and micronutrients. The “inclusion rate” of fish meal and fish oil is the percentage of the feed (by weight) comprised of those ingredients. For salmon feeds the fish meal and fish oil inclusion rates vary depending on several factors including the species and age of the fish being raised, the manufacturer, and the price of fish meal and fish oil relative to substitutes. On average, salmon diets are around one-half fish meal and fish oil (Morris, Beattie et al. 2003). Industry expert Ron Hardy estimates that at present the general range for fish meal in salmon diets is 30-35% (Hardy, 2003); in addition, fish oil comprises another ten to twenty percent of salmon aquafeeds. The use of fish oil is particularly notable, as the average pelagic fish yields three times as much fish meal as fish oil. Consequently, salmon aquaculture uses a greater share of world fish oil production than fish meal production. At present, aquafeeds appropriate about 70% of global fish oil production, but closer to 40% of global fish meal production.

Feed conversion ratio (FCR)

The FCR is the ratio of feed used (dry weight) to weight gained by a fish. An FCR of one would indicate that for every kilogram of dry feed used, the fish receiving the feed gained one kilogram in mass. Like the inclusion rate, the FCR is subject to considerable variation. Factors such as environmental conditions, feed composition, the species and genetic strain of fish, water temperature, disease, and environmental stress all affect salmon's ability to grow efficiently. Moreover, the FCR of farmed salmon changes significantly over the life of the fish; young fish are often more efficient and as salmon approach harvest, FCRs may thus increase (Norgarden, Oppendal et al. 2003).

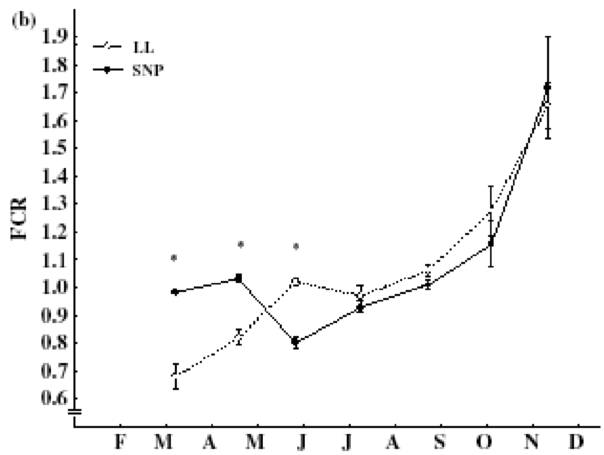


Figure 6 Feed intake (percentage of biomass) (a) and feed conversion ratio (b) in Atlantic salmon reared under continuous light (LL) or simulated natural photoperiod (SNP). See Fig. 2 for further details.

Source: (Norgarden, Oppendal et al. 2003)

In general, FCRs have improved (fallen) over the past two decades. Feed conversion ratios in some countries such as Norway—which has limitations on the amount of feed that can be used, and therefore uses expensive, high-fish meal diets—have fallen as low as 0.85 (Pike and Barlow 2001). Industry-wide FCRs for salmon farming are currently believed to be between 1.2 and 1.5, though probably closer to the lower end (Tacon and Forster 2000; Morris, Beattie et al. 2003). One method to lower FCRs is to use more digestible diets; high fish meal diets, for example (Hardy, 2003). Using feed with higher levels of vegetable proteins, and lower levels of fish meal, on the other hand, can impair salmon growth rates and feed conversion efficiency, increasing feed conversion ratios (Opstvedt, Aksnes et al. 2003).

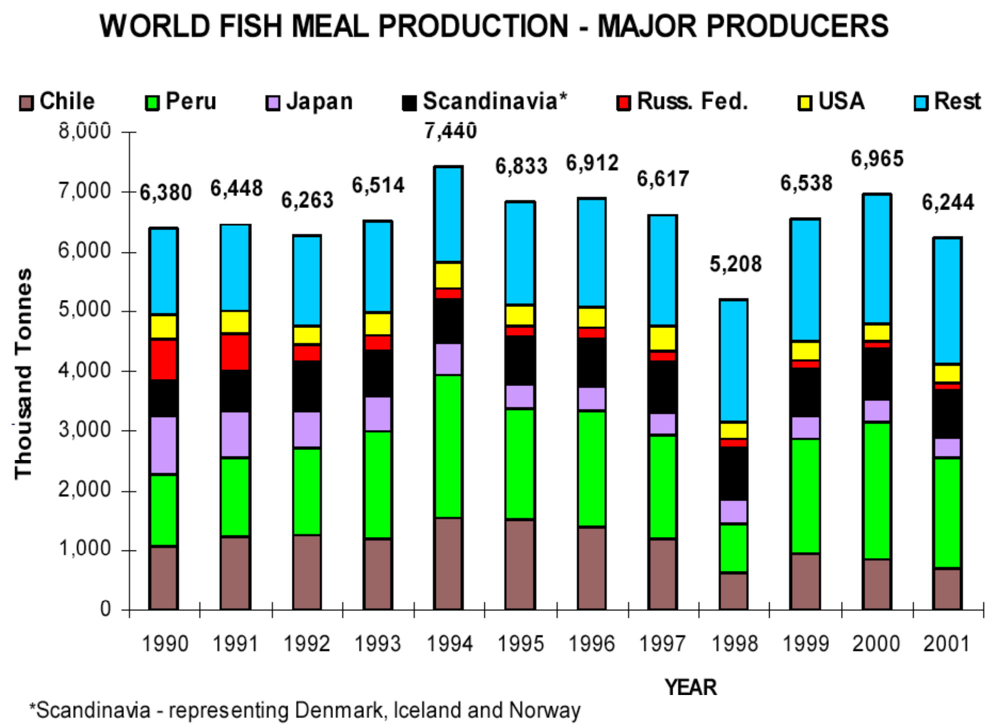
Ratio of wild fish to farmed salmon

Several studies have combined production figures with estimates of industry-wide inclusion rates and FCRs to determine the total amount of wild fish used in the salmon farming industry. In addition to the FCR and the inclusion rate, the third figure that is needed to produce this estimate is the average number of tons of wild fish required to produce a ton of fishmeal and fish oil. In 2001, the fish meal industry estimated 33 million tons of wild fish and fish parts were reduced to 1.2 million tons of fish oil and 6.2 million tons of fishmeal; a ratio of 4.5:1 (FIN 2002). Combining these numbers with averages for FCRs and inclusion rates, a 1997 study showed that approximately 1.8 million mt of wild fish were required to grow 644,000 mt of Atlantic salmon; a ratio of 2.8:1 (Naylor, Goldburg et al. 1998). However, as discussed above, fish meal inclusion rates and FCRs have generally been falling. A more recent study estimated the ratio of wild-fish-fed farmed salmon at just over 2.4 (Tacon and Forster 2000; Goldburg, Elliott et al. 2001); at current production levels, the global farmed salmon industry would appropriate roughly 2.5 million tons of wild fish for feed. Industry experts have criticized these numbers, yet have also indicated that under current practices it requires between 1.9 and 3.6 tons of wild fish to produce a single ton of farmed Atlantic salmon, depending on the specific feeds and growth rates obtained (Hardy, 2003 #195). Given current global farmed salmon production of over one million tons, the industry numbers indicate that between 2 and 3.5 million tons of wild fish are processed into salmon feed annually.

Impact on Marine Ecosystems

While it is a relatively straightforward calculation to determine how much fish meal and fish oil salmon farms appropriate, assessing the impact that the resource use has on marine ecosystems is more difficult for at least two reasons: the science on the ecosystem effects of removing large quantities of forage fish is unclear; and the baselines for what marine ecosystems were like before the harvest of large quantities of fish for aquaculture feed are unknown.

Fish meal is produced primarily from pelagic fish that live near the surface waters or at mid-water depths in the ocean (IFFO 2001). The fish species that comprise most fish meal include anchovy, sardine, menhaden, jack mackerel, sandeel, sprat, capelin, and whiting (IFFO 2001). In addition to pelagic fish, roughly a tenth of the global fish meal supply is produced from "offal", or fisheries processing wastes. Between 30 and 40 million tons of fish are processed annually worldwide for "reduction" to fish meal and oil, approximately one-third of the total global fisheries harvest (IFFO 2001; IntraFish 2001). With respect to geographic production distribution, the majority of fish meal is generated in six nations: Chile, Peru, Iceland, Norway, Denmark, and the United States (Barlow 2002).



Source: (Barlow 2002)

Because fish meal production is a global industry that harvests fish from several oceans, it is difficult to characterize the status of stocks of fish species captured for production of fish meal and oil used for salmon farming. Generally, forage fish stocks are managed using a number of measures such as catch limits and gear restrictions. Owing in part to their resilient life histories,[2] most forage fish stocks today are not overfished; instead, the FAO classifies most stocks as fully fished, though there is some regional variation.

Table 1: Management Controls on Species Used for Fish Meal

Species	Total Catch Limit	Area Catch Limits	Min. Mesh Size	Fleet Cap Controls	Closed Areas	Seasonal Bans	Min. Landing Sizes
Anchovy	√	√	√	√	√	√	√
Sardine	√	√	√	√	√	√	√
Jack Mackerel	√	√	√	√	√	√	√
Horse Mackerel	√	√	√	√	√	√	√
Sandeel	√	√	√	√	√	√	
Sprat	√	√	√	√	√	√	
Norway Pout	√	√	√	√	√	√	

[2] For example, the Peruvian anchovy is highly resilient to overfishing, requiring only 15 months for populations to double (Froese and Pauly, 2003).

Blue Whiting			√				
Capelin	√	√	√	√	√	√	√
Herring	√	√	√	√	√	√	√

Source: (Barlow 2002)

Most fish meal and fish oil used specifically in Chilean and Canadian salmon farming originates in Chile, Peru, and the United States. While detailed data are not available, Peru and Chile, the world's largest fish meal producers and exporters, presumably supply the bulk of the fish meal and fish oil to nearby Chilean salmon farms (IntraFish 2001). Similarly, Canadian fish meal imports mainly come from Peru, Chile, and the United States; over the past five years these three nations accounted for 85% of Canadian fish meal imports. Specifically, Peru and Chile made up 70% and the U.S. 15% of Canadian fish meal imports. Most Canadian imports of fish oil over the past five years originated in Peru, and to a lesser extent the United States (Canada 2003).

