AN ANALYSIS OF THE MANAGEMENT AND ECONOMICS OF SALMON AQUACULTURE

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Abstract

Salmon aquaculture can be a potential solution to bridge the gap between declining capture fisheries and increasing seafood demand. However, the environmental impacts it creates have generated criticism. The overall objectives of this dissertation are to examine the economic consequences of environmental issues associated with salmon aquaculture, and to explore policy implications and recommendations for reducing environmental impacts. These objectives are addressed in five main analyses.

The growth of salmon aquaculture is analyzed based on farmed salmon production in the four leading producing countries and the sector as a whole. Analyses indicate that salmon aquaculture is unlikely to continue to grow at its current pace.

A joint production function approach is used to estimate pollution abatement costs for the salmon aquaculture industry. Results reveal that pollution abatement costs vary among observations and models. On average, pollution abatement cost is estimated at 3.5% in terms of total farmed salmon production, and 6.5% in terms of total revenue of farmed salmon.

The ecological and economic impacts of sea lice from salmon farms on wild salmon population and fisheries are also studied. Analyses suggest that these effects are minor when the sea lice induced mortality rate is below 20%, while they can be severe if the mortality is greater than 30%. Sea lice have greater ecological and economic impacts on pink salmon than on chum salmon. These effects are greater under a fixed exploitation rate than under a target escapement policy.

The economic performance of open netcage and sea-bag production systems for salmon aquaculture is compared. Netcage systems appear to be more economically profitable than sea-bag systems when environmental costs are either not or only partially included. Sea-bag systems can be financially profitable only when the salmon they produce can achieve a price premium.

Finally, policy implications are explored and recommendations are made for sustaining salmon aquaculture in a holistic manner based on the results from previous chapters. Technologies, economic-based instruments and more stringent environmental policies can be employed to reduce environmental impacts. However, there is no single solution to solve these environmental impacts, and a combination of policy options is needed.

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Co-Authorship Statement

A version of chapter 2, "can farmed salmon production keep growing", is in press in the journal Marine Policy. U. Rashid Sumaila, my supervisor, is coauthor on the paper. Chapter 5, "economic analysis of Netcage versus sea-bag production systems for salmon aquaculture in British Columbia", has been published in the journal Aquaculture Economics and Management. U. Rashid Sumaila, my supervisor, is coauthor on the paper. A version of chapter 3, "estimating pollution abatement costs of salmon aquaculture", will be submitted to the journal Land Economics, with U. Rashid Sumaila and Sumeet Gulati, one of my committee members, as coauthors. A version of chapter 4, "the potential ecological and economic impacts of sea lice from salmon farms on wild salmon fisheries", will be submitted to the journal Canadian Journal of Fisheries and Aquatic Science, with U. Rashid Sumaila and John Volpe, one of my committee members, as coauthors. A version of Chapter 6, "salmon aquaculture and the environment: economic perspectives for policy development", is in preparation, with U. Rashid Sumaila and Ratana Chuenpagdee, one of my committee members, as coauthors. The first author for each Chapter which has been published, or is in press or will be submitted for publication has been the core contributor in terms of identifying, designing and performing of the research, conducting data analyses and preparing manuscripts. The coauthors all have been helping to prepare manuscripts.

Chapter 1 General Introduction and Review of Salmon Aquaculture

1.1 General Introduction and Thesis overview

Aquaculture has provided employment and income opportunities for coastal communities as well as foreign income to the producing countries, and affordable seafood for consumers. It has also been seen by many as a strong potential contributor to bridge the gap between dwindling capture fisheries and increasing seafood demand. With advanced technologies and globalization, aquaculture has become the fastest-growing food-producing sector in the world. However, the rapid expansion and development of aquaculture have created environmental problems, in particular, the industrial culture of carnivorous species, such as salmon.

Environmental problems that can be brought about by salmon aquaculture include disease and parasite transfer and spreading, escapees, waste discharges, introduction of exotic species (e.g., Atlantic salmon into the Pacific Ocean), uses of chemicals and drugs, and consumption of fishmeal and fish oil. The resources or sectors that can potentially be affected consist of wild and recreational fisheries, marine mammals, recreational activities, and upland properties, archaeological resources and navigation. These effects have made salmon aquaculture one of the most controversial forms of aquaculture in the world.

While the negative environmental impacts associated with salmon aquaculture have been widely acknowledged, economic analysis of these impacts is rarely conducted. Thus, this dissertation aims to examine the economic consequences of environmental impacts associated with salmon aquaculture. Based on the results of the economic analyses, I explore policy implications and recommendations for reducing environmental impacts and sustaining salmon aquaculture in a holistic manner. Different environmental problems addressed to achieve this objective are organized into six chapters as described below.

In Chapter 1, I present an overview of salmon aquaculture. Environmental and economic impacts associated with salmon aquaculture are reviewed. I follow this with a review of aquaculture practice in the four leading producing countries of the world. Then, the theoretical foundation of environmental problems from an economic perspective – externality – is presented. Finally, some existing methods and techniques for measuring environmental costs are introduced based on the literature review.

Salmon aquaculture has expanded rapidly in the last two decades. It is believed that salmon aquaculture will continue to increase to meet growing seafood demand since wild capture fisheries has stagnated. In Chapter 2, a question is posed: can farmed salmon production keep growing? To answer this question, the 5-year moving average rates of growth in salmon aquaculture production over time were analyzed for four of the world's leading salmon aquaculture countries, and globally.

Pollution discharged from salmon farms has intensified due to the rapid expansion of salmon aquaculture. In some coastal areas, salmon aquaculture has become the largest source of certain types of pollution (e.g., nitrogen and phosphorus) compared to agriculture, sewage and industry. In Chapter 3, I introduce an innovative production function approach to address pollution problems associated with salmon aquaculture. A joint production approach was developed to model the good outputs (salmon products) and bad outputs (pollution) from salmon aquaculture simultaneously. Two environmental production technologies were proposed, namely, regulated and unregulated technologies. Two production functions with different mapping rules were specified in the analysis. Empirical application was based on time series data from the Norwegian salmon aquaculture industry. Pollution abatement costs are estimated using this approach.

Sea lice problems associated with salmon aquaculture have been at the centre of debate over the environmental impacts of salmon aquaculture worldwide. It is believed that sea lice from salmon farms pose a high risk to the declining wild salmonids. In Chapter 4, I examine the potential ecological and economic impacts of sea lice problem on wild salmon fisheries. Salmon population dynamics and bioeconomic models are developed. Pink and chum salmon in the Broughton Archipelago, British Columbia, are used as case studies. Two management strategies are applied: fixed exploitation rate and target escapement. I also explore how the combined factors affected wild salmon populations and fisheries.

Conventional netcage technology for salmon aquaculture has been criticized because it is believed to be the key reason for generating environmental problems from salmon aquaculture. One way to prevent or minimize these problems is to use enclosed containment production systems, such as sea-bags. In Chapter 5, I compare the economic performance of netcage and sea-bag production systems with and without incorporating environmental costs into production decision making. Capital budget and investment appraisal methods are applied.

Based on the results of the analyses (Chap. 2 - 5) conducted earlier, it can be concluded that salmon aquaculture is unlikely to continue to grow at the current pace, and does potentially impose costs on the environment and natural resources, such as wild salmon. Without government intervention and economic incentives, the salmon aquaculture industry may not incorporate these environmental costs into their production decision making. Thus, in Chapter 6, policy implications and recommendations are explored for reducing environmental costs. Different options, such as technological approaches, institutional measures, environmental regulations and economic instruments (e.g., pollution taxes and subsidies) are proposed as potential solutions.

1.2 Review of Salmon Aquaculture

1.2.1 Introduction

Aquaculture is “the farming of aquatic organisms, including fish, mollusks, crustaceans and aquatic plants” (FAO 2000). Aquaculture is different from capture fisheries because it involves some form of intervention during the organism’s rearing process from larvae stage to adulthood. An important feature of aquaculture is that it is an activity owned by an entity (e.g., an individual or a company) unlike capture fisheries resources (FAO 2000). Aquaculture *per se* is not a new activity, and has been practiced for centuries in ancient Asia and the Mediterranean. The real evolution of aquaculture development started in the 1970s due to technological advancements and growing world seafood demand (Subasinghe 2005). Since then, aquaculture, in particular industrialized aquaculture, has dramatically expanded, and it has now become the fastest-growing food-producing industry in the world economy (Hishamunda and Ridler 2002; FAO 2007).

Aquaculture is highly diverse, and comprises a wide range of species, systems and production practices. Worldwide, over 200 species occupying different levels of the food web have been commercially cultivated (Subasinghe 2005). Based on the biological characteristics of cultured species and the physical features of location, different systems and technologies are required for each cultured species within various environments, extending from freshwater, brackish water to seawater, even flooded fields and rice paddies. Cultured species can be retained in a variety of facilities, such as ponds, pens, tanks, raceways, rafts and cages. Additionally, aquaculture practice can be operated at different scales depending on the levels of inputs used and outputs produced. Hence, aquaculture is often broken down into small-, medium- and large-scale operations (Barg and Phillips 1997).

It is estimated that aquaculture production has increased by an annual average growth rate of 8.8% since 1970, and it currently contributes one-third of the world's total seafood supply (FAO 2007). In 2005, about 91% of world aquaculture production came from Asia and the Pacific region, with China contributing 70% of the total production (FAO 2007). Even though there are concerns with the accuracy of Chinese figures, undoubtedly China is the biggest contributor to world aquaculture production. A major portion of the world's production comes from freshwater fish species (i.e., cyprinids), seaweed and mollusks (e.g., oyster and mussel). Capital-intensive and profit-driven aquaculture practices have been rapidly growing, but, aquaculture is still dominated by small-scale producers in developing countries (Garcia and Grainger 2005; FAO 2007). FAO predicts that aquaculture will continue its rapid expansion in order to meet growing seafood demand around the world (FAO 2007).

Aquaculture is well known for providing cheap protein sources and alleviating poverty in remote and poor rural coastal communities around the world. Aquaculture also creates employment and income opportunities as well as foreign earnings. Since capture fisheries have reached their upper ceiling (e.g., Watson and Pauly 2001), aquaculture has been seen by many to have a strong potential to bridge the gap between the dwindling supply from capture fisheries and increasing seafood demand (e.g., Tidwell and Alan 2001; Garcia and Grainger 2005; FAO 2007).

Despite the fact that aquaculture provides many benefits to the producers and society as a whole, some forms of aquaculture are under scrutiny and criticism because they generate negative economic and environmental impacts on the environment and natural resources. These impacts vary considerably in terms of species cultured, production system used, scale of operation, severity and magnitude of problems within aquaculture itself and other resource users. Among all the aquaculture practices, intensive aquaculture of carnivorous species (e.g., salmon and shrimp) is the most controversial practice because it can potentially create severe environmental problems.

1.2.2 Overview of Salmon Aquaculture

Salmon aquaculture first started as a way to enhance and restore declining wild salmon stocks in Japan, Canada and the US (Thorpe 1980). In the late 1960s and early 1970s, aquaculturists in Norway and Scotland started growing salmon in open floating cages close to seashores for delivering fresh salmon to the local markets (Willoughby 1999). Breakthroughs with respect to biological and technological bottlenecks, such as smolt rearing and formulation of dry feed, have dramatically advanced salmon aquaculture. The technology for commercial-scale salmon aquaculture was first successfully established in Norway and Scotland. This technology was introduced to Canada in the late 1970s and to Chile in the 1980s. Since then, salmon aquaculture has experienced exponential growth worldwide, and farmed salmon production has increased from around 500 tonnes in 1970 to over 1.3 million tonnes in 2005, according to FAO statistics (FISHSTAT). World farmed salmon production has exceeded wild salmon production since 1998 (FAO 2007).

Farmed salmon production is concentrated in a few regions and countries, namely, Norway, Chile, the UK and Canada. In total, these countries are the source of over 85% of the world's total production and value of farmed salmon. Norway is the number one producer, followed by Chile, the UK and Canada. The most remarkable increase has taken place in Chile. It is believed that Chile will soon replace Norway as the number one farmed salmon producer in the world if it continues to develop at the current rate. Farmed salmon species include Atlantic, chum, chinook, coho and sockeye salmon. Atlantic salmon is the dominant species with over 95% of the total world farmed salmon production. Atlantic salmon is native to the Atlantic Ocean and chum, chinook, coho and sockeye are native to the Pacific Ocean. However, Atlantic salmon has been introduced into the Pacific Ocean due to its strong resistance to environmental conditions and its fast growth. Figure 1.1 shows farmed salmon production by major salmon farming regions and species.

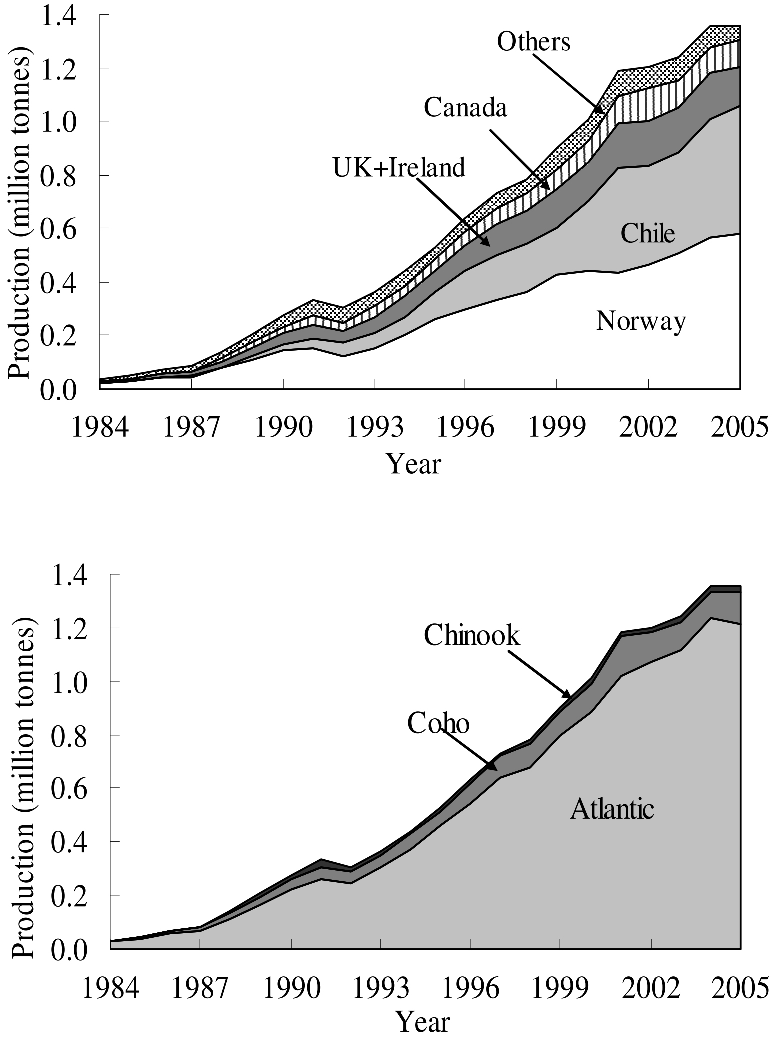

Figure 1.1. Farmed salmon production by major producing country and species.

Salmon aquaculture has experienced remarkable growth as a result of expanding new cultured locations, improved productivity, enhanced husbandry practices and management, and growing global markets (Bjørndal *et al.* 2002 & 2003; Asche and Khatun 2006). In the meantime, salmon aquaculture has undergone a number of structural and technical changes, and it has expanded, intensified and diversified. Salmon aquaculture was initially devised for improving the livelihoods of the coastal communities that depended upon salmon by increasing employment and income. In the beginning, salmon farms were small family businesses with the farms scattered along the sheltered inlets, and products targeted local markets (Willoughby 1999; Hjelt 2000). Today, salmon aquaculture has become a vertically-integrated industry with the farms concentrated in the coastal areas, and products are mainly exported; it has become a market and a profit-driven enterprise (Bjørndal *et. al.* 2003; Asche and Khatum 2006). It is estimated that 70% ~ 80% of farmed salmon production is delivered by a dozen multinational companies (Naylor *et al.* 2003).

1.2.3 Salmon Aquaculture and its Effects

There are two types of effects associated with salmon aquaculture: i) environmental effects, and ii) market effects, both of which are described below.

1.2.3.1 Salmon Aquaculture and Environmental Effects

Potential negative environmental problems associated with salmon aquaculture mainly include: 1) disease and parasite transfer and spreading, 2) escapees, 3) waste discharges, 4) introduction of exotic species (e.g., Atlantic salmon into the Pacific Ocean), 5) uses of chemicals and drugs, and 6) consumption of fishmeal and fish oil. The resources and activities that can be potentially affected by these problems include wild salmon and other wild fish stocks, marine mammals, recreational activities, upland properties, archaeological resources and navigation (Table 1.1). These environmental problems and their impacts have been widely acknowledged in a number of articles in the literature (e.g., Naylor *et al.* 2000 & 2003; Kautsky *et al.* 2001; Pauly *et al.* 2002; Morton *et al.* 2004; Morton and Routledge 2005; Krkošek *et al.* 2005 & 2006; Naylor and Burke 2005), and detailed in Table 1.1.

Table 1.1.Problems and negative impacts associated with salmon aquaculture

Problem	Potential effects	Affected resources (major)
Disease and parasites	Transfer of diseases and parasites.	Wild fish and shellfish fisheries; First Nations' subsistence fisheries.
Escapees	Inter-breeding with wild salmon; Competition for food and space; Transferring diseases and parasites.	Wild salmon; Pelagic fish fisheries; Other marine resources.
Waste discharges	Environment; Habitat destruction.	Shellfish and benthic communities; Biodiversity.
Use of chemicals and drugs	Environment; Risks to human health.	Bottom fish and shellfish fisheries; Human health.
Use of fishmeal and fish oil	Pressure on wild pelagic fisheries; Net loss.	Wild pelagic fisheries.
Introduction of exotic species	Inter-breeding with wild salmon; Competition for food and space; Transferring diseases and parasites.	Wild salmon populations and fisheries.
Attracted to aquaculture sites	Killing.	Marine mammals, birds.

Fish Feed Problems

Salmon is a carnivorous fish species, which requires high-protein feed to grow. Fishmeal and fish oil are primary animal protein sources in fish feed. Fishmeal and fish oil are made of small, bony and oily pelagic wild-caught fish as well as byproducts from fish processing plants, and bycatch from trawl fisheries (New and Wijkström 2002). These pelagic fisheries are generally not suitable for human consumption or not economically viable to be processed for human food (Hardy and Tacon 2002; Tacon *et al.* 2006). It is estimated that producing 1 kg of salmon requires 2.8 – 4.2 kg of wild capture fish as source of protein (Tuominen and Esmark 2003). Hence, some argue that salmon aquaculture is not a net contributor to seafood supply because it consumes a great amount of marine capture fishery resources as inputs (Naylor *et al.* 2000; Delgado *et al.* 2003).

About one-third of total landed wild capture fish is destined for reduction fisheries as feed sources for aquaculture, poultry and other farmed animals (FAO 2007). The world fishmeal and fish oil production have remained relatively stable, with 6 ~ 7 million tonnes of fishmeal and slightly over 1 million tonnes of fish oil (Tacon *et al.* 2006). Currently, about 50% of global fishmeal and 80% of global fish oil production are consumed by aquaculture, and the rest are consumed by poultry and other farmed land animals (Tacon *et al.* 2006). However, the demand for fishmeal and fish oil by the aquaculture sector will continue to increase if the intensive culture of carnivorous species continues to expand. Chile is a good example of this development. The country used to be the second biggest producing and exporting country of fishmeal and fish oil in the world. Today, Chile is a big consumer and importer of fishmeal and fish oil because of the remarkable growth of salmon aquaculture in the country. Increasing demand for fishmeal and fish oil for aquaculture has the potential to create pressure on marine capture fisheries (Folke and Kautsky 1992; Pauly *et al.* 2002; Garcia and Grainger 2005). The availability and cost of feed may serve as critical constraints to aquaculture expansion in the near future (Garcia and Grainger 2005).

There are a few studies dealing with the interaction between aquaculture and capture fisheries in relation to fishmeal and fish oil issues (e.g., Hannesson 2003; Asche and Tveretås 2004). Asche and Tveretås (2004) pointed out that aquaculture would not pose a threat to wild fisheries if a sufficient management regime was to be set up, and substitutes for fishmeal developed. Hannesson (2003) concluded that aquaculture could drive these pelagic fish stocks to overexploitation if the management regimes are not efficient. Hence, the growing aquaculture sector poses a potential threat to wild reduction fisheries if these fisheries are poorly managed and regulated.

Escaped Fish

Farmed salmon can escape from netcages due to storms, marine mammal attacks, and human error. There are three biological and ecological concerns associated with escaped farmed salmon. First, they may establish in the wild, and compete with wild salmon for food, habitat and spawning grounds (Carr *et al.* 1997; Volpe *et al.* 2001). This may potentially disturb already-stressed wild stocks. Second, escaped fish may spread diseases and parasites, such as sea lice, to the wild stocks (Naylor *et al.* 2000 & 2003). This poses another potential risk to wild fish stocks, especially wild salmon stocks. A third concern is that escaped fish may hybridize with wild salmonids, which may deteriorate wild salmon genetic gene pools (e.g., Youngson and Verspoor 1998; McGinnity *et al.* 2003). Atlantic salmon has been introduced to the Pacific due to its high growth rate and strong resistance to the environmental conditions. This introduction may intensify potential environmental risks to the indigenous species, such as sockeye, chinook, chum and coho salmon (Sumaila *et al.* 2005).

Pollution

Pollution from salmon aquaculture arises from uneaten feed, fish faeces, dead fish, chemical residuals and fouling compounds. These wastes are usually discharged directly into the surrounding environment without treatment. The waste discharges are disposed of in solid and soluble forms into the marine environment. These solid and soluble wastes result in three types of pollutants in the marine environment, i.e., those containing organic matter, nutrients and chemotherapeutic contaminants (Haya *et al.* 2001; Brooks and Mahnken 2003). The levels and composition of wastes vary, depending on a number of factors, such as feed composition, fish density, health of fish, feeding strategy, feeding method and feed conversion ratios (Ackefors and White 2002; Brooks and Mahnken 2003).

Solute wastes dissolve into the water body as phosphorus and nitrogen, which become inputs for marine plants. Small or modest additions of nutrients in nutrient-poor areas can increase biodiversity and productivity. However, a long-term accumulation of nutrients can cause eutrophication in low flushed areas or nutrient rich areas (Folke *et al.* 1994 & 1997). Eutrophication may result in harmful algae bloom and severe reductions in water quality. Fish can be poisoned and killed (Black *et al.* 1997; Troell *et al.* 1997). Hence, the ecological impacts of nutrients can be measured by the changes in water quality, phytoplankton production, and the losses of fish and shellfish stocks (Milewski 2001; Pillay 1992).

The organic or solid wastes can be dispersed without reaching high concentrations in areas with strong currents or tides. However, they can sink and may pile up on the seabed when they cannot be disseminated by the environment (Carroll *et al.* 2003). The build-up of organic wastes in the seabed sediment can create dead zones, which can result in negative biological and chemical structured changes (Janowicz and Ross 2001). The abundance of benthic organisms and communities may decline with increasing organic load (Brooks and Mahnken 2003; Brooks 2001). Further, the contaminated sediments may pose a potential risk to habitats or spawning grounds of traditional fish and invertebrate, such as herring, lobster, sea urchin and clam fisheries (Janowicz and Ross 2001; Pohle *et al.* 2001; Wildish *et al.* 2001). And they may result in reductions in productivity of fish and invertebrates (SAR 1997). For instance, in the Broughton Archipelago, British Columbia, some shellfish fishers complain that their clam beds have become black and smelly because of salmon farms nearby.

Another concern is chemotherapeutic pollution. Salmon farmers use chemicals and medicines to treat and prevent disease and parasites. These drugs and chemicals include antibiotics, pesticides, disinfectants, fungicides, ivermectin, and anaesthetics (Davies and Rodger 2000; Haya *et al.* 2001; Zitko 2001; Burridge 2003). Some drugs and chemicals are discharged into the environment with the wastes (Davies and Rodger 2000). The accumulated residuals of chemicals and drugs in the sediments may have toxic effects on the benthic organisms (Haya *et al.* 2001; Davies *et al.* 2001). Some studies demonstrated that toxicity may reduce the biomass of bacteria and alter species composition and abundances of microbial communities (Collier and Pinn 1998; Davies *et al.* 1998; Haya *et al.* 2001). Most research on these issues has been conducted in laboratories and focuses on targeted species such as shrimp and lobster (Burridge 2003). For instance, ivermectin used in the treatment of sea lice infections has been shown to be lethal to shrimp and lobster in laboratory experiments (Haya *et al.* 2001). Farmed salmon and some organisms or bacteria can gradually develop antibiotic resistance if they are treated or ‘bathed’ with the same drugs for long periods. This can lead to increased uses of some drugs and chemicals with the attendant problems.

Disease and Parasite Problems

Disease is a primary threat to the continued growth in salmon aquaculture because it can cause major economic losses to the sector (Asche *et al.* 1999; Hjelt 2000; Arthur *et al.* 2002). Salmon are usually raised in highly-dense netcage systems, leading to high stress levels, which is uncommon in their natural environment. This makes farmed fish more vulnerable to diseases and parasites. If one fish gets a contagious disease in a farm, the disease may be transferred or spread to the whole farm, even to neighbouring farms if they are close enough to each other. Diseases and parasites, such as furunculosis, bacterial kidney disease, infectious hematopoietic necrosis virus and sea lice, have progressively evolved along with the expansion of salmon aquaculture (Hjelt 2000).