Fish meal production is primarily based on the anchovy fishery, with some sardine bycatch, in Peru, and jack mackerel, anchovy, and pilchard in Chile. Stocks are, for the most part, stable though some have been depleted. The FAO (2002) reports:

> In the Southeast Pacific, total annual catches reached an all-time high in 1994, and then declined sharply as a consequence of the severe 1997-1998 El Niño and the depletion of the Peruvian anchoveta and other important stocks in the area. Post-El Niño recovery has been surprisingly fast, particularly in the stocks of Peruvian anchoveta. This has taken the total catches rapidly back to pre-El Niño levels, although some other important and declining stocks such as Chilean jack mackerel and the South American pilchard have given no signs of recovery.

In the United States, most fish meal is produced from menhaden, a small pelagic fish caught in the Atlantic and Gulf of Mexico. Fish meal from menhaden has traditionally been sold to terrestrial livestock, rather than the aquaculture industry. According to NMFS, neither the Atlantic nor the Gulf of Mexico menhaden fisheries are overfished or experiencing overfishing (NMFS 2002).

While pelagic fisheries are often able to sustain heavy fishing pressures, the ecological effects are not necessarily insignificant. A recent review of the ecological effects of fishing notes:

> Low trophic-level species—like sardines, herring, and anchovies—typically mature rapidly, live relatively short lives, and are extremely abundant. As a result, they are among the most heavily exploited species in the world. Single-species models, particularly those based on maximum sustainable yield, suggest that lower trophic-level species have tremendous potential for sustainable exploitation. Ecosystem models, on the other hand, present a more sobering view. First, these models suggest that heavy exploitation could effect increased populations of their competitors, and declines in populations of their predators. Second, ecosystem

> models suggest that large removals of forage species could work synergistically with heavy nutrient loading to exacerbate problems of eutrophication in enclosed coastal ecosystems (Dayton, Thrush et al. 2002).

Specifically, the extraction of anchovies and other forage fish undoubtedly affects the Southeast Pacific marine ecosystem. Intensive fishing currently reduces the quantity of prey available to large fish such as tunas, and the sizable populations of guano birds and pelicans that depend on Peruvian anchovies (Froese and Pauly 2003). Similarly, in U.S. waters menhaden form a key dietary component for several species of carnivorous fish including striped bass, tunas and swordfish, as well as marine birds (Franklin 2001; Froese and Pauly 2003). The menhaden fishery has come under fire for depleting the amount of prey available to these animals, as well as reducing the coastal ecosystem's ability to filter plankton out of the water column. One critic argues that:

> The population of menhaden has been so depleted in estuaries and bays up and down the Eastern Seaboard that even marine biologists who look kindly on commercial fishing are alarmed…. Menhaden have an even more important role that extends beyond the food chain: They are filter feeders that consume phytoplankton, thus controlling the growth of algae in coastal waters. As the population of menhaden declines, algal blooms have proliferated, transforming some inshore waters into dead zones (Franklin 2001).

Overall, fish meal and fish oil ultimately destined for Chilean and Canadian salmon farms originate primarily from Peruvian and Chilean anchovy stocks, and to a lesser extent U.S. menhaden. These stocks are highly resilient, and in most cases able to withstand current intensive fishing pressures, however there are concerns regarding the effect this removal continues to have on predators, prey, competitors, and water quality in surrounding ecosystems.

Contribution to these impacts from salmon farming

Perhaps the most contentious element to the debate over the use of fish meal and fish oil in aquaculture is the discussion of to what degree the aquaculture industry ought to be held morally or economically responsible for deleterious effects to forage fisheries (Naylor, Goldburg et al. 1998; Hardy 1999).

The capture of pelagic fish and production of fish meal and fish oil long predates aquaculture's dramatic rise over the past two decades. Traditionally, fish meal has been used as a fertilizer and also as a feed ingredient in poultry and swine feeds, as well as for ruminants, in pet foods, and on mink farms. Similarly, fish oil is used in the livestock, pharmaceutical, and chemical industries, as well as for direct consumption.

However, as aquaculture production has increased, fish meal use has slowly shifted from other industries—particularly poultry—to fish farms. Though fish meal production has remained relatively stable, demand for the product is slowly shifting between industries (Pike and Barlow 2001; Tidwell and Allan 2001). As the farmed salmon industry grew between 1988 and 1998, the proportion of the world's fish meal supply used in farmed fish feeds rose from 10% to 33% (Naylor, Goldburg et al. 2000). Today, aquaculture is the largest consumer of fish meal. Current industry estimates indicate aquaculture consumes about 34% of global fish meal production, followed by swine (29%), poultry (27%) and other users (10%) (Barlow 2002). However, swine and poultry feeds have significantly lower inclusion rates of fishmeal, often using fishmeal only for young animal diets. Use of fishmeal and other feed ingredients is typically dictated by least-cost models that incorporate the prices of numerous feedstuffs. Of the 34% of global fish meal consumed by aquaculture (the equivalent of 10 million tons of wild fish), only about a quarter of that is dedicated to salmon farming. The majority of aquaculture fishmeal is reportedly used in Chinese aquaculture (55%) (CRU 2002).

In contrast to fish meal use, the majority of global fish oil is dedicated to aquaculture at present. Current estimates indicate about 70% of global fish oil supply is consumed by the aquaculture industry, and over 40% of the aquaculture fish oil supply goes to Chilean and Canadian fish farms (CRU 2002). According to the International Fish Meal and Oil industry group, "Principally most of this fish oil is going into salmonid consumption in Norway, Chile, Canada and in various European countries" (Barlow 2002). Moreover, aquaculture's share is growing. Industry experts expect that by 2010, aquafeeds will appropriate half of global fish meal and 80-100% of global fish oil production (Starkey 2000; Barlow 2002).

Despite the increase in use of fish meal and oil in aquaculture, annual production of fish meal and fish oil has not increased to meet demand. Instead, aquaculture's growing demand has increased the price of fish meal, forcing the poultry industry to shift toward vegetable proteins (Tidwell and Allan 2001). Hence, it is unclear to what extent future demand for fish oil and fish meal will encourage the harvest of stocks that are not currently fully fished. Some have pointed out that if aquaculture stopped using fish meal, prices would fall and other industries would simply increase their use (Hardy 2001). However, economics indicates that if prices continue to rise, then fisheries that are currently marginal or unprofitable, may become profitable. At current prices, however, such effects are weak.

An additional component to the debate has been the effect of fish meal use on food security. The use of fish meal and fish oil has been criticized for depleting the amount of protein available for human consumption (Naylor, Goldburg et al. 2000), however several analysts have defended the practice of fish meal and fish oil use for efficiency reasons.

Proponents have indicated that in energy terms it is several times more efficient to harvest forage fish and feed them to farmed salmon, than to leave them in the ocean and harvest the wild fish that eat them (Forster 2002). However, comparing the bioenergetics of farmed fish against those of wild fish does not address the issue of ecosystem services and other non-use values of marine ecosystems that may conceivably exceed market values (Costanza, d'Arge et al. 1997). Moreover, the *total* energy requirements of salmon farming (incorporating fossil fuel use), may be significantly higher than those for wild fisheries (Costa-Pierce 2002).

It has also been demonstrated that farmed fish (being cold-blooded) are bio-energetically more efficient than many terrestrial livestock (Tidwell and Allan 2001). According to a summary provided by Costa-Pierce, the production efficiency of aquaculture operations is in the range of 2.5-4.5 kg of dry feed used per kg of edible product (Costa-Pierce 2002). For salmon, this ratio is likely to be closer to 2.0 given the relatively low FCR and high percent of the edible harvested fish. Milk, eggs, and chicken, for comparison, have ratios closer to 3.0, while swine and beef have higher ratios at 5.6 and 10.2 respectively. Farmed fish require less feed per unit of output than terrestrial animals.

This discussion is largely tangential to the primary concern of this review, which is not the bioenergetics of food production, but rather the critical issue of marine ecosystem integrity and structure. Terrestrial operations generally use minimal concentrations of fish meal and fish oil in feeds, and as such place a lower demand on marine ecosystems per unit of production. To the extent that they do place high demands on marine resources, they are equally culpable. Moreover, agriculture and terrestrial livestock appear to have lower overall energy demands than salmon farming (Costa-Pierce 2002).

Overall, like much of the sustainability discussion in general, the debate over fish meal is fundamentally one of environmental ethics. The crucial question remains: should harvesting of fish not destined for direct human consumption be encouraged, and, if not, to what extent should responsibility lie with the consuming industries as opposed to the extractive industry. A review of farmed salmon should acknowledge, at the very least, the extensive use of marine resources in feeds and their concomitant environmental impacts.

For consistency, this evaluation applies the same standards developed to rank the sustainability of bycatch in wild fisheries. In wild fisheries assessments, fisheries that capture twice as much marine life as they land are given a red ranking in the bycatch category regardless of the stock status of the bycatch species. For example, if a wild shrimp fishery discards more than a ton of bycatch for every ton of shrimp landed, it is given a red ranking. The same system is applied here to fish meal use: aquaculture operations that are estimated to use more than twice as much wild fish in feeds as the quantity of farmed fish they produce are given a red ranking. In contrast, those aquaculture operations that produce more fish than they utilize in feeds are given a green ranking. The middle ground (a wild fish:farmed fish ratio between 1.1 and 2) is deemed the equivalent of a moderate bycatch ranking, and is given a yellow ranking.

Evaluation of Factors

Feed Use Components to Evaluate

A) Amount of wild-caught fish (excluding fishery by-products) used to create fish meal and fish oil (ton/ton):
   - **4.5**

B) Inclusion rate of fish meal, fish oil, and other marine resources in feed (%):
   - **45%**

C) Efficiency of feed use: estimated average economic feed conversion ratio (FCR)

in grow-out operations:
- **1.2**

D) Wild fish input:farmed fish output ratio
- [Wild fish: (fish meal + fish oil)] x [Inclusion rate] x [FCR] = **2.4**

Primary Factor to Evaluate

Estimated wild fish used to produce farmed fish (ton/ton, from above):
- Extensive use of marine resources (> 2.0)

Secondary Factors to Evaluate

Stock status of the reduction fishery used for feed for the farmed species:
- Close to B_{MSY} (50 – 125%) OR unknown

Source of stock for farmed species:
- Stock from closed life cycle hatchery OR wild caught and intensity of collection clearly does not result in depletion of brood stock, wild juveniles or associated non-target organisms

Evaluation Guidelines

- Low use of marine resources is when the wild fish:farmed fish ratio is between 0.0 and 1.1.
- Moderate use of marine resources is when the wild fish:farmed fish ratio is between 1.1 and 2.0.
- Extensive use of marine resources is when the wild fish:farmed fish ratio is greater than 2.0.
- Use of marine resources is deemed "Critical", and the species under consideration given the recommendation "**Avoid**" regardless of other criteria, if the stock status of the reduction fishery is ranked red OR the wild fish:farmed fish ratio is greater than 2.0 and the source of seed stock is ranked red.