The economic impacts of disease can be substantial. The direct and immediate economic impacts of disease are suffered by aquaculture farms themselves (Mustafa *et al.* 2001; Subasinghe *et al.* 2001; Menzies *et al.* 2002). The effects of disease on aquaculture can be measured through reduction in growth, low market prices, and increasing mortality rate (McVicar 1997 & 2004; Mustafa *et al.* 2001; Tully and Nolan 2002). If a disease causes severe reduction in output, the dynamics of supply and demand may change, resulting in high demand relative to supply, and, therefore, high market price will emerge. It may, however, also cause lower market prices if people get concerned about seafood safety and human health, which may lead to declining demand (Israngkura and Sae-Hae 2002). The net effect of disease on demand and price will depend on which of these two factors is greater.

Besides the impacts on aquaculture itself, disease can also impose impacts on wild fisheries. Most diseases are infective and epidemic, thus, they can be spread and transferred to the environment and other biotic resources. For instance, sea lice problems from salmon farms have been at the centre of the debate over declining wild salmon fisheries (e.g., Krkošek *et al.* 2005 & 2006; Brooks and Stucchi 2006). Sea lice are common parasites for both farmed and wild salmon, but a high level of sea lice from salmon farms may amplify pathogen concentrations within the farm and increase infection risk to proximate wild salmon populations through escaped fish and the water. A number of studies have demonstrated that such high concentrations of sea lice have contributed to the decline of some wild salmonid stocks in different jurisdictions, such as in Norway (Finstad *et al.* 2000; Bjorn and Finstad 2002), Scotland (Gargan *et al.* 2002) and the west coast of Canada (Morton *et al.* 2004; Krkošek *et al.* 2005 & 2006).

Another concern regarding disease and parasite problems is the use of chemicals and drugs. The residuals of some drugs and chemicals in the fish body may pose a health risk to humans. For instance, Hites *et al.* (2004) in their controversial study indicated that the concentration of organic contaminants (PCBs) was significantly higher in farmed salmon than in the wild. Nevertheless, the development of vaccines has greatly reduced the use of antibiotics (Asche *et al.* 1999; Bjørndal *et al.* 2002; Tveretås 2002), and hence reduced the potential risks from this source.

Tremendous efforts have been put into reducing disease problems both in terms of research and funding. However, some impacts may be catastrophic. For instance, *Gyrodactylus salaries*, a freshwater parasite in salmonids, has spread to 41 rivers and 36 hatcheries in Norway since it was first introduced in 1975 from Sweden through transportation (Johnsen and Jensen 1992; Johnsen 2006). The only way to eradicate this parasite once it strikes is to kill all the fish in the infected rivers and hatcheries by treating with rotenone (a pesticide) treatment. After treatment, the rivers and hatcheries may not be used for years, and the wild salmon stocks in such contaminated rivers may go extinct (Johnsen 2006). In addition, parasite treatment using rotenone is not always successful. Therefore, a new attempt is being made in one Norwegian river, where acid aluminium is being used. One such treatment would cost around NOK 1.2 million[1]. For the larger rivers, there is no appropriate way to treat the parasite because the water body is so large and the whole river system is so complicated. Since its beginning, approximately NOK 250 million has been used for the treatment program (NASCO 2006). So far, due to disease and escapement

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[1] $1CAD \approx 5.5NOK$

problems among 453 wild salmon populations, 50 of them have already become extinct and another 135 are threatened or vulnerable, while the rest remain healthy (Porter 2005).

1.2.3.2 Salmon Aquaculture and Economical Effects

In addition to environmental problems, salmon aquaculture also creates potential market effects through declining prices of both farmed and wild salmon sectors. Salmon aquaculture provides to the market products that are similar to the wild counterpart; thus, market competition intensifies with increasing supplies from salmon aquaculture. This results in declines in profits for wild salmon fisheries (Naylor *et al.* 2003; Knapp 2005; Knapp *et al.* 2007). Alaska is affected the most because it lands the largest wild salmon catch in the world. Salmon aquaculture is banned in Alaska. Currently, total ex-vessel values of the Alaskan wild salmon fisheries are just one quarter of what they used to be only a decade ago. In this case, the price of salmon fishing permits has fallen by 75 – 90% (Naylor *et al.* 2003; Knapp *et al.* 2007). Fishers who bought their fishing boats and permits during the high-price years of the late 1980s and early 1990s can no longer afford to stay in the fisheries and pay off their debts (Naylor *et al.* 2003). The BC wild salmon fisheries have also been hard hit by the salmon aquaculture industry, but the overall economic impacts are not as great as in Alaska since the BC wild salmon fisheries are relatively smaller.

Since the late 1980s, the prices of both farmed and wild salmon have declined. Fresh wild salmon products are only available for a specific period of the year during the fishing season. Salmon aquaculture, on the other hand can supply stable and predictable volumes of salmon products with consistent quality year-round. On average, farmed salmon achieve a higher market price than wild salmon (Figure 1.2). However, wild salmon may have some market advantages over farmed salmon simply because it is ‘wild’. Hence, some consumers may be willing to pay a higher price for wild salmon products, making it command a price premium. Figure 1.2 shows the nominal prices of farmed and wild salmon in BC and USA. It should be noted that the reported prices for farmed salmon are those for Atlantic salmon, while wild salmon prices in USA and Canada are the average prices of all wild salmon species except pink salmon.

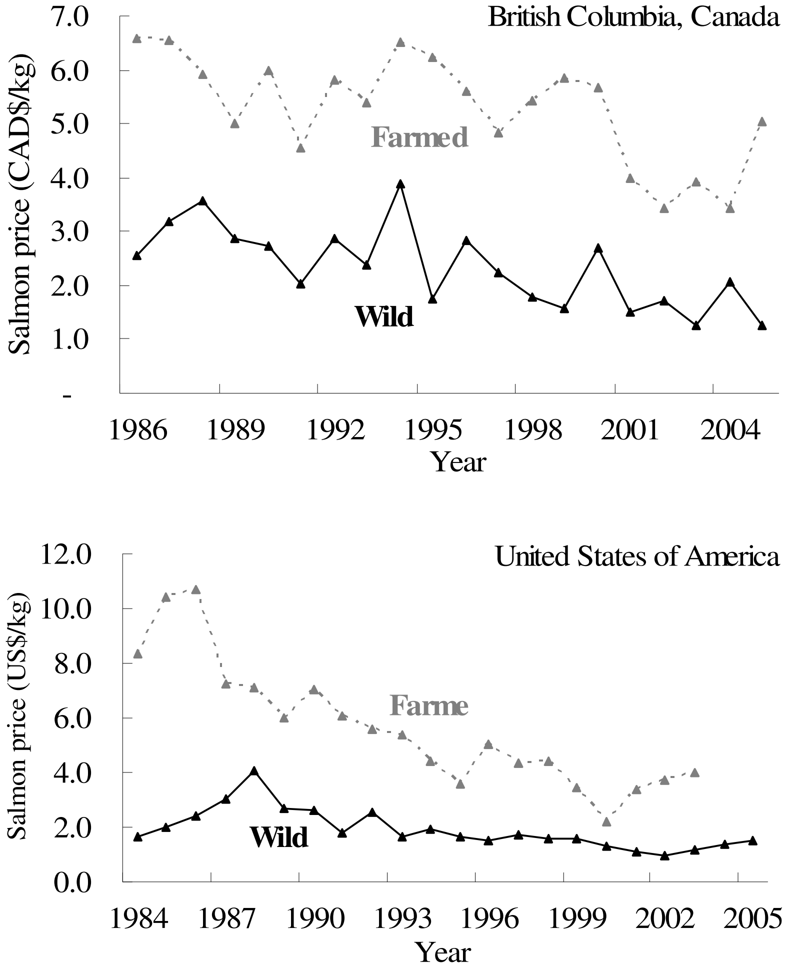

Figure 1.2. Nominal prices of farmed and wild salmon in British Columbia and the United States.

The salmon aquaculture industry has also suffered profit losses from declining prices. For instance, based on the Norwegian salmon aquaculture data, the profit margin has declined gradually, with dramatic declines in 2002 and 2003. Some salmon farms even made zero profits. Salmon farms, especially small farms, that incur high production costs may not stay in business. This has led to a reduction in Norwegian production of farmed salmon in recent years.

In addition, fishmeal and fish oil used by salmon aquaculture are primarily derived from pelagic fishes, such as anchovies, sardines, mackerel, herring. These fishes are low-value species, and in general not economically profitable to process for human consumption. However, these fish may be important protein sources for some people in developing countries. For instance, some of these species are considered as food fish to provide protein sources in the Philippines, Indonesia and China. Hence, the use of pelagic fishes for fishmeal and fish oil may create potential food security issues (Pauly *et al*. 2005).

In sum, salmon aquaculture does produce environmental and economic impacts on the surrounding environment and natural resources. Some negative impacts are local in scope, for example, organic pollution, habitat destruction and loss of biodiversity; some may be regional, for instance, disease transfers and degradation of wild stocks via escapees; a few are even global, such as the use of fishmeal and fish oil and declining prices of wild salmon fisheries products through international trade. These effects have made salmon aquaculture one of the most controversial aquaculture industries in the world. In this dissertation, I focus on environmental and economic effects associated with salmon aquaculture with an emphasis on pollution and disease and parasite problems.

1.2.4 Salmon Aquaculture Practice in Leading Producing Countries or Regions

1.2.4.1 British Columbia, Canada

Canada is the fourth-largest salmon farming country in the world after Norway, Chile and the UK, with BC contributing two-thirds of total Canadian production. Salmon aquaculture began in BC in the early 1970s along the Sunshine Coast, as family-run small businesses concentrating on native salmon species, such as chinook and coho (Volpe 2001). In order to boost the economy of coastal communities from the declining fishing and forest sectors, Atlantic salmon was introduced to BC waters in the early 1980s. BC has the advantage of exporting its farmed salmon to the US, with cheap transportation cost and short transport time. The US, as one of the biggest international markets for farmed salmon, has experienced increasing demand for farmed salmon products over the years. As a result, salmon aquaculture in BC has boomed. Like producers in other jurisdictions, salmon aquaculture in BC has moved from localized small businesses to multinational enterprises. For instance, around 100 small businesses two decades ago were replaced by half a dozen large multinational and corporate producers in recent years (Cox 2004). These multinational operations are also vertically integrated, i.e., they engage in hatchery, grow-out, processing, and marketing of salmon.

Over the years, farmed salmon production and farmgate values increased exponentially. Today, salmon aquaculture has become a vital part of the local economy, and farmed salmon production accounts for 15% of total BC agricultural production in terms of weight (MAFF 2004). While creating employment and income for local communities, the industry is becoming the biggest agricultural food exporter, earning millions of valuable export dollars (MAFF 2004). Currently, there are 23 companies who own 131 tenures occupying 2,400 hectares. Most of BC farm sites are concentrated in three areas: the Broughton Archipelago, Johnstone Strait and Clayoquot, and Barkley Sounds. Around 80% of tenures are actually active (MAFF 2004).

The dramatic expansion has led to public concerns and debates over environmental and economic impacts brought about by salmon aquaculture. For instance, wild and farmed salmon have experienced changes over time. Figure 2.3 shows the quantity and value of farmed and wild salmon in BC from 1986 to 2005. Wild salmon production and landed value have declined while farmed salmon production and farmgate value have increased over time. The decline in wild salmon production and value may be at least partially attributed to the rise of salmon aquaculture due to falling prices and environmental impacts (e.g., disease and parasite).

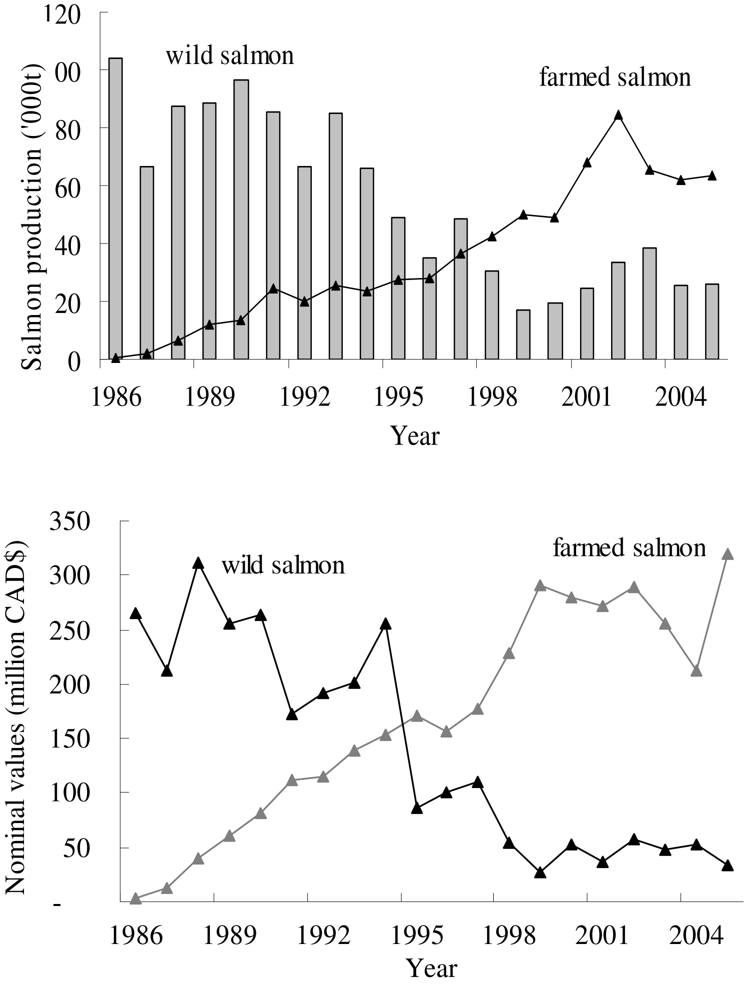

Figure 1.3. Production and value of farmed and wild salmon in BC.