Use of Marine Resources Rank:

Low Moderate **Extensive** Critical

Criterion 4: Risk of Pollution and Habitat Effects

Guiding Principle: Sustainable aquaculture operations employ methods to treat and reduce the discharge of organic waste and other potential contaminants such that the resulting discharge cannot be demonstrated to adversely affect the integrity and function of the surrounding ecosystem.

Origin of Organic Wastes
Organic wastes from fish farms consist of excretory products and uneaten feed that enter the water column. Because salmon net pens are open systems, wastes flow directly into the surrounding waters where they are diluted and eventually assimilated. Most salmon farm waste is deposited, untreated, directly into the waters beneath and around net pens (Sutherland, Martin et al. 2001).

The penultimate origin of organic waste from salmon net pens is pelletized feed. Feed pellets are more dense than water, thus fall through the water column where they are either consumed by fish in the pen, thus processed and partially excreted by the fish, or exit the pen uneaten to be eaten by other organisms or otherwise decompose on the ocean floor. A 1997 study found that 15-20% of dry feed and more than 20% of moist feed entered the marine environment uneaten from salmon farms (Burd 1997). This percentage is likely to be considerably less today because of advances in feeding techniques, such as the use of video imaging and feeding devices. A more recent estimate is that less than 5% of feed goes uneaten in modern operations (Nash, Brooks et al. 2001). However, while the percentage of uneaten feed may have declined, in recent years the amount of feed used in aquaculture has substantially increased, presumably resulting in an overall increase in the amount of fish feed entering and decomposing in coastal waters near salmon farms.

In addition to uneaten feed, much of the consumed feed is excreted by salmon in the form of feces, urine, and mucus. According to one summary:

> Weston (1986) estimated that 25–33% of feed consumed by the fish was ejected as feces. Modern diets are approximately 87–88% digestible (J. Mann, EWOS Canada Ltd., personal communication). The remaining ash consists primarily of calcium and inorganic phosphate, and represents 8.0–8.5% of the feed. This implies approximately 12.5% of the weight of ingested feed will be ejected in feces. (Nash, Brooks et al. 2001)

While fish feces are natural products, the density and immobility of salmon in areas of intensive production is not congruent with the natural ecosystem. During the 1970's and 1980's most salmon farms were only raising tens of thousands of fish per site. Today it is common for a single farm to raise hundreds of thousands of fish (Milewski 2002). The decomposition of large quantities of uneaten fish feed beneath and around salmon farms, in concert with the decomposition of farmed salmon feces from these many fish in high density, has been shown to impact the surrounding environment.

Local impacts of organic wastes
Localized impacts of waste from salmon farms are the most apparent environmental impact of cage-based aquaculture, and as such are relatively well documented (Kelly, Stellwagen et al. 1996; McDonald, Tikkanen et al. 1996; Silvert and Sowles 1996; Burd 1997; Findlay and Watling 1997; Hansen, Ervik et al. 2001). Organic matter often accumulates under and around net pens, increasing carbon levels in the sediments and

reducing their oxidation-reduction (redox) potential. Sediments and biota can move into a state of overloading, anoxia, and outgassing of carbon dioxide, methane, and hydrogen sulfide (Chang and Thonney 1992; Black, Kiemer et al. 1996). In documenting these impacts, many studies have noted the ecological impacts in terms of changes in infaunal species biomass and species diversity within the impacted area (Findlay, Watling et al. 1995; Costa-Pierce 1996; Burd 1997; Mazzola, Mirto et al. 2000).

The primary effect of chemical and biological accumulation in nearfield sediments is an increased level of organic carbon and sulfides, and consequently altered patterns of species diversity in the benthos (Brooks, Stierns et al. 2003; Wildish, Hargrave et al. 2003). Species diversity in the benthic environment directly beneath salmon net pens with moderate to poor flushing is usually reduced to two taxa: the polychaete complex; and a few nematode species (Findlay, Watling et al. 1995; Pohle and Frost 1997; Mazzola, Mirto et al. 2000). Researchers have found these two taxa occur without fail at salmon farms worldwide (Burd 1997). A reduction in species numbers can extend to distances over 200 meters from the net pen perimeter during peak production and in areas of poor flushing, though the most severe effects are generally found within 50 meters of sites (Nash, Brooks et al. 2001; Carroll, Cochrane et al. 2003). The magnitude of the change in animal biomass correlates with the degree of tidal flushing in and around each farm site, as local characteristics such as depth and current levels are key in influencing the nature and magnitude of the impacts. At well-flushed sites, the addition of organic carbon from the farm can stimulate an increase in abundance and diversity of the infaunal community (Nash, Brooks et al. 2001).

Barring severe anoxia, effects on species diversity in the water column are not readily evident. In some cases, salmon farms may increase the abundance of megafauna in surrounding waters by providing physical structure and food. Anecdotally, increased abundances of fish, shrimp, and other organisms have been observed near net pens, which may serve as artificial reefs (Nash, Brooks et al. 2001). Wild fish around farms often feed on uneaten aquafeeds, and as a result may have altered tastes and chemical compositions (Skog, Hylland et al. 2003).

The accumulation of copper (from copper-treated nets) and zinc (a feed additive) in the substrate around net pens is another waste concern. However, effects from these heavy metals appear to be minor (Nash, Brooks et al. 2001). Moreover, while the biological and chemical impacts of organic waste accumulation will persist as long as net pens remain in operation, remediation can be a relatively short process. If net pens are allowed to lie fallow, the majority of measurable biological and chemical remediation is likely to occur within a few months to two years (Burd 1997; Mazzola, Mirto et al. 2000; Pohle, Frost et al. 2001). The rate of remediation depends largely on local hydrographic characteristics, as well as the intensity and duration of past farming efforts.

Regional impacts of organic wastes

In contrast to local effects from organic wastes, few studies have examined the ecological effects of waste discharge from salmon farms across larger spatial and longer temporal scales (Milewski 2002). For example, no studies have shown what impact, if any, nutrient waste has on nearby marine ecosystems (Costa-Pierce 1996). It is difficult to predict what effects the development of a salmon farm within a bay or inlet will have on larger tracts of ocean over long periods of time. One concern is that the transport of organic materials from distant terrestrial and marine areas, and their addition to coastal areas in the form of feces and aquafeeds, can contribute to eutrophication. It has been demonstrated that the initial nutrient input beneath salmon farms can promote phytoplankton growth (Molver, Stigebrandt et al. 1988), and some have argued that such additions could conceivably lead to toxic blooms and hypoxia in the water column (Silvert and Sowles 1996). However, apart from poorly-sited operations (e.g., enclosed bays with poor flushing) such incidents are rare and difficult to attribute cause to or document. According to a NMFS review, "The literature indicates that the concentration of dissolved inorganic nitrogen added to marine water at salmon farms is very low on the perimeter of net pen farms, and essentially immeasurable at distances greater than 9 m from the farm perimeter" (Nash, Brooks et al. 2001).

Salmon aquaculture is just one small contributor to the larger problem of eutrophication in marine ecosystems. Eutrophication is a major problem in coastal areas worldwide. The addition of nutrients and change in nutrient ratios can trigger algal blooms and more fundamentally affect the dynamics and species composition of ecological communities through bottom-up processes (Boesch, Burroughs et al. 2001). On a global scale, the contribution of nutrients from salmon farms borders on insignificance when compared to nutrients from terrestrial agriculture and livestock, urban runoff, and atmospheric deposition. However, eutrophication is largely a problem of diffuse sources. Moreover, regionally, such as in the intensive aquaculture areas of Chile and Canada where salmon farms are relatively abundant, salmon operations may represent a significant anthropogenic contribution to overall nutrient and suspended solid concentrations (Strain, Wildish et al. 1995).

Chemical Pollution

In addition to organic wastes, open aquaculture systems can introduce chemicals into the marine environment. Aquaculture, like terrestrial agricultural and livestock industries, routinely employs a variety of chemicals for multiple purposes, such as promoting growth and preventing disease. The range of chemicals that can be used on a salmon farm includes such diverse groups of products as antibiotics, pesticides, fungicides, vitamin supplements, coloring agents, spawning hormones and anaesthetics. Tacon and Forster (2003) provide (below) a summary of the range of chemicals used in salmonid and non-salmonid aquaculture operations.

Major category of chemicals used in aquaculture[a]

Chemicals and their application
Chemicals associated with structural materials: plastic additives—stabilizers, pigments, antioxidants, UV absorbers, flame retardants, fungicides, and disinfectants; antifoulants—tributyltin
Soil and water treatments: flocculants—alum, EDTA, gypsum (calcium sulphate), ferric chloride; alkalinity control—lime/limestone; water conditioners/ammonia control—zeolite, *Yucca* extracts, grapefruit seed extract (KILOL); osmoregulators—sodium chloride, gypsum; hydrogen sulphide precipitator—iron oxide
Fertilizers: inorganic salts—limestone, marl, nitrates, phosphates, silicates, ammonium compounds, potassium and magnesium salts, trace element mixes; organic fertilizers—urea, animal and plant manures
Disinfectants: general—formalin, hyprochlorite, iodophores—PVPI, sulphonamides, ozonation; topical—quaternary ammonium compounds, benzalkonium chloride
Antibacterial agents: β-lactams—amoxycillin; nitrofurans—furazolidone, nifurpirinol; macrolides—erythromycin, phenicols—chloramphenicol, thiamphenicol, florphenicol; quinolones—nalidixic acid, oxolinic acid, flumequine; rifampicin, sulphonomides, tetracyclines—oxytetracycline, chlortetracycline, doxycycline
Therapeutants and other antibacterials: acriflavine, copper compounds, dimetridazole, formalin, glutaraldehyde, hydrogen peroxide, levamisole, malachite green, methylene blue, niclosamide, potassium permanganate, trifluralin
Pesticides: ammonia, azinphos ethyl, carbaryl, dichlorvos, ivermectin, nicotine, organophosphates, organotin compounds, rotenone, saponin, trichlorofon, teased cake, mahua oil cake, derris root powder, lime, potassium permanganate, urea, triphenyltin, copper sulphate
Herbicides/algicides: 2,4-D, Dalapon, Paraquat, Diuron, ammonia, copper sulphate, simazine, potassium ricinoleate, chelated copper compounds, food colouring compounds
Feed additives: acidifiers—citrates; antioxidants—butylated hydoxyanisole, butylated hydroxytoluene, ethoxyquin, propyl gallate; binders—animal protein, mineral (bentonite, magnesite), plant, seaweed, synthetic (urea formaldehyde, polyvinyl-pyrrolidone); feed enzymes; emulsifiers/surfactants—natural, synthetic; growth promoters—natural, synthetic; minerals—major and trace; pigments—food dyes, carotenoids (natural, synthetic); synthetic vitamins, amino acids and feeding attractants; immunostimulants, probiotics, mould inhibitors—natural, synthetic)
Anaesthetics: benzocaine, carbon dioxide, metomidate, quinaldine, phenoxyethanol, tricaine methanesulphonate
Hormones: growth hormone, methyl-testosterone, oestradiol, ovulation-inducing drugs, serotonin
Fuels and lubricants: petroleum products—kerosene, petrol, diesel, oil
Environmental contaminants/pollutants—heavy metals/other metals—mercury, lead, mercury, arsenic, cadmium, chromium, copper, iron, manganese, nickel, selenium, silver, zinc; Chlorinated insecticides—DDT, dieldrin, lindane and their degradation products; PCBs and Dioxins

Source: Tacon and Forster, 2003.