In response to these debates, the BC Provincial Government placed a moratorium on new salmon farm tenures in 1995, and the Salmon Aquaculture Review (SAR) was constituted to examine aquaculture practices, and to investigate environmental problems associated with salmon aquaculture. In 1997, SAR was completed, and 49 recommendations were made. SAR concluded that "salmon farming in British Columbia, as presently practiced and at current production levels, presents a low overall risk to the environment" (SAR 1997). In the following five years, a number of environmental monitoring programs were implemented. In 2002, the moratorium was lifted, and new tenures have since been approved and issued.

1.2.4.2 Norway

Norway is the world leader in salmon aquaculture. It is also a pioneer in technological innovation and development of new markets for farmed salmon products (Aarset 1998). It has been the number one salmon producer in the world since the beginning of salmon development. Salmon aquaculture in Norway started as a government-supported activity to rebuild the livelihoods of rural fishing communities facing depressed economies due to declining wild fisheries (Hjelt 2000; Sønvisen 2003). Hence, most farms are located in rural areas and small municipalities. The major markets for Norwegian farmed salmon are the EU, the US and Japan.

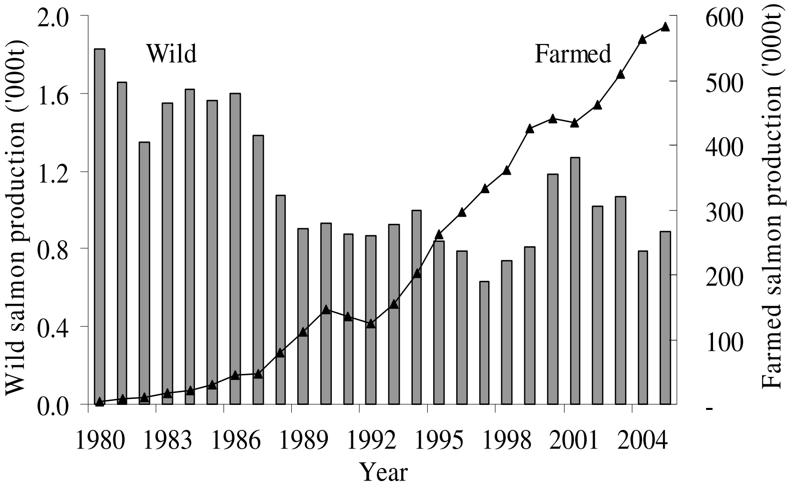

Figure 1.4. Farmed and wild salmon production in Norway.

Today, salmon aquaculture has become an important industry in Norway. It has not only generated employment for coastal communities, but it has also generated foreign income for the country. Farmed salmon production has increased exponentially since the early 1980s (Fig. 1.4). Recently, slumping market prices have led to declines in the growth rate of salmon production. In contrast, wild salmon production is small compared to farmed salmon. It accounts for less than 1% of the total farmed salmon production, according to Norway Statistics (2006). Wild salmon fisheries include sea and river fishing. They are not a large commercial fishing industry, but mostly consist of recreational activities.

Salmon aquaculture in Norway is a highly-capitalized, highly technological and less labour-intensive practice than in other countries, because labour in Norway is very expensive. The productivity has improved over time. Production cost per tonne has declined over time (Fig. 1.5), while total production costs have increased. However, the declines in feed, smolt and labour costs have slowed down in recent years.

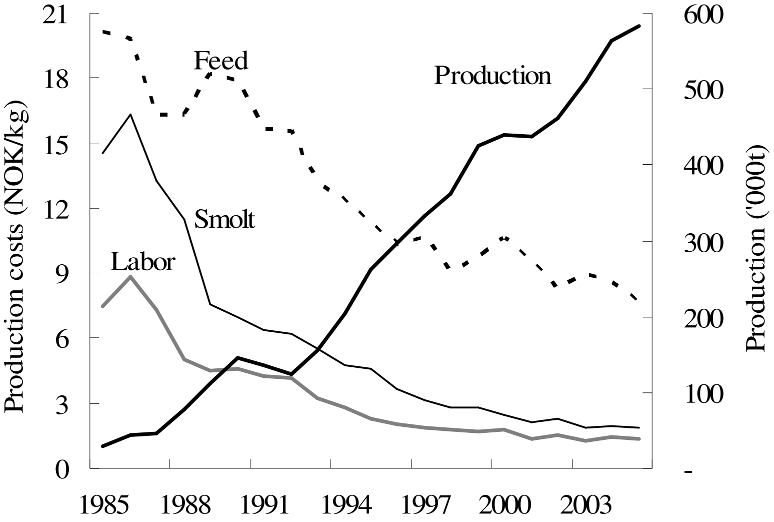

Figure 1.5. Production and production costs of Norwegian farmed salmon.

In Norway, pollution, genetic impact, biodiversity and disease are the main problems faced by the salmon aquaculture industry and society at large (Hjelt 2000). With the environmental problems associated with salmon aquaculture increasing over time, the policy for salmon aquaculture has shifted from developing regional economies and expanding farmed salmon production to environmental protection from disease and other environmental problems (Sønvisen 2003). Norway has relatively strict regulations and policies on salmon aquaculture, such as limited entry, constraints in farm sizes and fish density, feed quota, and control on location and ownership (Bjørndal 1990 & 2002; Sønvisen 2003). In fact, these regulations have created economic incentives for salmon producers to internalize some of the external costs of aquaculture into their production decision-making (Asche *et al.* 1999; Bjørndal *et al.* 2002; Tveretås 2002). However, due to limited availability of suitable space and stringent aquaculture policy, Norwegian producers have moved their investments to countries such as Canada, the US and Chile.

1.2.4.3 Chile

Chile is the world's fastest-growing salmon aquaculture producer. Its production is growing at an exponential rate. The salmon aquaculture sector is Chile's fourth-largest exporter. Most of Chile's production is exported to Japan and the US, while small amounts go to Latin American and EU markets (Bjørndal and Aarland 1999; Bjørndal 2002). It is believed that Chile will soon become the world's largest farmed salmon producer and exporter if it continues expanding at its current rate. Besides being endowed with a long coast line and good environmental conditions, Chile also has the advantage of having abundant cheap labour. In addition, it is the world's second-biggest fishmeal and fish oil producer after Peru. Hence, it has reliable and cheap feed available. Chile uses more labour-intensive production technology and has the lowest production costs among salmon-producing countries (Barton 1997; Bjørndal & Aarland 1999; Bjørndal 2002).

Most of Chilean salmon aquaculture production is concentrated on the Puerto Montt region, southern Chile (i.e., Region X), which is currently operating almost at full capacity. Thus, further expansion can only occur in the Los Lagos region, further south (i.e., Regions XI and XII) (Buschmann *et al.* 2006). However, the infrastructure in these regions is so poor that it may become the limiting factor for further expansion (Bjørndal 2002). In addition, Chilean salmon aquaculture still depends, to a great degree, on imported eggs; hence, egg supply could be another obstacle for further expansion (Bjørndal 2002). Salmon is not native to Chilean waters, so there is no ecological competition and genetic interaction between wild and farmed salmon. However, escapes and pollution problems still exist, which can affect other species and resource users in the surrounding environment (Buschmann *et al*. 2006). In Chile, low wages and workplace safety problems are the biggest challenges (Barrett *et al.* 2002). Chile is also reported to have fewer environmental regulations and enforcement capacities compared to Norway, the UK and Canada (Bjørndal 2002).

1.2.4.4 The UK

Salmon aquaculture in the UK is concentrated in Scotland. Commercial salmon aquaculture in Scotland started in the 1960s. It has similar development trends as in Norway. The major market for farmed salmon in the UK is the EU countries. Due to a limited coastline, suitable sites for salmon farms are almost fully occupied (Porter 2005). Increases in farmed Atlantic salmon production have correlated with marked declines in wild salmon and sea trout populations (Fig. 1.6). However, wild salmon and sea trout production are currently insignificant compared to farmed salmon. They are mostly exploited by recreational fishers. The most controversial issue in Scotland is the negative impacts of sea lice from salmon farms on wild sea trout stocks. It is widely argued that the high level of infestation of sea lice and escapees associated with salmon aquaculture have contributed to the decline of wild salmon and sea trout populations in Scotland (Gargan *et al.* 2002).

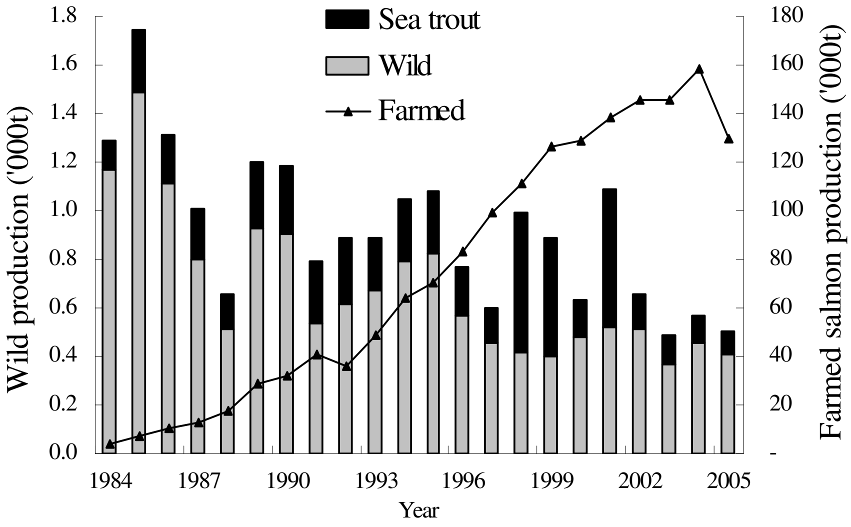

Figure 1.6. Wild and farmed salmon and wild sea trout production in the UK.

Overall, these different salmon-producing countries have a lot in common. All of their production has increased exponentially over the last two decades. These producers use the same production technology, and compete in the same global market. In addition, they face similar challenges and problems, such as high production costs, low market prices and controversies over environmental problems. However, they have different institutional structures, practices and management strategies. Salmon aquaculture growth has slowed down in Norway, Scotland and BC, as a result of environmental concerns and low market prices, while its growth has continued to increase in Chile. Further, the rigorous regulations in Norway have pushed salmon aquaculture producers out of Norway to places where there is less regulation and more potential for profit-making, such as, Chile, which offers low labour costs and has good feed sources, less regulation, good environmental conditions and governmental support.

Salmon aquaculture producers have faced different environmental problems. Disease and escapement problems are more serious and controversial in Norway, the UK and BC, because they are commonly believed to be the cause of declines of wild salmonids stocks. On the other hand, the focus of arguments in Chile is on contamination of the marine environment, low wages and unsafe working conditions in the sector. Even though disease and escapement problems have also taken place in Chile, they are not as controversial as in Scotland and BC, because Chile does not have wild salmon fisheries.

1.2.5 Economics of Environmental Problems

While the environmental impacts associated with salmon aquaculture have been widely acknowledged, economic analysis is needed to foster a sustainable aquaculture practice. Economics, in particular environmental economics, has emerged as a policy-supporting tool to quantify the environmental impacts associated with aquaculture (e.g., Folke *et al.* 1994; Barbier 2000; Sathirathai and Barbier 2001; Barbier 2003). In the literature, a small number of studies have addressed environmental problems associated with shrimp aquaculture (e.g., Babier 2000; Sathirathai and Barbier 2001; Barbier 2003). In the case of salmon aquaculture, there are huge gaps between environmental impacts and their associated economic consequences.

1.2.5.1 Externality

When an action or economic activity of a party or an agent impacts on people other than themselves, and the impact is not taken into account by the party causing it, an externality is said to exist. In other words, externalities are effects of an action or economic activity that are borne by a third party, not by the agent undertaking that action or activity (Field and Olewiler 2002). Furthermore, these effects are not reflected in the prices of products or services. Externalities can be positive or negative. If externalities are negative, the third party (e.g., an individual or firm) has to bear costs, known as external costs, while if externalities are positive, the third party enjoys external benefits. Externalities are categorized in a number of ways: producer-on-producer externalities, producer-on-consumer externality, consumer-on-consumer externality and consumer-on-producer externality (Field and Olewiler 2002).

In an economically-efficient operation, marginal costs should equal marginal benefits, then the level of output and market prices of inputs and outputs are said to be socially optimal, and net social benefits are maximized. All the costs and benefits should be included. When external costs or benefits exist, the private calculation of costs and benefits differs from society's valuation. Thus, private optimal actions are inefficient from the perspective of the society, and net social benefits will not be maximized. This results in market failure because market prices and levels of output are not socially optimal, as they do not reflect external costs and benefits. Hereafter, I will focus on producer-on-producer externality, which means I will emphasize external costs.