In net pen systems, chemicals are generally applied in water, where they can disperse and affect non-target species (NRC 1999). However, not all of the chemicals listed by Tacon and Forster are used on salmon farms or in other marine net pen systems and many of the chemicals that are used are not considered hazardous. With respect to salmon farming, concern over chemical use has centered on the effects of specific drugs, most notably antibiotics and pesticides, on human health and the surrounding environment (NRC 1999).

Antibiotics

Use of antibiotics is thought to be widespread in salmon aquaculture in some areas, though not in others. They are more likely to be employed in areas that have a high concentration of salmon farms within a relatively small geographical area (Benbrook 2002). Conversely, there are some salmon aquaculture sites that have had no disease problems and use no antibiotics (Swanson 2001). Antibiotics are usually administered to farmed salmon through feed. For instance, Rangen, Inc. sells a "medicated feed" that "is formulated with high quality proteins and lipid to contribute to added palatability and increased digestibility at a time when the fish are not feeding readily. Oxytetracycline at 4000 and 8000 gms/ton and Romet-30 at 1.67% are available" (Rangen 2002).

Though many aquaculture facilities regularly treat farmed salmon with antibiotics, most facilities are not required to report the type and strength of the antibiotic, nor the frequency of use. Thus, there is very limited information available on the amount of antibiotics used in salmon aquaculture. However, over the last decade antibiotic use appears to have decreased. According to one industry review, "Major advances in the development and application of vaccines against key salmonid diseases have resulted in dramatic, industry-wide reduction in anti-biotic use" (Forster 2002).

Environmental and health effects of antibiotics

Depending on the antibiotic used, between 60% and 85% of a drug can be excreted through feces, unchanged (Alderman, Rosenthal et al. 1994; Samuelsen 1994; Weston 1996). Some drugs, such as oxytetracycline, are poorly absorbed through the intestinal tract of salmon, and consequently must be administered at high dosage rates for up to two weeks (Miranda and Zemelman 2002). The most widely used antibiotics, oxytetracycline and oxolinic acid, have been shown to stay in sediments for ten and six months, respectively (Weston 1996). The environmental effects of antibiotic buildup beneath and around salmon farms remain unquantified, but are likely to be small (Weston 1996; GESAMP 1997).

With respect to human health, antibiotic use encourages the growth of antibiotic resistant strains of bacteria. Some criticism has been leveled at the aquaculture industry for promoting the development of antibiotic resistant bacteria (Angulo and Griffin 2000; Goldburg, Elliott et al. 2001; Miranda and Zemelman 2002). However, few antibiotics are actually approved for aquaculture operations. Moreover, none of the drugs approved for use in salmon farming in North America are antibiotics of last resort in humans (NRC 1999). As a consequence, antibiotic use in the salmon industry compares favorably relative to antibiotic use in the terrestrial livestock industry, where it is often applied for non-therapeutic purposes (Mellon, Benbrook et al. 2001).

Information on antibiotic use in Chilean aquaculture is sparse. Reportedly, oxytetracycline is the most frequently used antibiotic on Chilean salmon farms; consequently there has been a build-up of resistance to this antibiotic in the microflora surrounding Chilean salmon farms. A review of oxytetracycline resistant bacteria in Chile concluded that, "salmon culture centers may play an important role as reservoirs of antibiotic-resistant bacteria and thereby increase a potential public health hazard" (Miranda and Zemelman 2002). However, aquaculture is not the only source of antibiotic resistant bacteria, even in the Chilean marine environment. Bacteria in wild fish captured near sewage outfalls may also develop heightened resistance to oxytetracycline and other antibiotics from antibiotic residues present in the sewage (Miranda and Zemelman 2001).

Pesticides
Along with antibiotics, salmon farms often use pesticides to control parasites such as sea lice (Roth 2000). A year 2000 review of pesticides used in salmon farming showed that the global industry currently uses at least eleven different chemical compounds, representing five pesticide types, to treat sea lice (Roth 2000). Pesticides included are: 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). The number of compounds routinely available in any one country is highly variable, ranging from 9 in Norway, to 6 in Chile and the United Kingdom, to 4 in Ireland, the Faeroe Islands and Canada, to 2 in the United States (formalin and hydrogen peroxide) (Roth 2000). For reference, cypermethrin use is authorized in Norway, Scotland, Ireland, and the Faeroe Islands. Additionally, it is under a trial permit in Chile and Investigational New Animal Drug status in the United States. Azamethiphos is authorized in Norway, Scotland, Canada, the Faeroe Islands, and Chile (Grant 2002).

Environmental effects of pesticides
Similar to antibiotics, pesticides can enter the marine environment either by not binding with organic matter in the net pen or passing through a fish unchanged. Some pesticides, such as emamectin benzoate and tefluebenzuron, are added into feeds. Other pesticides such as dichlorvos, azamethiphos, and cypermethrin, are applied in bath treatments (Grant 2002; Rae 2002). Bath treatments are normally applied by enclosing net pens with impermeable tarpaulins and mixing the pesticide in the water; after the required treatment period, the tarp is removed and the chemical-infused water is allowed to mix with surrounding waters (Ernst, Jackman et al. 2001). Given the higher quantities of waste, bath treatments are considered to have a higher potential to affect the environment than oral treatments (Grant 2002).

Once released into the marine environment, pesticides may be toxic to non-target organisms (GESAMP 1997). Though there is very little information on the environmental impacts of pesticides, some have been shown to be harmful to other animals such as shrimp and lobsters, especially during early life stages (Abgrall, Rangeley et al. 2000). Specifically, synthetic pyrethroids and organophospates interfere with the nervous system of crustaceans and insects (Grant 2002).

The effects of pesticides can vary with the specific chemical used, the amount and duration of application, and the local water conditions. A Canadian study, for example, indicated that while the application of azamethiphos presents only a mild environmental risk, cypermethrin plumes may remain toxic to certain organisms over distances that extend far beyond the boundaries of the net pen (Ernst, Jackman et al. 2001). The concentration of added chemical, however, is also important in determining the environmental impact. The Canadian study applied cypermethrin at considerably higher concentrations than recommended, and in an empty pen with reduced uptake potential. As cypermethrin is known to bind rapidly (Maund, Mamer et al. 2002), released plumes are likely to remain toxic for a period of time substantially shorter than the five hours suggested by the authors. Similarly, shellfish such as mussels are able to bioaccumulate cypermethrin in soft tissues; however, bioaccumulation probably does not occur at recommended concentrations (Gowland, Webster et al. 2002). Similarly, azamethiphos can be lethal to crustaceans at very high concentrations, while lobsters exposed to sublethal concentrations of azamethiphos have reduced reproductive success (Haya, Burridge et al. 2001). Ivermectin, another of the compounds used to treat sea lice in Canada and elsewhere, also does not appear to have accumulated in marine life to date. In Canadian sampling efforts, the chemical was not found in wild lobsters or shrimp near fish farms, and in less than 2% of sampled mussels. However, the potential for negative effects remains, as ivermectin was detected in sediments up to 50 meters from farm sites (Nash, Brooks et al. 2001).

Evaluation of Factors

Primary Factors to Evaluate

Part A: Organic waste effects

Salmon net-pen water treatment:

- Water not treated before exiting net pens

Evidence of substantial local effects from organic wastes (within 2x the diameter of the site), including altered benthic communities, presence of signature species, modified redox potential, etc.:

- Empirical and theoretical evidence of local effluent effects

Evidence of regional effects from organic wastes (including harmful algal blooms, altered nutrient budgets, etc.):

- Likely risk of negative effects on theoretical grounds OR unknown

Extent of local or regional effects from organic wastes:

- Effects infrequently exceed set standards

Part B: Habitat effects

Potential to impact habitats - Location:

- Operations in areas of moderate sensitivity (e.g., coastal and near-shore waters, rocky intertidal or subtidal zones, river or stream shorelines)

Potential to impact habitats - Extent of operations (density of sites/area or fish/site):

- High densities of fish/site or sites/area relative to flushing rate and carrying capacity for open systems

Evaluation Guidelines

- Risk of pollution/habitat effects is Low if three or more factors rank green and none of the other factors are red.
- Risk of pollution/habitat effects is Moderate if factors "average" to yellow.
- Risk of pollution/habitat effects is High if three or more factors rank red.

Risk of Pollution and Habitat Effects Rank:

Low Moderate **High**

Criterion 5: Effectiveness of the Management Regime

Guiding Principle: Sustainable aquaculture operations respect all local, national and international laws and customs and utilize a precautionary approach (which favors conservation of the environment in the face of major environmental risks) for daily operations and industry expansion.

Background

Salmon aquaculture facilities are regulated by a variety of both state and federal agencies around the world. In addition, some guidance internationally is provided by the United Nations Food and Agricultural Organization in the form of a *Code of Conduct for Responsible Aquaculture*, and the more detailed *Responsible Aquaculture at the Production Level*. While all of the major farmed salmon-producing nations have management bodies in place to oversee the practices of aquaculture operations, this section examines the extent to which management bodies regulate operations with regards to environmental issues such as siting of net pens, fish escapes, disease control, wastes, chemical use, and predation deterrents.

United States

In the United States salmon aquaculture regulations are overseen by both state and federal agencies including the Environmental Protection Agency (EPA), the United States Department of Agriculture (USDA), the National Marine Fisheries Service (NMFS), the Army Corps of Engineers, the Maine Department of Marine Resources and the Washington Department of Fish and Wildlife.

While the promulgation of regulations for aquaculture has historically been left to the states, in February of 2002 the EPA took the first steps to regulate U.S. salmon aquaculture waste by issuing the first water quality permit to a marine net pen facility. According to the EPA, issuing these permits will help ensure that the waste generated from permitted facilities is not harming the surrounding marine environment (EPA 2002). Specifically, by issuing water quality permits to salmon farms the EPA hopes to:

- Limit the total annual amount of fish feed that may be used at the site unless studies are completed to show that higher levels of nutrient addition can safely be allowed. The permit would have to be formally modified with opportunity for public comment before allowing a higher feed level;
- Require bottom monitoring with enforceable limits on conditions under and around the pens;
- Require frequent water column monitoring with specific dissolved oxygen limits at the pen site;
- Limit the use of fish medications;
- Incorporate U.S. Fisheries and Wildlife Service recommendations for wild Atlantic salmon protection.

In addition to the actions taken by the EPA, therapeutic drugs used in U.S. aquaculture operations must first be approved by the U.S. Food and Drug Administration. Only a half-dozen drugs have been approved by the FDA to date, including just two antibiotics. Several therapeutants are allowed as Investigational New Animal Drugs (INAD) for experimental purposes. However, relative to other salmon farming nations, the diversity and extent of drugs used on U.S. salmon farms appears low.

A third important federal agency is the National Marine Fisheries Service, which enforces several laws including the Marine Mammal Protection Act that prohibits seals and other mammalian predators from being harmed by farm operators.

On a state level, both Maine and Washington impose numerous requirements on salmon farms.

Maine

For siting purposes, Maine requires the gathering of information on the geophysical site characteristics, benthic habitat characteristics, subsequent changes in community structure, effects on the water column, feed and production data, information on smolt and broodstock movements, disease incidence, and the application of chemical therapeutants (Maine 1991).

The Maine Department of Marine Resources and Department of Environmental Protection also administer a Finfish Aquaculture Monitoring Program that is responsible for collecting data on farms to assess whether or not they are operating within prescribed environmental limits. The program includes:

- Twice-yearly video surveys of active farms performed in the spring and fall to provide information on benthic conditions;
- Dissolved oxygen readings collected in late summer when water temperatures are highest;

- A benthic survey conducted every other year to assess the abundance and diversity of animals in the sediments. (DMR 2003)

Washington

The Washington State departments of Agriculture, Ecology, and Natural Resources, along with individual counties, help to regulate the eight salmon farms in the state. Washington issues discharge permits for salmon net pens, and requires the development of pollution prevention plans in compliance with best management practices (BMPs). Periodic assessments review carbon levels in sediments and other indicators; observable impacts from effluents are only allowed to extend 100 feet from salmon net pens.

In addition, in 2003, Washington added new rules to existing salmon farming regulation. These included:

- A requirement for the prior approval of the species, stock and race of marine fish to be grown;
- A prohibition on growing transgenicfish;
- Required escape prevention, escape reporting, and escape recapture plans. (WDFW 2003)

Canada

Canada is the second largest exporter of farmed salmon to the United States. In Canada, the provincial governments' environmental assessment offices manage Canada's salmon aquaculture and production is divided between British Columbia in the Pacific and New Brunswick in the Atlantic.

British Columbia

After a six-year moratorium on new salmon farms in British Columbia (BC) to study the environmental effects of salmon aquaculture, Canada began accepting applications for new operations in April 2002. The Salmon Aquaculture Review, generated by British Columbia's Environmental Assessment Office concluded that environmental risks of salmon farming under existing rules were low (EAO 1997).

However, the report qualifies this finding with the following:

> This general finding is tempered by certain reservations. First, continuing concern about localized impacts on benthic (seabed) organisms, shellfish populations and marine mammals suggests the need for additional measures to protect them. Second, significant gaps in the scientific knowledge on which the Technical Advisory Team's conclusions are based point to the need for monitoring and research in areas such as the potential impacts of interactions of escaped farmed salmon with wild populations, identification and control of disease and disease pathogens, potential for disease transfer and impacts from antibiotic residues, and effects of waste discharges on water quality and seabed life. (EAO 1997)

With respect to specific management practices, British Columbia explicitly restricts siting farms in the following locations:

- Within three kilometers of any existing finfish aquaculture site, and in accordance with local area plans or Coastal Zone Management Plans.
- Within a kilometer of the mouth of a significant salmonid-bearing stream, herring spawning area of "high" importance, ecological reserves, or the line of sight of a marine protected area.
- Within 300 m of inter-tidal fished shellfish beds that are exposed to water flow from a salmon farm.
- Within 125 m of all other wild shellfish beds and shellfish aquaculture operations.
- Within an appropriate distance, as determined by the Department of Fisheries and Oceans, Canada (DFO) and the provincial government, from areas of "sensitive fish habitat" or used extensively by marine mammals. (BC 2000)

Waste management regulation in British Columbia is conducted under the auspices of B.C.'s Ministry of Water, Land, and Air Protection, which recently finalized new Aquaculture Waste Control Regulations under the *Waste Management Act*. The new act requires all active sites to conduct operational monitoring and reporting within 30 days of achieving peak biomass at a site. Sites must be monitored for sulfide content of soft-bottom sediments. In addition, a biological standard is applied at the perimeter of the lease site. Specific chemical conditions and monitoring requirements must be met if various chemical levels are exceeded during a production cycle.

Escapes are required to be reported, and records kept of fish transportation and drug use. The Ministry conducts annual inspections between May and October, which review management plans for therapeutant and chemical use, stock inventories, net maintenance and operations. In addition, spot dive audits can be conducted to assess the condition of the underwater components of containment systems.

In 2004, British Columbia will also extend a sea lice control strategy to the province. This includes:

- A legal requirement to have approved plans for managing fish health, including mandatory monitoring for sea lice on farms.
- A corridor of fallow sites in the Broughton Archipelago.
- Coordinated area-wide fish health treatment.
- Scientific research regarding characteristics and behaviors of sea lice, and development of control measures.
- Coordination and communication of sea lice information between government and industry.
- Education and training in sea lice identification. (MAFF 2003)

New Brunswick

On Canada's East Coast, the majority of salmon farms are located in New Brunswick. Aquaculture licensing is overseen by New Brunswick's Department of Agriculture, Fisheries, and Aquaculture. The Department's Bay of Fundy Marine Aquaculture Site Allocation process sets out several guidelines for the siting of salmon farms in New Brunswick (DAFA 2003).

New Brunswick is currently in the process of instituting a new management plan based on single-year class farming. To this end, the Bay of Fundy has been divided into distinct zones referred to as Aquaculture Bay Management Areas (ABMA). The boundaries of each ABMA will be based on a combination of oceanographic, fish health and business considerations. To improve health management and reduce environmental impacts, salmon farms are required to adopt single-year-class practices only.

With regard to industry expansion, New Brunswick is currently limiting applications to eligible fish farmers who are already in the industry. Only one application from each eligible proponent will be accepted (DAFA 2003).

New Brunswick, like British Columbia, permits the use of acoustic harassment devices (AHDs) to deter seal predation (Tehrune, Hoover et al. 2002). AHDs emit piercing sounds underwater to discourage the presence of predatory animals. Unfortunately, the use of AHDs can exclude non-target species such as harbor porpoises (*Phocoena phocoena*) in the Bay of Fundy and killer whales (*Orcinus orca*) in the Pacific Northwest from the area surrounding the net pens (Johnston 2002; Morton and Symonds 2002; Olesiuk, Nichol et al. 2003).

Canada's national agencies have only approved four pesticides for use, and few antibiotics (Roth, 2000).

Chile

Chile is the largest exporter of farmed salmon to the United States. In Chile, the National Fisheries Service is charged with enforcing regulations for salmon farms, which include regulating the locations of marine-based fish farms and limiting the number of fish contained at each facility. Further regulations have been developed by Fundación Chile to create stricter environmental standards and certification for salmon farms (FC 2001). These standards focus on reducing salmon farm waste and salmon escapes (FC 2001). Though not required by law, the certification process is supported by some of Chile's largest farmed salmon producers, including Marine Harvest Chile, Patagonia Salmon Farming, and Landcatch Chile (FC 2001).

Chilean aquaculture production is concentrated in two regions of the country (Regions X and XI). While siting regulations and effluent restrictions are developed on a regional level, the national government has set out several guidelines to oversee the process.

- Intensive aquaculture operations must be sited a minimum of 2,800 meters from each other, and 400 meters from extensive aquaculture operations.
- Aquaculture operations must be sited in waters with sufficient flushing to prevent the development of anaerobic conditions at any point.

- Siting requirements should take into consideration the surrounding topographic and hydrographic conditions, substrate, as well as the number and location of other aquaculture operations.
- Escape prevention and management plans are mandatory, as is escape reporting.
- The development of anaerobic conditions will result in immediate actions and a reduction of stocking densities by 30% the following year. (Sernapesca 2001)

Little information is available in the published literature on the efficacy of Chile's management regime.

Drug use in Chilean aquaculture appears to be moderate. Just six of the eleven available pesticides to treat sea lice are allowed in Chile (Roth 2000), and oxytetracycline appears to be the most common antibiotic used (Miranda and Zemelman 2002).

The extent of the use of depredation controls in Chile has not been documented.

Evaluation of Factors

Primary Factors to Evaluate

Use of licensing to control the location (siting), number, size and stocking density of farms:

- Yes, but concerns exist about density of sites and operations

Demonstrated application of existing federal, state and local laws to current aquaculture operations:

- Yes, federal, state and local laws are applied

Existence and effectiveness of "better management practices" for aquaculture operations, especially to reduce the number of fish escapes:

- Exist but effectiveness is under debate or unknown

Existence and effectiveness of measures to prevent disease and treat outbreaks that do occur (e.g., vaccine programs, pest management practices, fallowing of pens, retaining diseased water, etc.):

- Exist but effectiveness is under debate or unknown

Existence of regulations for therapeutants, including their release into the environment, such as antibiotics, pesticides, and herbicides:

- Exist but effectiveness is under debate, or unknown

Use and effect of predator controls (e.g., for birds and marine mammals) in farming operations:

- Predator controls used with limited mortality or displacement effects

Existence and effectiveness of policies and incentives utilizing a precautionary approach against major risks to guide expansion of the aquaculture industry:

- Exist but effectiveness is under debate

Evaluation Guidelines

- Management is "Highly Effective" if four or more factors have a rank of green.
- Management is "Moderately Effective" if the factors "average" to yellow
- Management is deemed "Ineffective" if three or more factors rank red.