One can describe external costs using demand and supply curves. The demand curve expresses the marginal willingness to pay (WTP) for a product by consumers, while the supply curve represents the marginal cost of supplying a given product to the market. Thus, the demand curve captures the marginal benefits, and the supply curve captures the marginal costs from an activity. Without externalities, the private benefits and costs should theoretically equal the social benefits and costs at the margin. If external costs exist, the total social costs are equal to the private costs plus external costs. I describe them in a graph. In Figure 1.7, the marginal benefits, marginal private cost, and marginal social cost curves are denoted as DD, MPC and MSC, respectively. The intersection points A and A* give the market equilibrium where the quantity produced and consumed is efficient at the market price, and hence, net social benefits are maximized (Field and Olewiler 2002).

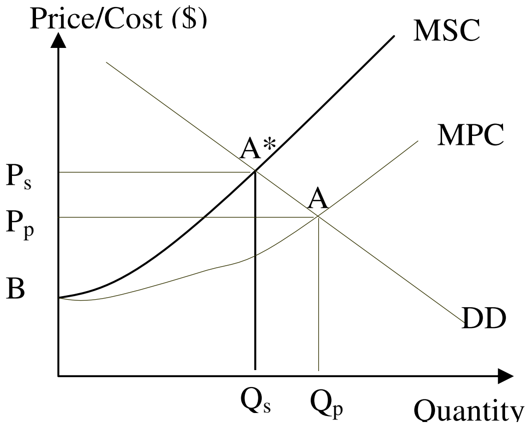

Figure 1.7. External costs and market effects.

In Figure 1.7, at point A, without incorporating external costs, the producer maximizes profits by producing the quantity (Q_p) at the price P_p. The quantity (Q_p) is the socially optimal level, and price ($P_{p)}$ reflects real costs of production. The private marginal benefit and cost are the same as social marginal benefit and cost. At point A*, when external costs are present, the private marginal cost curve (MPC) shifts upward to become the social marginal cost curve (MSC). The social cost equals the sum of private cost and external cost. The market equilibrium is shifted from A to A*. In the new market equilibrium, the socially optimal quantity (Q_s) is produced at the price (P_s). The socially optimal output level (Q_s) is lower than the private equilibrium output level (Q_p), while the socially optimal price (P_s) is higher than the private equilibrium price (P_p) because society has to bear the external costs, which private producers do not take into account without government intervention. In other words, the price (P_p) for a private producer does not reflect the real costs of production, and market failure occurs. If an economic incentive is implemented (such as an emission tax or effluent discharge fee), the private producer will internalize the external cost in his decision making, and the social optimum ought to be achieved at the market price (P_s). However, in most cases, producers do not take into account these external costs because of poor understanding of externalities and inadequate policy instruments (Field and Olewiler 2002).

1.2.5.2 Salmon Aquaculture and Externality

The environmental impacts associated with salmon aquaculture represent negative externalities from the production process, and these externalities are the costs incurred by the affected resource users, such as commercial and recreational fishers. For salmon aquaculture producers, they are external costs, which are not incorporated into their production decision-making without the relevant policy being in place. For instance, disease can cause economic losses to both salmon aquaculture producers and the wild salmon fishers. Aquaculture producers will internalize the costs resulting from reduction in revenues and increase in their production costs if they are known; the costs to wild salmon fisheries will not be internalized by salmon farmers without government intervention or economic incentives. In the case of pollution, the external costs may include potential impacts on benthic communities, seaweed, shellfish and wild fish fisheries.

Salmon aquaculture is a commercial activity, and its primary objective is to maximize its profits from aquaculture operation by maximizing revenue and/or minimizing production costs. If a salmon aquaculture operation continuously makes negative profit, the operation will have to fold. Therefore, salmon aquaculture producers will not take into account these external costs without government intervention. However, some environmental impacts may have feedbacks on the productivity of salmon production, in which case producers will internalize these environmental impacts into their production process (Asche *et al.* 1999; Bjørndal *et al.* 2002; Tveretås 2002). For instance, Asche *et al.* (1999) and Bjørndal *et al.* (2002) pointed out that environmental impacts were, to a large extent, internalized into the decision-making in the Norwegian salmon aquaculture.

1.2.5.3 Methods for Measuring Environmental Costs

While externalities are acknowledged, how to calculate them is a big challenge. The economic evaluation of environmental costs "involves putting prices or social values on physical environmental changes" (Angelsen and Sumaila 1996). Environmental economists have developed a variety of methods or techniques to assess these environmental values. Broadly speaking, these valuation methods can be categorized into three types. The first type refers to direct market valuation methods, which attempt to quantify environmental costs based on physical changes and observed market prices; it is relatively straightforward. For instance, the costs due to the loss of fish and shellfish catches can be estimated based on the reduction in the amount of fish or shellfish catch resulting from diseases and/or pollution and the market prices of these fish and shellfish.

The second type is revealed preference methods, which use indirect or surrogate market prices to estimate environmental costs. They include the travel cost method, hedonic pricing and surrogate market pricing. The travel cost method is used to estimate the values of recreational amenities. Hedonic pricing is used to estimate the use values of environmental amenities, for instance through their effects on upland property values. Surrogate market pricing is used to estimate costs, e.g., replacement/restoration costs, compliance cost, abatement/prevention costs. Abatement cost methods apply different technologies for reducing environmental impacts, while compliance costs methods implement environmental regulations or policies to force producers to mitigate environmental impacts. Abatement and compliance costs can be the same if applying a technology is mandated by environmental regulation.

The third method allows people to state, choose or rank their preferences or options based on a hypothetical market. It is commonly called ‘stated preference’ techniques. The most widely-used method is the contingent valuation method, which is a survey-based technique. It has been extensively used for estimating non-market values of resources and environmental service. In a contingent survey, a variety of questions will be designed based on a hypothetic market. Then, people will be asked to state their preference by answering questions about hypothetic choices. The questions can include how much people are willing to pay for improving specific environmental quality or service, or willing to accept in compensation for giving up specific environmental service or enduring a welfare loss from deteriorated water quality or damages caused by salmon aquaculture.

These three types of valuation methods have been widely described in the literature (e.g., Muir *et al.* 1999; Barbier 1994 and 2000; Boardman *et al.* 2001; Field and Olewiler 2002). Some of these methods have been used for estimating the external costs associated with aquaculture. For instance, Folke *et al.* (1994) used a 'modified' contingent valuation method to estimate the cost of reducing eutrophication from salmon aquaculture in the Baltic Sea. Smearman *et al.* (1997) conducted a contingent valuation survey by asking people's willingness-to-pay for improving water quality that was degraded by trout farming in West Virginia. The cost of the damage from the waste was estimated to be about 25% of the production costs, whereas applying a filtration technology to prevent waste discharges would cost farmers about 6% of the production cost. Sathirathai and Barbier (2001) applied a direct market valuation method and bioeconomic models to estimate the external costs generated by mangrove destruction and water pollution from shrimp farming in Thailand. They concluded that shrimp farming would not be economically viable if external costs were incorporated. Babier (2003) developed a bioeconomic model to estimate the welfare losses in coastal fisheries due to mangrove deforestation resulting from shrimp farming in Thailand.

Nevertheless, some environmental costs can be measured in monetary terms, while some are difficult to quantify because they are not traded on the market, such as biodiversity losses due to pollution. In some cases, ecological or environmental impacts are not fully understood and large gaps exist in our knowledge of actual and long-term impacts on the environment and resources. Some environmental costs are difficult to quantify because they may result from different sources, and the measured using different methods. Thus, alternatively, abatement costs and compliance costs can be used as environmental costs. Both abatement and compliance costs are relatively easy to estimate and less controversial than directly estimating environmental costs. For instance, implementing new technologies (e.g., Buschmann *et al.* 2001; Chopin *et al.* 2001; EPA 2002; Troell *et al.* 2003) and best management practices (e.g., Ackefors and White 2002; Boyd 2003; Neori *et al.* 2004) have been seen as feasible and achievable means to mitigate and prevent environmental impacts associated with salmon aquaculture.

However, different methods or techniques have different advantages and disadvantages. There is no ‘perfect’ method or technique. Many environmental economists have put great efforts into measuring environmental costs imposed by different sectors. In the following chapters, I will apply different valuation methods/techniques to deal with pollution and disease problems associated with salmon aquaculture.

1.3 References

Ackefors, H. and P. White, 2002. A framework for developing best environmental practices for aquaculture. World Aquaculture 33(2): 54-59.

Angelsen, A. and U.R. Sumaila**,** 1996. Hard methods for soft policies: environmental and social cost benefit analysis. Forum for Development Studies 1: 87-114.

Arthur, J.R., M.J. Phillips, R.P. Subasinghe, M.B. Reantaso and I.H. MacRae, 2002. Primary Aquatic Animal Health Care in Rural, Small-scale, Aquaculture Development. FAO Fisheries Technical Paper 406, Rome, Italy. 381p.

Asche, F. and F. Khatum, 2006. Aquaculture: Issues and Opportunities for Sustainable Production and Trade. Issue Paper No. 5. International Centre for Trade and Sustainable Development, Geneva, Switzerland. 63p.

Asche, F. and S. Tveretås, 2004. On the relationship between aquaculture and reduction fisheries. Journal of Agricultural Economics 55(2): 245-265.

Asche, F., A.G. Guttormsen and R. Tveterås, 1999. Environmental problems, productivity and innovations in Norwegian salmon aquaculture. Aquaculture Economics and Management 3(1): 19-29.

Aarset, B., 1998. Norwegian salmon-farming industry in transition: dislocation of decision control. Ocean and Coastal Management 38: 187-206.

Barbier, E.B., 1994. Valuing environmental functions: tropical wetlands. Land Economics 70(2): 155-173.

Barbier, E.B., 2000. Valuing the environment as input: review of applications to mangrove-fishery linkages. Ecological Economics 35: 47-61.

Barbier, E.B., 2003. Habitat-fishery linkages and mangrove loss in Thailand. Contemporary Economic Policy 21(1): 59-77.

Barg, U. and M.J. Phillips, 1997. Environment and sustainability. In: Review of the State of World Aquaculture. FAO Fisheries Circular No. 886 (Rev. 1): 55-66.

Barrett, G., M.I. Caniggia and L. Read, 2002. There are more vets than doctors in Chiloé": social and community impact of the globalization of aquaculture in Chile. World Development 30(11): 1951-1965.

Barton, J., 1997. Environment, sustainability and regulation in commercial aquaculture: the case of Chilean salmonid production. Geoforum 28(3-4): 313-328.

Bjorn, P.A. and B. Finstad. 2002. Salmon lice, *Lepeophtheirus salmonis* (Kroyer), infestation in sympatric populations of Arctic char, *Salvelinus alpinus* (L.), and sea trout, *Salmo trutta* (L.), in areas near and distant from salmon farms. ICES Journal of Marine Science 59: 131-139.

Bjørndal, T. 1990. The Economics of Salmon Aquaculture. Cambridge, Mass. Blackwell Scientific Publications. 118p.

Bjørndal, T., G.A. Knapp and A. Lem, 2003. Salmon – A Study of Global Supply and Demand. Report No. 92. Centre for Fisheries Economics, Institute for Research in Economics and Business Administration, Bergen, Norway. 157p.

Bjørndal, T., R. Tveterås and F. Asche, 2002. The development of salmon and trout aquaculture. In Paquotte, P., C. Mariojouls and J. Young (Eds): Seafood Market Studies for the Introduction of New Aquaculture products. Cahiers Options Méditerranéennes 59: 101-115.

Bjørndal, T. and K. Aarland, 1999. Salmon aquaculture in Chile. Aquaculture Economics and Management 3(3): 238-53.

Bjørndal, T., 2002. The competitiveness of the Chilean salmon aquaculture industry. Aquaculture Economics and Management 6(1-2): 97-116.

Black, E., R. Gowen, H. Rosenthal, E. Roth, D. Stechy and F.J.R. Taylor, 1997. The costs of eutrophication from salmon farming: implications for policy - a comment. Journal of Environmental Management 50(1): 105-09.

Boardman, A.E., D.H. Greenberg, A.R. Vining and D.L. Weimer, 2001. Cost-Benefit Analysis: Concepts and Practice (2nd Edition). Upper Saddle River, NJ: Prentice Hall. 526p.

Boyd, C.E., 2003. Guidelines for aquaculture effluent management at the farm-level. Aquaculture 226(1-4): 101-12.

Brooks, K.M. and C.V.W. Mahnken, 2003. Interactions of Atlantic salmon in the Pacific Northwest environment II. Organic wastes. Fisheries Research 62(3): 255-93.

Brooks, K.M., 2001. An Evaluation of the Relationship between Salmon Farm Biomass, Organic Inputs to Sediments, Physicochemical Changes Associated with Those Inputs and the Infaunal Response---with Emphasis on Total Sediment Sulfides, Total Volatile Solids, and Oxidation---Reduction Potential as Surrogate Endpoints for Biological Monitoring. Ministry of Environment, Lands and Parks, Nanaimo, BC, Canada, 210p.