Effectiveness of the Management Regime Rank:

Highly Effective **Moderately Effective** Ineffective

Overall Evaluation and Seafood Recommendation

This report reviewed and assessed the current scientific information and risks associated with the environmental impacts of salmon farming as of February 2004. To judge the sustainability of farming practices, five criteria were individually analyzed; escapes, disease, fish meal use, pollution, and management. Analysis of current salmon farming practices resulted in one "**Critical Conservation Concern**" ranking, three "**High Conservation Concern**" rankings, and one "**Moderate Conservation Concern**" ranking, meriting an overall recommendation of "**Avoid**" for farmed salmon.

- **Risk of Escaped Fish to Wild Stocks:** There is solid evidence that escaped farmed salmon are jeopardizing the health of endangered salmon populations in the Atlantic through interbreeding. By reducing the fitness of wild stocks, farmed salmon may imperil remaining wild Atlantic salmon stocks. In the Pacific, escaped farmed salmon represent a potentially invasive species. The potential for negative effects from interbreeding of farmed and wild salmon in the Atlantic and invasive behavior of escaped farmed Atlantic salmon in the Pacific poses a **Critical Conservation Concern.**

- **Risk of Disease Transfer to Wild Stocks:** Salmon farming operations can serve as a vector for diseases and ectoparasites, notably sea lice, which can negatively affect wild salmon. While biosafety controls reduce the risks of translocating disease, evidence that sea lice from salmon farms are harming wild salmonid populations is substantial, particularly in Europe. The threat of disease to already stressed wild salmon populations also presents a substantial risk. The threat of disease to wild fish populations and ecosystems is thus of **High Conservation Concern.**

- **Use of Marine Resources**: Salmon are carnivorous fish and farmed salmon are fed diets largely comprised of processed wild fish. The implicit demand salmon aquafeeds place on marine ecosystems off of South America and the Gulf of Mexico is both a practical and ethical issue that affects the sustainability of farming practices, and thus is of **High Conservation Concern**.

- **Risk of Pollution and Habitat Effects:** Because salmon are raised in open marine net-pens, wastes, organic and chemical, are not collected or treated. Organic wastes from uneaten feed and feces can accumulate on sediments and affect the species distribution within the immediate vicinity of net pens. Infaunal species diversity is typically lower beneath and down current from net pens with low to moderate flushing rates. Regional impacts of nutrient additions are unclear. Overall, pollution from organic and chemical wastes is of **High Conservation Concern**.

- **Effectiveness of the Management Regime:** Management practices vary significantly between nations. Management has increased in recent years but concerns remain regarding the density of net-pen sites in specific regions, the approval of pesticide and antibiotic use, and the use of acoustic predator deterrent devices which may affect non-target marine mammals. The current management climate is of **Moderate Conservation Concern**.

Evaluation Guidelines

- A seafood product is given the recommendation "Best Choices" if it has a total of three or more green rankings, and no red rankings.
- A seafood product is given the recommendation "**Good Alternative**" if rankings "average" to yellow.
- A seafood product is given the recommendation "Avoid" if it has a total of two or more red rankings, or has one or more **critical** conservation concern rankings.

Summary: Table of Sustainability Ranks

	Conservation Concern			
Sustainability Criteria	**Low**	**Moderate**	**High**	**CRITICAL**
Risk of Escaped Fish to Wild Stocks				√
Risk of Disease Transfer to Wild Stocks			√	
Use of Marine Resources			√	
Risk of Pollution & Habitat Effects			√	
Effectiveness of the Management Regime		√		

Overall Seafood Recommendation:

Best Choice Good Alternative **Avoid**

Literature Cited

Abgrall, P., R. W. Rangeley, et al. (2000). "Sublethal effects of azamethiphos on shelter use by juvenile lobsters (Homarus americanus)." Aquaculture **181**: 1-10.

Alderman, D. J., H. Rosenthal, et al. (1994). Chemicals used in mariculture, ICES Working Group Environmental Interactions of Mariculture.

Alverson, D. and G. Ruggerone (1997). Escaped farm salmon: Environmental and ecological concerns. Technical Advisory Team Discussion Papers. B. C. E. A. Office.

Anderson, J., F. Whoriskey, et al. (2000). "Atlantic salmon on the brink." Endangered Species UPDATE **17**(1): 15-21.

Angulo, F. and P. Griffin (2000). "Changes in antimicrobial resistance in *Salmonella enterica* Serovar Typhimurium." Emerging Infectious Diseases **6**(4): 436-437.

Arthington, A. H. and D. R. Bluhdorn (1996). The effect of species interactions resulting from aquaculture operations. Aquaculture and Water Resource Management. D. J. Baird, M. C. M. Beveridge, L. A. Kelly and J. F. Muir, Blackwell Science, U.K.**:** 114-139.

Bakke, T. A. and P. D. Harris (1998). "Diseases and parasites in wild Atlantic salmon (Salmo salar) populations." Can. J. Fish. Aquat. Sci. **55 (Suppl. 1)**: 247-266.

Barlow, S. (2002). The world market overview of fish meal and fish oil. Second Seafood Byproducts Conference, Alaska.

BC (2000). British Columbia Aquaculture Siting Criteria.

Benbrook, C. M. (2002). Antibiotic Drug Use in U.S. Aquaculture, The Northwest Science and Environemental Policy Center.

Birkeland, K. (1996). "Consequences of premature return by sea trout (Salmo trutta) infested with salmon louse: migration, growth, and mortality." Can. J. Fish. Aquat. Sci. **53**: 2808-2813.

Black, K. D., M. C. B. Kiemer, et al. (1996). Benthic impact, hydrogen sulphide and fish health: field and laboratory studies. Aquaculture and Sea Lochs. K. D. Black, Scottish Association for Marine Sciences**:** 16-26.

Boesch, D., R. Burroughs, et al. (2001). Marine Pollution in the United States: Significant Accomplishments, Future Challenges. Arlington, VA., Pew Oceans Commission.

Bowden, T., D. Small, et al. (2002.). "Development of a reproducible infectious pancreatic necrosis virus challenge model for Atlantic salmon, Salmo salar L." Journal of Fish Diseases **25**: 555-563.

Brackett, J. (1991). "Potential disease interactions of wild and farmed fish." Bulletin Of The Aquaculture Association Of Canada **91-3**: 79-80.

Bridger, C. and A. Garber (2002). Aquaculture escapement, implications and mitigation: The salmonid case study. Ecological Aquaculture. B. Costa-Pierce. Oxford, UK, Blackwell.

Brooks, K., A. Stierns, et al. (2003). "Chemical and biological remediation of the benthos near Atlantic salmon farms." Aquaculture **219**: 355-377.

Burd, B. (1997). Key Issue C: Waste Discharges. B.C. Salmon Aquaculture Review Interim Draft Report, B.C. Environmental Assessment Office**:** 157.

Butler, J. (2002). "Wild salmonids and sea louse infestations on the west coast of Scotland: sources of infection and implications for the management of marine salmon farms." Pest Management Science **58**: 595-608.

Canada, I. (2003). Strategis Canada: Trade by Country Databse.

Carlton, J. (2001). Introduced Species in U.S. Coastal Waters. Arlington, VA, Pew Oceans Commission.

Carr, J. W., J. M. Anderson, et al. (1997). "The occurence and spawning of cultured Atlantic salmon (Salmo salar) in a Canadian river." ICES J. Mar. Sci. **54**: 1064-1073.

Carroll, M., S. Cochrane, et al. (2003). "Organic enrichment of sediments from salmon farming in Norway: environmental factors, management practices, and monitoring techniques." Aquaculture **226**: 165-180.

Chang, B. D. and J. P. Thonney (1992). "Overview and environmental status of the New Brunswick salmon culture industry." Bulletin of the Aquaculture Association of Canada **92**(3): 61-63.

Costa-Pierce, B. (2002). Ecology as the paradigm for the future of aquaculture. Ecological Aquaculture. B. Costa-Pierce. Oxford, UK, Blackwell**:** 382.

Costa-Pierce, B. A. (1996). Environmental Impacts of nutrients from aquaculture: Towards the evolution of sustainable aquaculture. Aquaculture and Water Resource Management. D. J. Baird, M. C. M. Beveridge, L. A. Kelly and J. F. Muir, Blackwell Science, U.K.**:** 81-113.

Costanza, R., R. d'Arge, et al. (1997). "The value of the world's ecosystem services and natural capital." Nature **387**(6630): 253-260.

Crozier, W. W. (1993). "Evidence of genetic interaction between escaped farmed salmon and wild Atlantic salmon (Salmo salar L.) in a Northern Irish river." Aquaculture **113**: 19-29.

CRU (2002). Review and Synthesis of the Environmental Impacts of Aquaculture. Edinburgh, Scotland, Scottish Executive Central Research Unit.

DAFA (2003). Bay of Fundy Marine Aquaculture Site Allocation Policy, New Brunswick Department of Agriculture, Fisheries and Aquaculture.

Dayton, P., S. Thrush, et al. (2002). Ecological Effects of Fishing in Marine Ecosystems of the United States. Arlington, VA, Pew Oceans Commission.

DMR (2003). Environmental Research and Monitoring, Maine Department of Marine Resources. **2003**.

Douglas-Helders, G., D. Dawson, et al. (2002). "Wild fish are not a significant reservoir for Neoparamoeba pemaquidensis (Page, 1987)." Journal of Fish Diseases **25**: 569-574.

EAO (1997). The Salmon Aquaculture Review Final Report. British Columbia, Environmental Assessment Office, British Columbia.

Easton, M., D. Luszniak, et al. (2002). "Preliminary examination of contaminant loadings in farmed salmon, wild salmon, and commercial salmon feed." Chemosphere **46**: 1053-1074.

Einum, S. and I. A. Fleming (1997). "Genetic divergence and interactions in the wild among native, farmed and hybrid Atlantic salmon." Journal of Fish Biology **50**: 634-651.

EPA (2002). EPA Press Release: EPA Issues Aquaculture Permit for Maine Fish Farm, Environmental Protection Agency.

Ernst, W., P. Jackman, et al. (2001). "Dispersion and toxicity to non-target aquatic organisms of pesticides used to treat sea lice on salmon in net pen enclosures." Marine Pollution Bulletin **42**(6): 433-444.