Brooks, K.M. and D.J. Stucchi. 2006. The effects of water temperature, salinity and currents on the survival and distribution of the Infective copepodid stage of the salmon louse (*Lepeophtheirus salmonis*) originating on Atlantic salmon farms in the Broughton Archipelago of British Columbia, Canada (Brooks, 2005) – a response to the Reubttal of Krkosek *et al.* (2005). Review of Fishery Science 14**:**13-23.

Burridge, L.E., 2003. Chemical Use in Marine Finfish Aquaculture in Canada: A Review of Current Practices and Possible Environmental Effects. Fisheries and Oceans Canada, 21-29.

Buschmann, A.H., M. Troell and N. Kautsky, 2001. Integrated algal farming: a review. Cahiers De Biologie Marine 42(1-2): 83-90.

Buschmann, A.H., V.A. Riquelme, M.C. Herna´ndez-Gonza´lez, D. Varela, J.E. Jime´nez, L.A. Henrı´quez, P.A. Vergara, R. Guı´n˜ez and L. Filu´n, 2006. A review of the impacts of salmonid farming on marine coastal ecosystems in the southeast Pacific. ICES Journal of Marine Science 63: 1338-1345.

Carr, J.W., J.M. Anderson, F.G. Whoriskey and T. Dilworth, 1997. The occurrence and spawning of cultured Atlantic salmon (*Salmo salar*) in a Canadian river. ICES Journal of Marine Science 54(6): 1064-1073.

Carroll, M.L., S. Cochrane, R. Fieler, R. Velvin and P. White, 2003. Organic enrichment of sediments from salmon farming in Norway: environmental factors, management practices, and monitoring techniques. Aquaculture 226(1-4): 165-80.

Chopin, T., A.H. Buschmann, C. Halling, M. Troell, N. Kautsky, A. Neori, G.P. Kraemer, J.A. Zertuche-Gonzalez, C. Yarish, and C. Neefus, 2001. Integrating seaweeds into marine aquaculture systems: a key toward sustainability. Journal of Physiology 37(6): 975-86.

Collier, L.M. and E.H. Pinn, 1998. An assessment of the acute impact of the sea lice treatment ivermectin on a benthic community. Journal of Experimental Marine Biology and Ecology 230(1): 131-47.

Cox, S.K. 2004. Diminishing Returns – An Investigation into the Five Multinational Corporations that Control British Columbia's Salmon Farming Industry. Coastal Alliance for Aquaculture Reform. 118p.

Davies, I.M., P.A. Gillibrand, J.G. McHenery and G.H. Rae, 1998. Environmental risk of ivermectin to sediment dwelling organisms. Aquaculture 163(1-2): 29-46.

Davies, I.M. and G.K. Rodger, 2000. A review of the use of ivermectin as a treatment for sea lice [*Lepeophtheirus salmonis* (Krøyer) and *Caligus elongatus* Nordmann] infestation in farmed Atlantic salmon (*Salmo salar* L.). Aquaculture Research 31 (11): 869-883.

Davies, I.M., G.K. Rodger, J. Redshaw and R.M. Stagg, 2001. Targeted environmental monitoring for the effects of medicines used to treat sea-lice infestation on farmed fish. ICES Journal of Marine Science 58(2): 477-85.

Delgado, C.L., N. Wada, M.W. Rosegrant, S. Meijer, and M. Ahmed, 2003. Fish to 2020: Supply and Demand in Changing Global Markets. International Food Policy Research Institute and WorldFish Centre. 232p.

EPA, 2002. Development Document for Proposed Effluent Limitations Guidelines and Standards for the Concentrated Aquatic Animal Production Industry Point Source Category. Engineering & Analysis Division Office of Science and Technology, Environmental Protection Agency, United States, Washington, DC. 571p.

FAO, 2000. FAO Yearbook of Fishery Statistics: Aquaculture Production. FAO Fisheries Series, 86/2. Rome, Italy.

FAO, 2007. The State of World Fisheries and Aquaculture 2006. Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, Italy. 180p.

Field, B. and N. Olewiler, 2002. Environmental Economics. 2nd Canadian edition. McGraw-Hill Ryerson. 498p.

Finstad, B., P.A. Bjorn, A. Grimnes and N.A. Hvidsten, 2000. Laboratory and field investigations of salmon lice [*Lepeophtheirus salmonis*] infestation on Atlantic salmon (*Salmo salar* L.) post-smolts. Aquaculture Research 31: 795-803.

Folke, C. and N. Kautsky, 1992. Aquaculture with its environment: prospects for sustainability. Ocean and Coastal Management 17: 5-24.

Folke, C., N. Kautsky and M. Troell, 1994. The costs of eutrophication from salmon farming: implications for policy. Journal of Environmental Management 40: 173-182.

Folke, C., N. Kautsky and M. Troell, 1997. Salmon farming in context: response. Journal of Environmental Management 50(1): 95-103.

Garcia, M.S. and R.J.R. Grainger, 2005. Gloom and doom? The future of marine capture fisheries. Philosophical Transactions of Royal Society of Biology 360: 21-46.

Gargan, P.G., O. Tully, and W.R. Poole, 2002. The relationship between sea lice infestation, sea lice production and sea trout survival in Ireland, 1992-2001. In: Mills, D. (Ed): Salmon on the Edge. Chapter 10: 119-135.

Hannesson, R., 2003. Aquaculture and fisheries. Marine Policy 27: 169-178.

Hardy, R.W. and A.G.J. Tacon, 2002. Fish meal: historical uses, production trends and future outlook for sustainable supplies. In Stickney, R. R. and J. P. McVey (Eds), Responsible Marine Aquaculture. CAB International, 311-25.

Haya, K., L.E. Burridge and B.D. Chang, 2001. Environmental impact of chemical wastes produced by the salmon aquaculture Industry. ICES Journal of Marine Science 58(2): 492-96.

Hishamunda, N. and N.B. Ridler, 2002. Macro policies to promote sustainable commercial aquaculture. Aquaculture International 10: 491-505.

Hites, R.A., J.A. Foran, D.O. Carpenter, M.C. Hamilton, B.A. Knuth, S.J. Schwager, 2004. Global assessment of organic contaminants in farmed salmon. Science 303 (5655): 226-229.

Hjelt K.A., 2000. The Norwegian regulation system and the history of the Norwegian salmon farming industry. In Liao, C.I and C. Kwei (Eds): Cage Aquaculture in Asia: Proceedings of the First International Symposium on Cage Aquaculture in Asia. Asian Fisheries Society, Quezon City, Philippines.1-17p.

Israngkura, A. and S. Sae-Hae, 2002. A review of the economic impacts of aquaculture animal disease. In: Arthur, J.R., M.J. Phillips, R.P. Subasinghe, M.B. Reantaso and I.H. MacRae (Eds): Primary Aquatic Animal Health Care in Rural, Samll-scale, Aquaculture Development. FAO Fisheries Technical Paper 406: 253-286.

Janowicz, M. and J. Ross, 2001. Monitoring for benthic impacts in the Southwest New Brunswick salmon aquaculture industry. ICES Journal of Marine Science 58(2): 453-59.

Johnsen, B.O. 2006. NOBANIS – Invasive Alien Species Fact Sheet – *Gyrodactylus salaris*. – From: Online Database of the North European and Baltic Network on Invasive Alien Species – NOBANIS www.nobanis.org, access Feb. 2007.

Johnsen, B.O. and A.J., Jensen, 1992. Infection of Atlantic salmon, *Salmo salar* L., by *Gyrodactylus salaris*, Malmberg 1957, in the River Lakselva, Misvær in northern Norway. Journal of Fish Biology 40: 433-444.

Kautsky, N., C. Folke, P. Ronnback, M. Troell, M. Beveridge and J. Primavera, 2001. Aquaculture and Biodiversity. In: Levin.S., G. Daily, R. Colwell, J. Lubchenco, H. Mooney, E-D. Schultze, D. Tilman (eds.): Encyclopedia of Biodiversity. Academic Press. 1185-1198p.

Knapp, G., 2005. Implications of aquaculture for wild fisheries: the case of Alaska wild salmon. Presentation for the Bevan Sustainable Fisheries Lecture Series, University of Washington, Seattle, Washington, Feb. 10. Available at http://www.iser.uaa.alaska.edu/iser/people/knapp/Knapp_UW_Bevan_Series_Salmon_Lecture_050210.pdf

Knapp, G., C. Roheim and J.L. Anderson, 2007. The Great Salmon Run: Competition Between Wild and Farmed Salmon. TRAFFIC North America. Washington D.C.: World Wildlife Fund. 302p.

Krkošek, M., M.A. Lewis and J.P. Volpe, 2005. Transmission dynamics of parasitic sea lice from farm to wild salmon. Proceedings of the Royal Society of London Series B 272: 689-696.

Krkošek, M., M.A. Lewis, A. Morton, L.N. Frazer and J.P. Volpe, 2006. Epizootics of wild fish induced by farm fish. Proceedings of the National Academy of Sciences of the USA 103(42): 15506-15510.

MAFF, 2004. Fisheries and Aquaculture. Ministry of Agriculture, Food and Fisheries. Available at http://www.agf.gov.bc.ca/fisheries/index.htm, access May 2006.

McGinnity, P., P. Prodfhl, A. Ferguson, R. Hynes, N. O´ Maoile´idigh, N. Baker, D. Cotter, B. O'Hea, D. Cooke, G. Rogan, J. Taggart and T. Cross, 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 of London Series B—Biological Science 270: 2443–2450.

McVicar, A., 1997. Disease and parasite implications of the coexistence of wild and cultured Atlantic salmon populations. ICES Journal of Marine Science 54: 1093-1103.

McVicar, A., 2004. Management actions in relation to the controversy about salmon lice infections in fish farms as a hazard to wild salmonid populations. Aquaculture Research 35(8): 751-758.

Menzies, F.D., T. Crockford, O. Breck and P.J. Midtlyng, 2002. Estimation of direct costs associated with cataracts in farmed Atlantic salmon (*Salmo salar*). Bulletin of the European Association of Fish Pathologists 22(1): 27-32.

Milewski, I., 2001. Impacts of salmon aquaculture on the coastal environmental: a review. In Tlusty, M.F., D.A. Bengston, H.O. Halvorson, S.D. Oktay, J.B. Pearce and J.R.B. Rheault (Eds): Marine Aquaculture and the Environment: A Meeting for Stakeholders in the Northeast. Falmouth, Massachusetts, Cape Cod Press, 35p.

Morton, A. and R. Routledge, 2005. Mortality rates for juvenile pink *Oncorhynchus gorbuscha* and chum *O. keta* salmon infested with sea lice *Lepeophtheirus salmonis* in the Broughton Archipelago. Alaska Fisheries Research Bulletin 11: 146-152.

Morton, A., R. Routledge, C. Peet and A. Ladwig. 2004. Sea lice (*Lepeophtheirus salmonis*) infection rates on juvenile pink (*Oncorhynchus gorbuscha*) and chum (*Oncorhynchus keta*) salmon in the nearshore marine environment of British Columbia, Canada. Canadian Journal of Fisheries and Aquatic Sciences 61: 147-157.

Muir, J.F., C. Brugere, J.A. Young and J.A. Stewart, 1999. The solution to pollution? The value and limitations of environmental economics in guiding aquaculture development. Aquaculture Economics and Management 3(1): 43-57.

Mustafa, A., W. Rankaduwa and P. Campbell, 2001. Estimating the cost of sea lice to salmon aquaculture in eastern Canada. Canadian Veterinary Journal 42: 54-56.

NASCO, 2004. Report of the twenty-first annual meetings of the commissions. Reykjavik, Iceland, 7-11 June. 302p. available at http://www.nasco.int/pdf/2004%20commissions%20report.pdf.

Naylor, R.L., R. J. Goldburg, J.H. Primavera, N. Kautsky, M.C.M. Beveridge, J. Clay, C. Folke, J. Lubchenco, H. Mooney and M. Troell, 2000. Effect of aquaculture on world fish supplies. Nature 405(6790): 1017-1024.

Naylor, R. and M. Burke, 2005. Aquaculture and Ocean resources: raising tigers of the sea. Annual Review of Environmental Resources 30: 185–218.

Naylor, R.L., J. Eagle and W.L. Smith, 2003. Salmon aquaculture in the Pacific Northwest - a global industry. Environment 45 (8): 18-39.

Neori, A., T. Chopin, M. Troell, A.H. Buschmann, G.P. Kraemer, C. Halling, M. Shpigel and C. Yarish, 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modem mariculture. Aquaculture 231(1-4): 361-391.

New, M.B. and U.N. Wijkström, 2002. Use of Fishmeal and Fish Oil in Aquafeeds: Further Thoughts on the Fishmeal Trap. FAO Fisheries Circular No. 975. FAO, Rome, 61p.

Pauly, D., V. Christensen, S. Guenette, T.J. Pitcher, U.R. Sumaila, C.J. Walters, R. Watson and D. Zeller, 2002. Towards sustainability in world fisheries. Nature 418 (6898): 689-695.

Pauly, D., R. Watson and J. Alder, 2005. Global trends in world fisheries: impacts on marine ecosystems and food security. Philosophical Transactions of the Royal Society B 360: 5-12.

Pillay, T.V.R., 1992. Aquaculture and the Environment. New York, Halsted Press, 189p.

Pohle, G., B. Frost and R. Findlay, 2001. Assessment of regional benthic impact of salmon mariculture within the Letang Inlet, Bay of Fundy. ICES Journal of Marine Science 58(2): 417-26.

Porter, G. 2005. Protecting Wild Atlantic Salmon from Impacts of Salmon Aquaculture: A Country-by-Country Progress Report 2nd Edition. World Wildlife Fund and Atlantic Salmon Federation. 58p.

SAR 1997. Salmon Aquaculture Review. Environmental Assessment Office, Victoria, BC, Canada, Vol 3, 201p.

Sathirathai, S., and E.B. Barbier, 2001. Valuing mangrove conservation in Southern Thailand. Contemporary Economic Policy 19(2): 109-122.

Smearman, S.C., G.E. D'Souza and V.J. Norton, 1997. External costs of aquaculture production in West Virginia. Environmental and Resource Economics 10(2): 167-175.

Sønvisen, S. A., 2003. Integrated Coastal Zone Management (ICZM): the Allocation of Space in Norwegian Aquaculture – from Local Lottery to Central Planning? Norwegian College of Fishery Science, University of Tromsø. 95p.

Subasinghe, R.P., R.G. Bondad-Reontase and S.E. McGladdery, 2001. Aquaculture development, health and wealth. In: Subasinghe, R.P., P. Bueno, M.J. Philips, C. Hough, S.E. McGladdery and J.R. Arthur (eds): Aquaculture in the Third Millennium Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20-25 February 2000. NACA, Bangkok and FAO, Rome, 167-191.

Subasinghe, R.P., 2005. Epidemiological approach to aquatic animal health management: opportunities and challenges for developing countries to increase aquatic production through aquaculture. Preventive Veterinary Medicine 67: 117-124.

Sumaila, U.R., J. Volpe and Y. Liu, 2005. Ecological and economic impact assessment of sablefish aquaculture in British Columbia. Fisheries Centre Research Reports 13(3). 33p.

Tacon, A.G.J., M.R. Hasan and R.P. Subasinghe, 2006. Use of fishery resources as feed inputs for aquaculture development: trends and policy implications. FAO Fisheries Circular No.1018, Rome, FAO, 99p.

Thorpe, J.E., 1980. The development of salmon culture towards ranching. In J. E. Thorpe (Eds), Salmon Ranching. London, Academic Press, 1-12.

Tidwell, J.H. and G.L. Allan, 2001. Fish as food: aquaculture's contribution - ecological and economic impacts and contributions of fish farming and capture fisheries, EMBO Rep. 2 (11): 958-963.

Troell, M., C. Halling, A. Neori, T. Chopin, A.H. Buschmann, N. Kautsky and C. Yarish, 2003. Integrated mariculture: asking the right questions. Aquaculture 226 (1-4): 69-90.

Troell, M., C. Halling, A. Nilsson, A.H. Buschmann, N. Kautsky and L. Kautsky, 1997. Integrated marine cultivation of *Gracilaria Chilensis* (*Gracilariales, Rhodophyta*) and salmon cages for reduced environmental impact and increased economic output. Aquaculture 156(1-2): 45-61.

Tully, O. and D.T. Nolan, 2002. A review of the population biology and host–parasite interactions of the sea louse *Lepeophtheirus salmonis* (Copepoda: Caligidae). Parasitoloy 124: 165-182.

Tuominen, T-R and M. Esmark, 2003. Food for Thought: the Use of Marine Resources in Fish Feed. WWF - Norway. 53p.

Tveterås, S. 2002. Norwegian salmon aquaculture and sustainability: the relationship between environmental quality and industry growth. Marine Resource Economics 17: 117-128.

Volpe, J.P., B.R. Anholt and B.W. Glickman, 2001. Competition among juvenile Atlantic salmon (*Salmo salar*) and steelhead trout (*Oncorhynchus mykiss*): Relevance to invasion potential in British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 58: 197-207.

Watson, R. and D. Pauly, 2001. Systematic distortions in world fisheries catch trends. Nature 424: 534-536.

Wildish, D.J., B.T. Hargrave and G. Pohle, 2001. Cost-effective monitoring of organic enrichment resulting from salmon mariculture. ICES Journal of Marine Science 58(2): 469-76.

Willoughby, S., 1999. Manual of Salmonid Farming. Oxford ; Malden, MA, Fishing News Books, 329p.

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

Zitko, V., 2001. Analytical chemistry in monitoring the effects of aquaculture: one laboratory's perspective. ICES Journal of Marine Science 58(2): 486-91.

Chapter 2 Growth of Salmon Aquaculture[2]

2.1 Introduction

There is ample evidence that the world's capture fisheries catches have reached their upper ceiling (e.g., Watson and Pauly 2001). Studies have demonstrated that the catches of some species, especially top predators, have dramatically declined recently (e.g., Pauly *et al.* 2002; Meyer and Worm 2003). Increasingly, aquaculture has been seen by many as a solution to bridge the gap between the dwindling capture fisheries catch and increasing seafood demand (e.g., Tidwell and Alan 2001; Garcia and Grainger 2005).

It is estimated that aquaculture production has been growing annually at an average rate of 8.8% since 1970. Turning to farmed salmon, its production has increased from around 500 tonnes in 1970 to over 1.3 million tonnes in 2005. Salmon aquaculture has been increasing at an average rate of 24.6% since 1980 to present (FAO, FISHSTAT). World farmed salmon production first exceeded wild salmon production in 1998. Over the years, aquaculture's contribution to the world's seafood supply has increased. Currently, aquaculture contributes about one-third of the world's total seafood supply (FAO 2007). These numbers have fuelled optimism, leading the Food and Agricultural Organization of the United Nations (FAO) to predict that aquaculture will continue its rapid expansion in order to meet growing population and seafood demand around the world in the future (FAO 2007).

Given this overwhelming growth in farmed salmon production, it has been hard to pullback and to investigate the question: can farmed salmon production keep growing at recent rates? To answer this question, it is not enough to look at the total growth in production or even the average growth rate over time but rather it is necessary to look at

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[2] A version of this chapter is currently in press. Liu, Y. and Sumaila, U.R. (2008) Can Farmed Salmon Production Keep Growing? Marine Policy.

the year-on-year growth of farmed salmon production to determine whether the annual incremental growth rate of production is increasing, decreasing or remaining stable. Further, we also analyzed the growth in all finfish aquaculture and all finfish capture fisheries to compare them with the growth in farmed salmon.

Many reasons have been advanced in the literature that suggest that aquaculture, in particular intensive aquaculture of carnivorous species such as shrimp and salmon, cannot continue to grow at its current pace (Pauly *et al.* 2002; Naylor *et al.* 2003; Naylor and Burke 2005; Tacon *et al.* 2006). The current contribution distinguishes itself by analysing the data. First, we present the growth of salmon aquaculture production over time. Then, based on FAO, time series production data in the leading producing countries and for the sector as a whole are used to compute the 5-year moving average rate of growth[3] in salmon aquaculture production. Based on the grow rates calculated, a regression line is drawn starting at the peak point[4]. Similarly, I also calculate the 5-year moving average rates of growth in all finfish aquaculture and capture fisheries and draw their regression lines, respectively.

2.2 Global Salmon Aquaculture Production

Salmon aquaculture has experienced remarkable growth as a result of expanding new cultured locations, improved productivity, enhanced husbandry practices and management, and growing global markets (Bjorndal 2002; Bjorndal *et al.* 2003; Asche and Khatum 2006). In the meantime, salmon aquaculture has undergone a number of structural and technical changes, and it has expanded, intensified and diversified during the course of the last two decades. Figure 2.1 shows salmon aquaculture production by the four major salmon fishing countries over time. It can be seen from this figure that there has indeed been remarkable growth.

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[3] The moving average growth rate is a better measure than the normal growth rate because it can help to reveal the ‘hidden’ trend in an evolving dataset, and also filters some of the noise in the dataset.

[4] Farmed salmon production in fact increases in an increasing rate initially, then increases in a declining rate, and begins to decrease. One could have fitted a traditional S-curve covering the whole period of the time series. However, these S-curves will not help me to achieve my goal.

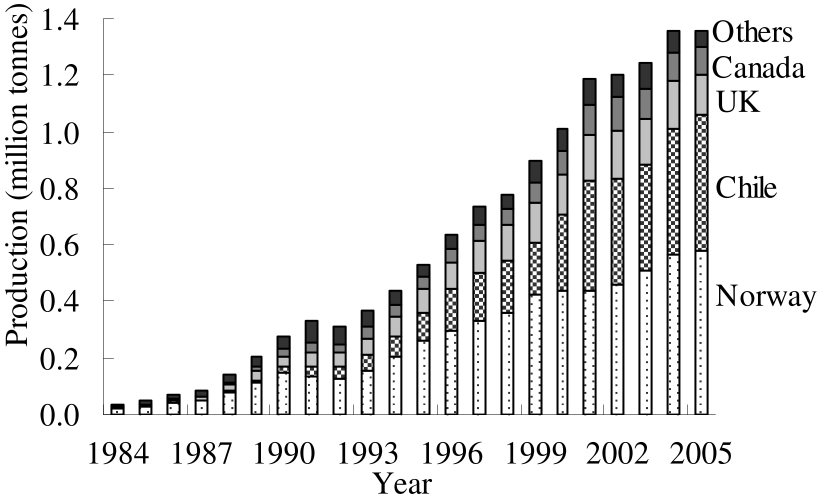
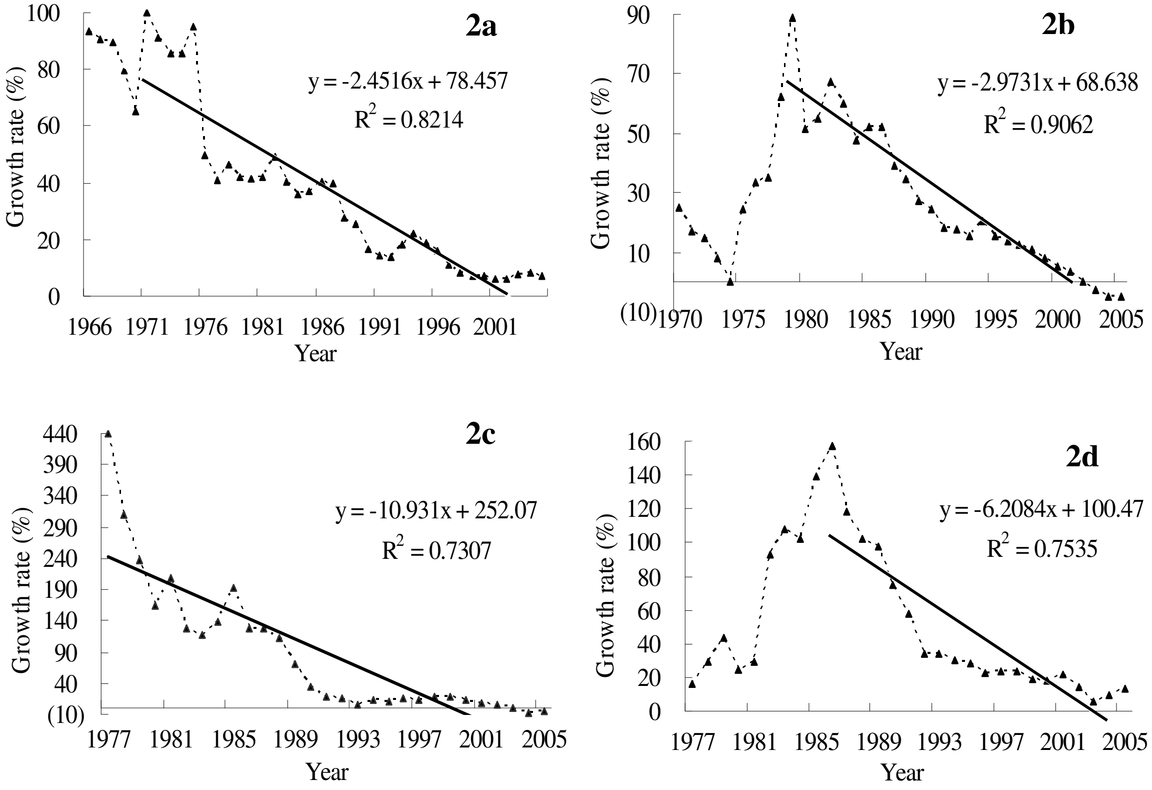


Figure 2.1. Farmed salmon production by major producing country. Data source: FAO FISHSTAT (http://www.fao.org/fi/website/FIRetrieveAction.do?dom=topic&fid=14795).