FAO (2002). FAO Yearbook. Fishery Statistics. Aquaculture Production 2002. Vol 94/2. Rome, Italy, United Nations Food and Agricultural Organization.

FAO (2002). FAO Yearbook. FIshery Statistics. Capture Production 2002, Vol 94/1. Rome, Italy., United Nations Food and Agricultural Organization.

FAO (2002). FIDI Statistical database-Fishstat+, United Nations Food and Agriculture Organization.

FC (2001). Code of Good Environmental Practices For Well Managed Salmonid Farms, Fundación Chile.

Ferguson, A., P. McGinnity, et al. (1997). Will interbreeding between wild and cultured fish have negative consequences? ICES/NASCO Symposium Final abstracts: Interactions between salmon culture and wild stocks of Atlantic salmon: the scientific and management issues. NASCO.

FIN (2002). Fishmeal Facts and Figures, Fishmeal Information Network.

Findlay, R. H. and L. Watling (1997). "Prediction of benthic impact for salmon net-pens based on the balance of benthis oxygen supply and demand." Marine Ecology Progress Series **15**: 147-157.

Findlay, R. H., L. Watling, et al. (1995). "Environmental Impact of Salmon Net-Pen Culture on Marine Benthic Communities in Maine: A Case Study." Estuaries **18**(1A): 145-179.

Flagg, T., B. Berejikian, et al. (2000). Ecological and behavioral impacts of artificial production strategies on the abundance of wild salmon populations, U.S. Department of Commerce**:** 92.

Fleming, I. A. and S. Einum (1997). "Experimental tests of genetic divergence of farmed from wild Atlantic salmon due to domestication." ICES J. Mar. Sci. **54**: 1051-1063.

Fleming, I. A., K. Hindar, et al. (2000). "Lifetime success and interactions of farm salmon invading a native population." Proceedings of the Royal Society London **267**: 1517-1523.

Fleming, I. A., B. Jonsson, et al. (1996). "An experimental study of the reproductive behaviour and success of farmed and wild Atlantic salmon (Salmo salar)." Journal of Applied Ecology **33**(4): 893-905.

Folke, C., N. Kautsky, et al. (1994). "The costs of eutrophication from salmon farming: Implications for policy." Journal of Environmental Management **40**(2): 173-182.

Forster, J. (2002). "Farming salmon: An example of aquaculture of the mass market." Reviews in Fisheries Science **10**(3-4): 577-591.

Franklin, H. (2001). "The most important fish in the sea." Discover **22**(9): 44-50.

Froese, R. and D. Pauly (2003). FishBase.

FWS (1999). Status Review of Altantic Salmon, U.S. Fish and Wildlife Service.

Gajard, G. and L. Laikre (2003). "Chilean aquaculture boom is based on exotic salmon resources: A conservation paradox." Conservation Biology **17**(4): 1173-1174.

Garant, D., I. Fleming, et al. (2003). "Altnernative life-history tactics as potential vehicles for speeding introgression of farm salmon traits into wild populations." Ecology Letters **6**: 541-549.

Gaudet, D. (2002). Atlantic Salmon, A White Paper, Alaska Department of Fish and Game.

GESAMP (1997). Towards safe and effective use of chemicals, GESAMP (IMO, FAO, UNESCO-IOC, WMO, WHO, IAEA, UN, UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution).

Glover, K., L. Hamre, et al. (In Press). "A comparison of sea louse (Lepeophtheirus salmonis) infection levels in farmed and wild salmon (Salmo salar L.) stocks." Aquaculture.

Goldburg, R. J., M. Elliott, et al. (2001). Marine Aquaculture in the United States. Arlington, VA, Pew Oceans Commission.

Gonzalez, L. and J. Carvajal (2003). "Life cycle of Caligus rogercresseyi (Copepoda: Caligidae) parasite of Chilean reared salmonids." Aquaculture **220**: 101-117.

Gowland, B., L. Webster, et al. (2002). "Uptake and effects of the cypermethrin-containing sea lice treatment Excis in the marine mussel, Mytilus edulis." Environmental Pollution **120**: 805-811.

Grant, A. (2002). "Medicines for sea lice." Pest Management Science **58**: 521-527.

Gross, M. R. (1998). "One species with two biologies: Atlantic salmon (Salmo Salar) in the wild and in Aquaculture." Can. J. Fish. Aquat. Sci. **55 (Suppl.1)**: 131-144.

Halver, J. and R. Hardy (2002). Fish Nutrition, Third Edition. New York, NY, Academic Press.

Handeland, S., B. Bjornsson, et al. (2003). "Seawater adaptation and growth of post-smolt Atlantic salmon (Salmo salar) of wild and farmed strains." Aquaculture **220**: 367-374.

Hansen, L. P., D. G. Reddin, et al. (1997). "Short communication: The incidence of reared Atlantic salmon (Salmo salar L.) of fish farm origin at West Greenland." ICES Journal of Marine Science **54**(1): 152-155.

Hansen, P. K., A. Ervik, et al. (2001). "Regulating the local environmental impact of intensive, marine fish farming II. The monitoring programme of the MOM system (Modelling-Ongrowing fish farms - Monitoring)." Aquaculture **194**(1-2): 75-92.

Hardy, R. (2001). "One size doesn't fit all." Aquaculture Magazine **27**(5): 17-18.

Hardy, R. (2003). "Fish Meal To Farmed Fish Conversions." Aquaculture Magazine **29**(4): 36-40.

Hardy, R. W. (1999). "Problems and Opportunities In Fish Feed Formulation." Aquaculture Magazine **25**(4).

Haya, K., L. Burridge, et al. (2001). "Environmental impact of chemical wastes produced by the salmon aquaculture industry." ICES Journal of Marine Science **58**: 492-496.

Heuch, P., C. Revie, et al. (2003). "A comparison of epidemiologic patterns of salmon lice, Lepeophtheirus salmonis, in Norway and Scotland." Journal of Fish Diseases **26**(9): 539-552.

Hites, R., J. Foran, et al. (2004). "Global assessment of organic contaminants in farmed salmon." Science **303**: 226-229.

Hjeltnes, B., O. Bergh, et al. (1995). "Susceptibility of Atlantic cod Gadus morhua, halibut Hippoglossus hippoglossus and wrasse (Labridae) to Aeromonas salmonicida subsp. salmonicida and the possibility of transmission of furunculosis from farmed salmon Salmo salar to marine fish." Diseases of Aquatic Organisms **23**: 25-31.

Hutchinson, P. (1997). "Interactions between salmon culture and wild stocks of Atlantic salmon: the scientific and management issues." ICES J. Mar. Sci. **54**: 963-1225.

IFFO (2001). Fishmeal Information Network: Sustainability Dossier, International Fishmeal & Fish Oil Organisation.

IntraFish (2001). China is the world's biggest buyer of fishmeal, IntraFish.

Jacobs, M., A. Covaci, et al. (2002). "Investigation of selected persistent organic pollutants in farmed Atlantic salmon (Salmo salar), salmon aquaculture feed, and fish oil components of the feed." Environmental Science Technology **36**(13): 2797-2805.

Johnson, S. C., R. B. Blaylock, et al. (1996). "Disease induced by the sea louse Lepeophtheirus salmonis in wild salmon stocks of Alberni Inlet, British Columbia." Can. J. Fish. Aquat. Sci. **53**: 2888-2897.

Johnston, D. (2002). "The effect of acoustic harassment devices on harbour porpoises (Phocoena phocoena) in the Bay of Fundy, Canada." Biological Conservation **108**: 113-117.

Kelly, L. A., J. Stellwagen, et al. (1996). "Waste loadings from a freshwater Atlantic salmon farm in Scotland." Water Resour. Bull. **32**(5): 1017-1025.

Kent, M. L. (1994). The impact of diseases of pen-reared salmonids on coastal environments. Canada-Norway workshop on environmental Impacts of Aquaculture, Havforskningsinstututtet, Bergen.

LaPatra, S. (2003). "The lack of scientific evidence to support the development of effluent limitations guidelines for aquatic animal pathogens." Aquaculture **226**(191-199).

Lassuy, D. R. (1995). Introduced species as a factor in extinction an endangerment of native fish species. Am. Fish. Soc. Symp.

MAFF (2003). Sea lice strategy extend to the entire coast for 2004, British Columbia Ministry of Agriculture, Food and Fisheries.

Maine (1991). Maine Code of Regulations. Aquaculture Monitoring Program. **381**.

Marin, S., F. Sepulveda, et al. (2002). "The feasibility of using Udonella sp. (Platyhelminthes: Udonellidae) as a biological control for the sea louse Caligus rogercresseyi, Broxhall and Bravo 2000, (Copepoda: Caligidae) in southern Chile." Aquaculture **208**: 11-21.

Maund, S., M. Mamer, et al. (2002). "Partitioning, bioavailability, and toxicity of the pyrethroid insecticide cypermethrin in sediments." Environmental Toxicology and Chemistry **21**: 9-15.

Mazzola, A., S. Mirto, et al. (2000). "Fish-farming effects on benthic community structure in coastal sediments; analysis of meiofaunal recovery." ICES J. Mar. Sci. **57**: 1454-1461.

McDonald, M. E., C. A. Tikkanen, et al. (1996). "A bioenergetics based model for aquacultural wasteload application." Aquacult. Eng. **15**(4): 243-259.

McDowell, N. (2002). "Stream of escaped farm fish raises fear for wild salmon." Nature **416**: 571.

McGinnity, P., P. Prodohl, et al. (2003). "Fitness reduction and potential extinction of wild populations of Atlantic salmon Salmo salar as a result of interactions with escaped farm salmon." Proceedings of the Royal Society, London B **DOI 10.1098/rspb.2003.2520**.

McGinnity, P., C. Stone, et al. (1997). "Genetic impact of escaped farmed Atlantic salmon (Salmo salar L.) on native populations: use of DNA profiling to assess freshwater performance of wild, farmed, and hybrid progeny in a natural river environment." ICES J. Mar. Sci. **54**: 998-1008.

Mellon, M., C. Benbrook, et al. (2001). Hogging it: Estimates of Antimicrobial Abuse in Livestock. Cambridge, MA, Union of Concerned Scientists.

Milewski, I. (2002). Impact of Salmon Aquaculture on the Coastal Environment: A Review. New Brunswick, Conservation Council of New Brunswick**:** 34.

Miranda, C. and R. Zemelman (2001). "Antimicrobial resistant bacteria in fish from the Conception Bay, Chile." Marine Pollution Bulletin **42**(11): 1096-1102.

Miranda, C. and R. Zemelman (2002). "Bacterial resistance to oxytetracycline in Chilean salmon farming." Aquaculture **212**: 31-47.

Molver, J., A. Stigebrandt, et al. (1988). On the excretion of nitrogen and phosphorus from salmon. Aquaculture International Congress and Exposition, Vancouver, B.C.

Morris, P., C. Beattie, et al. (2003). "Effects of the timing of the introduction of feeds containing different protein and lipid levels on the performance and quality of Atlantic salmon, Salmo salar, over the entire seawater phase of growth." Aquaculture **225**: 41-65.

Morton, A. and H. Symonds (2002). "Displacement of Orcinus orca (L.) by high amplitude sound in British Columbia, Canada." ICES Journal of Marine Science **59**: 71-80.

NASCO (2003). Report of the North Atlantic Salmon Conservation Organization, 2002-2003. Edinburgh, Scotland, North Atlantic Salmon Conservation Organization.

Nash, C. E. e., K. M. Brooks, et al. (2001). The net-pen salmon farming industry in the Pacific Northwest (NOAA Technical Memo), U.S. Department of Commerce, NMFS.

Naylor, R., J. Eagle, et al. (2003). "Salmon aquaculture in the Pacific Northwest: A global industry with local impacts." Environment **45**(8): 18-38.

Naylor, R. L., R. J. Goldburg, et al. (1998). "Nature's Subsidies to Shrimp and Salmon Farming." Science **282**(5390): 883-884.

Naylor, R. L., R. J. Goldburg, et al. (2000). "Effect of Aquaculture on World Fish Supplies." Nature **405**: 1017-1024.

Naylor, R. L., S. L. Williams, et al. (2001). "Aquaculture--A Gateway for Exotic Species." Nature **294**: 1655-1656.

NMFS (2002). Report to Congress: Status of Fisheries of the United States - 2002, U.S. National Marine Fisheries Service.

NMFS (2003). NMFS Foreign Trade Information Database, U.S. National Marine Fisheries Service. **2003**.

Norgarden, U., F. Oppendal, et al. (2003). "Seasonally changing metabolism in Atlantic salmon (Salmo salar L.) I - Growth and feed conversion rates." Aquaculture Nutrition **9**: 287-293.

NRC (1999). The Use of Drugs in Food Animals: Benefits and Risks. N. A. Press. Washington, D.C., U.S. National Research Council.

NRC (2004). Atlantic Salmon in Maine: Report of the Committee on Atlantic Salmon in Maine. N. A. Press. Washington, D.C., U.S. National Research Council of the National Academy of Sciences**:** 260.

Oekland, F., T. G. Heggberget, et al. (1995). "Migratory behaviour of wild and farmed Atlantic salmon (Salmo salar) during spawning." Journal of Fish Biology **46**(1): 1-7.

Olafsen, J. and R. Roberts (1993). Salmon disease: The microbial ecology of aquaculture. Salmon Aquaculture. K. Heen, R. Monahan and F. Utter. Oxford, UK, Fishing News Books**:** 166-186.

Olesiuk, P., L. Nichol, et al. (2003). "Effects of the sound generated by an acoustic deterrent device ont he relative abundance and distribution of harbour poproise (Phocoena phocoena) in Retreat Passage, British Columbia." marine Mammal Science **18**: 843-862.

Opstvedt, J., A. Aksnes, et al. (2003). "Efficiency of feed utilization in Atlantic salmon (Salmo salar L.) fed diets with increasing substitution of fish meal with vegetable proteins." Aquaculture **221**: 365-379.

Pike, I. H. and S. M. Barlow (2001). Fish meal and oi to the year 2010, supplies for aquaculture. World Aquaculture 99, Sydney, Australia.

Pike, I. H. and S. M. Barlow (2001). FISH MEAL AND OIL TO THE YEAR 2010, SUPPLIES FOR AQUACULTURE. WORLD AQUACULTURE 99, SYDNEY, AUSTRALIA.

Pohle, G. and B. Frost (1997). Establishment of standard benthic monitoring sites to assess long-term ecological modification and provide predictive sequence of benthic communities in the inner Bay of Fundy. St. Andrews, Cana, Huntsman Marine Science Centre**:** 119.

Pohle, G., B. Frost, et al. (2001). "Assessment of regional benthic impact of salmon mariculture within the Letang Inlet, Bay of Fundy." ICES J. Mar. Sci. **58**.

Rae, G. (2002). "Sea louse control in Scotland, past and present." Pest Management Science **58**(515-520).

Rangen (2002). Aquaculture Feed Website, Rangen Inc.

Revie, C., G. Gettinby, et al. (2002). "The epidemiology of the sea lice, Caligus elongates Nordmann, in marine aquaculture of Atlantic salmon, Salmo salar L., in Scotland." Journal of Fish Diseases **25**: 391-399.

Roth, M. (2000). "The availability and use of chemotherapeutic sea lice control products." Contributions to Zoology **69**: 109-118.

Samuelsen, O. B. (1994). Environmental Impact of Antibacterial Agents in Norwegian Aquaculture. Proceeding of the Canada-Norway Workshop on Environmental Impacts of Aquaculture, Havforskningsinstututtet, Bergen (Norway).

Schiermeier, Q. (2003). "Fish farms' threat to salmon stocks exposed." Nature **425**: 753.

Sepulveda, F., S. Marin, et al. (In Press). "Metazoan parasites in wild fish and farmed salmon from aquaculture sites in southern Chile." Aquaculture **Accepted September 5, 2003**.

Sernapesca (2001). Reglamento ambiental para la Acuicultra, number 320. Santiago, Chile, Chilean Department of Economics.

Silvert, W. and J. W. Sowles (1996). "Modelling environmental impacts of marine finfish aquaculture." Journal of Applied Ichthyology **12**: 75-81.

Simberloff, D. and B. Von Holle (1999). "Positive interactions of nonindigenous species: invasional meltdown?" Biological Invasions **1**: 21-32.

Skaala, O. and K. Hindar (1997). Genetic changes in the R. Vosso salmon stocks following a collapse in the spawning population and invasion of farmed salmon. ICES/NASCO Symposium Final abstracts: Interactions between salmon culture and wild stocks of Atlantic salmon: the scientific and management issues. NASCO.

Skog, T., K. Hylland, et al. (2003). "Salmon farming affects the fatty acid composition and taste of wild saithe Pollachius virens L." Aquaculture Research **34**: 999-1007.

Soto, D., F. Jara, et al. (2001). "Escaped salmon in the inner seas, Southern Chile: Facing ecological and social conflicts." Ecological Applications **11**(6): 1750-1762.

Starkey, T. (2000). IFOMA annual meeting and fishmeal report. Global Aquaculture Advocate**:** 45.

Stephen, C. and G. Iwama (1997). Key Issue B: Fish Health. Salmon Aquaculture Review, B.C. Environmental Assessment Office**:** 157.

Strain, P., D. Wildish, et al. (1995). "The application of simple models of nutrient loading and oxygen demand to the management of a marine tidal inlet." Marine Pollution Bulletin **30**(4): 253-261.

Sutherland, T., A. Martin, et al. (2001). "Characterization of suspended particulate matter surrounding a salmonid net-pen in the Broughton Archipelago, British Columbia." ICES Journal of Marine Science **58**: 404-410.

Swanson, E. (2001). Personal Communication.

Sylvia, G., J. L. Anderson, et al. (2000). The New Order in Global Salmon Markets and Aquaculture Development: Implications for Watershed-Based Management in the Pacific Northwest, Lewis Publishers, CRC Press, Boca Raton.

Tacon, A. and I. Forster (2000). Global trends and challenges to aquaculture and aquafeed development in the new millennium. International Aquafeed--Directory and Buyers' Guide 2001. T. RIA. Uxbridge, UK**:** 4-25.

Tehrune, J., C. Hoover, et al. (2002). "Potential detection and deterrence ranges by harbor seals of underwater acoustic harassment devices (AHD) in the Bay of Fundy, Canada." Journal of the World Aquaculture Society **33**(2): 176-183.

Tidwell, J. H. and G. L. Allan (2001). "Fish as food: aquaculture's contribution." EMBO: European Molecular Biology Organization **2**(11): 958-963.

Tyedmers, P. H. (2000). Salmon and Sustainability: The Biophysical Cost of Producing Salmon Through the Commercial Salmon Fishery and the Intensive Salmon Culture Industry. Resource

Management and Environmental Studies. British Columbia, The University of British Columbia**:** 258.

USDA (1998). 1998 Census of Aquaculture, U.S. Department of Agriculture.

Vitousek, P., H. Mooney, et al. (1997). "Human domination of Earth's ecosystems." Science **277**: 494-499.

Volpe, J. P., E. B. Taylor, et al. (2000). "Evidence of Natural Reproduction of Aquaculture-Escaped Atlantic Salmon in a Coastal British Columbia River." Conservation Biology **14**: 899-903.

Wagner, G., R. McKinley, et al. (2003). "Physiological impacts of sea lice on swimming performance of Atlantic salmon." Journal of Fish Biology **62**(5): 1000-1009.

Waknitz, F., T. Tynan, et al. (2002). Review of potential impacts of Atlantic salmon culture on Puget Sound chinook salmon and Hood Canal summer-run chum salmon evolutionarily significant units, U.S. Department of Commerce**:** 83.

WDFW (2003). Marine Finfish Aquaculture Fact Sheet, Washington Department of Fish and Wildlife.

Webb, J. H., D. W. Hay, et al. (1991). "The spawning behaviour of escaped farmed and wild Atlantic salmon (Salmo salar L.) in a northern Scottish river." Aquaculture **98**: 97-100.

Weston, D. P. (1996). Environmental Considerations in the Use of Antibacterial Drugs in Aquaculture. Aquaculture and Water Resource Management. D. J. Baird, M. C. M. Beveridge, L. A. Kelly and J. F. Muir**:** 140-165.

Whoriskey, F. G. (2000). Infectious Salmon Anemia: A review and the lessons learned from wild salmon on Canada's east coast. Aquaculture and the Prtection of Wild Salmon. P. Gallaugher and C. Orr, Simon Fraser University**:** 46-51.

Wildish, D., B. Hargrave, et al. (2003). "Detection of organic enrichment near finfish net-pens by sediment profile imaging at SCUBA-accessible depths." Journal of Experimental Marine Biology and Ecology **285-286**: 403-413.

Youngson, A. and E. Verspoor (1998). "Interactions between wild and introduced Atlantic salmon (Salmo salar)." Canadian Journal of Fisheries and Aquatic Sciences **55**(Supplement 1): 153-160.