2.3 Analyses of Growth in Salmon Aquaculture

The results are presented in Figure 2.2. The figures show, unequivocally, that in all four countries, and for the world as a whole, the year-on-year growth rate of salmon production quickly reaches a peak and then begins sliding down towards zero. The analysis reveals a decline of 1.2 percent per year in global farmed salmon production since it peaked in 1966 (Figure 2.2e). From Figure 2.2a, it can be seen that growth rate in farmed salmon production in Norway peaked in 1971 at a rate of 100%. The growth rate has been declining at 2.5% per year since it peaked. In the case of the UK, the growth rate peaked in 1979 at about 89%, and since then, the country has witnessed a decline of 3% per year in the rate of growth of farmed salmon production. Canada's rate of growth of farmed salmon production peaked in 1977 at about 440%. Since the peak year, the growth rate has been declining at a rate of 10.9% per year. Chile's rate of farmed salmon growth in production peaked in 1986, at a growth rate of about 157%, with a decline of 6.2% per year since the peak year.

One can conclude from this result that the ability of salmon aquaculture to keep growing at its current pace[5] is doubtful. Analysis of production data for all farmed finfish, both marine and freshwater, shows a decline of 0.34% per year in the growth rate from the peak year. These results have implications for global fisheries policy because they mean that the world may not be able to rely on aquaculture to supply fish protein for human consumption as assumed by some.



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[5] The current pace refers to the widely average annual growth rate of 8.8% estimated by FAO based on aquaculture data from 1970 to present.

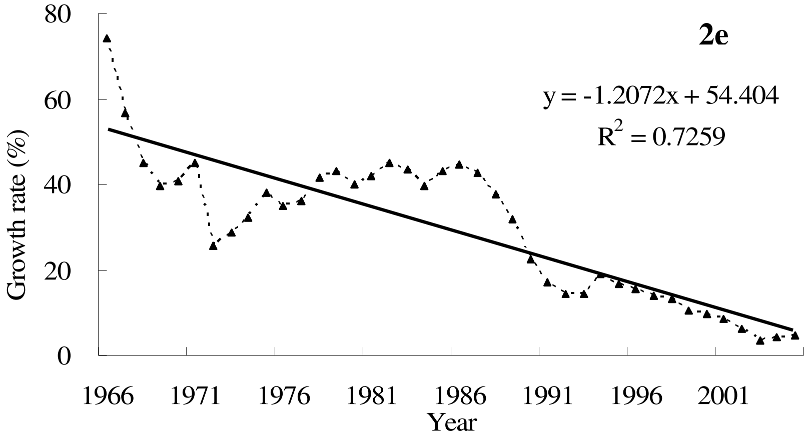

Figure 2.2. 5-year moving average of year-on-year growth rate of farmed salmon production in Norway (2a), the UK (2b) Canada (2c), Chile (2d), and globally (2e).

A relevant question to ask at this juncture is, whether the decline reported above is happening only in the case of farmed salmon. If the answer is yes then it can be argued that the finding will not have a huge policy implication. To address this question, an analysis of production data for 'all finfish aquaculture' was carried out. The results from this analysis are presented in Figure 2.3.

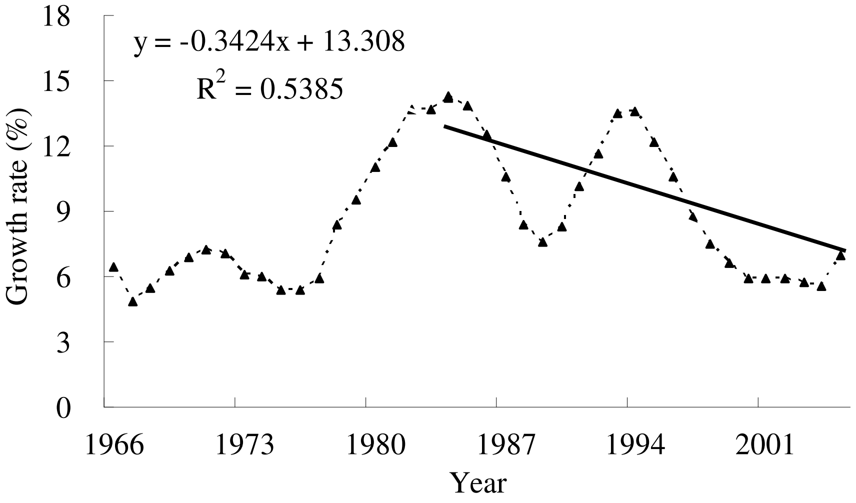

Figure 2.3. 5-year moving average of year-on-year growth rate of production of 'all finfish aquaculture'.

It is shown in the figure that for the period from 1966 to 2005, the rate of growth in production of all finfish aquaculture, i.e., marine, diadromous and freshwater, peaked in 1984, and has since been declining at the rate of 0.34% per year.

Finally, the paper investigated whether what is demonstrated for aquaculture is also true for capture fisheries. An analysis of catch data for ‘all capture finfish’ was conducted, the results of which are reported in Figure 2.4. This figure shows that the trend in the growth rate of catch of capture fish is similar to the trend in the growth rate of production of farmed fish, implying that when it comes to trends in growth rates of production/catch, there is no difference between capture and farmed fish.

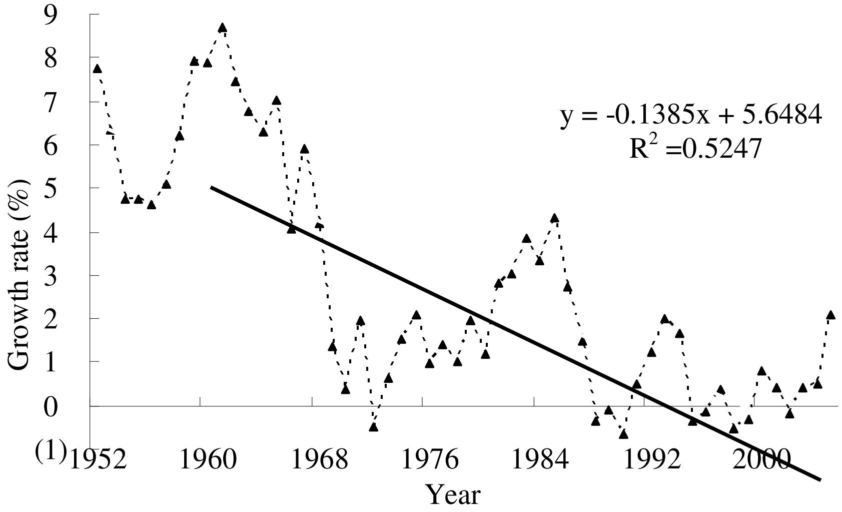

Figure 2.4. 5-year moving average of year-on-year growth rate of catch of ‘all capture finfish species’.

2.4 Discussions and Conclusions

It has been demonstrated in Chapter 3 that farmed salmon production has witnessed a significant increase in the last three to four decades. More importantly, a simple analysis of production data for the major salmon aquaculture countries, and the world, shows that the optimistic view that aquaculture will continue its rapid expansion in order to meet growing population and seafood demand around the world is not supported by production data for salmon farming and for 'all finfish aquaculture'[6].

The declining growth rate in the production of farmed salmon and all finfish aquaculture is an indication that the expectation that fish from aquaculture will continue increasing into the future at recent rates, thereby providing a solution to the declining catch from global capture fisheries, is not likely to come to fruition. The declining growth rate may indicate that the productivity of salmon aquaculture is beginning to decline. This decline may be attributed to changes in market conditions, e.g., falling prices, demand, new markets (Tveterås and Heshmati 2002; Asche and Khahun 2006), the scarcity of inputs and their costs, e.g., feed (Tacon *et al*. 2006), scarcity of suitable space (Bjørndal 2002; Sønvisen 2003) and environmental concerns resulting in stricter regulations, and increasing consumer awareness about food safety and quality of farmed productions (Whitmash and Wattage 2006). These are some of the reasons why salmon aquaculture cannot continue to increase at recent growth rates forever.

The substantial increase in farmed salmon production is accompanied by a decrease in market prices for farmed salmon products. In the meantime, production costs have steadily declined as a result of technological innovations and productivity growth (Bjørndal *et al.* 2002; Asche and Khatun 2006). Salmon aquaculture is driven by profit-making. Hence, the more profitable salmon aquaculture is, the more expansion takes place, everything being equal. Initially, due to high market prices, salmon producers received higher returns on investment and greater incentive to expand. The rapid expansion has led to greater competition, lower market prices, and increasing environmental problems.

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[6] There is no doubt that aquaculture is playing an important role for providing seafood for consumers. In some countries or regions, a significant amount of seafood consumed is from aquaculture. Even with a 1-2% annual growth rate, total production from aquaculture will be significant. However, this growth rate may not meet the needs of the world's growing population if the demand for seafood keeps growing at a higher rate (>1-2%) than aquaculture.

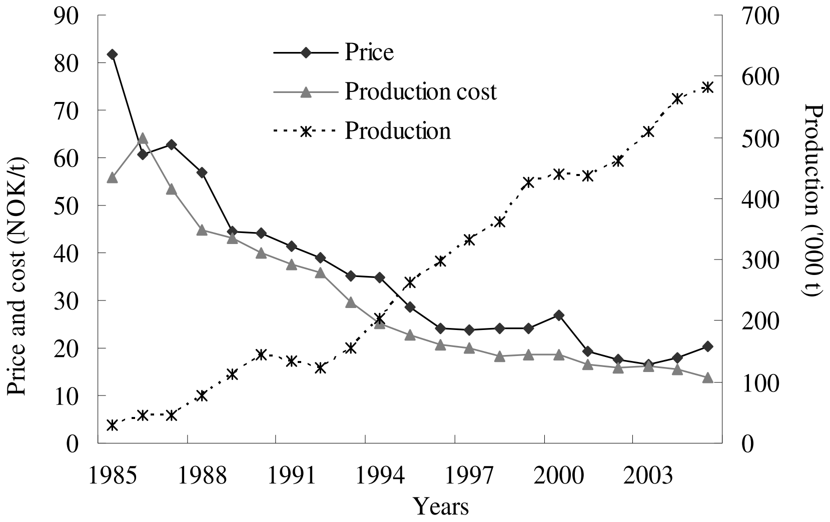

Figure 2.5. Changes in production, cost and price of Norwegian farmed salmon.

As Norway has the most data available, information on Norwegian salmon aquaculture are used to demonstrate these relationships. Figure 2.5 shows changes in price, cost and production for the Norwegian salmon aquaculture industry from 1985 to 2005 (on average, 1CAD$ = 5.5NOK). As may be seen from the figure, price and production costs have been declining, while production has been increasing over time. In some years, price and production cost were almost equal, implying profits were low. As long as salmon aquaculture is still profitable, its growth will continue. Farmed salmon products used to be luxury seafood available in restaurants for the elite, but today they have become more affordable seafood available in most seafood markets (Forster 2002; Knapp *et al.* 2007). This is one benefit of salmon aquaculture – it leads to increasing consumer surplus.

The result of this simple study has far-reaching policy implications – it means that the convenient assumption by some that because of aquaculture, the world need not worry about the pending demise of capture fisheries may be unfounded.

2.5 References

Asche, F. and F. Khatum, 2006. Aquaculture: Issues and Opportunities for Sustainable Production and Trade. Issue Paper No. 5. International Centre for Trade and Sustainable Development, Geneva, Switzerland. 63p.

Bjørndal, T., R. Tveterås and F. Asche, 2002. The development of salmon and trout aquaculture. In Paquotte, P., C. Mariojouls and J. Young (Eds): Seafood Market Studies for the Introduction of New Aquaculture products. Cahiers Options Méditerranéennes 59: 101-115.

Bjørndal, T., 2002. The competitiveness of the Chilean salmon aquaculture industry. Aquaculture Economics and Management 6(1-2): 97-116.

Bjørndal, T., G.A. Knapp and A. Lem, 2003. Salmon – A Study of Global Supply and Demand. Report No. 92. Centre for Fisheries Economics, Institute for Research in Economics and Business Administration, Bergen, Norway. 157p.

FAO, 2007. The State of World Fisheries and Aquaculture 2006. Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, Italy. 180p.

Forster, J., 2002. Farming salmon: an example of aquaculture for the mass market. Reviews in Fisheries Science 10(3&4): 557-591.

Garcia, M.S. and R.J.R. Grainger, 2005. Gloom and doom? The future of marine capture fisheries. Philosophical Transactions of Royal Society of Biology 360: 21-46.

Knapp, G., C. Roheim and J.L. Anderson, 2007. The Great Salmon Run: Competition Between Wild and Farmed Salmon. TRAFFIC North America. Washington D.C.: World Wildlife Fund. 302p.

Meyers, R.A. and B. Worm, 2003. Rapid worldwide depletion of predatory fish communities. Nature 423: 280-283.

Naylor, R.L. and M. Burke, 2005. Aquaculture and Ocean resources: raising tigers of the sea. Annual Review of Environmental Resources 30: 185–218.

Naylor, R.L., J. Eagle and W.L. Smith, 2003. Salmon aquaculture in the Pacific Northwest - a global industry. Environment 45 (8): 18-39.

Pauly, D., V. Christensen, S. Guenette, T.J. Pitcher, U.R. Sumaila, C.J. Walters, R. Watson and D. Zeller, 2002. Towards sustainability in world fisheries. Nature 418 (6898): 689-695.

Sønvisen, S.A., 2003. Integrated Coastal Zone Management (ICZM): the Allocation of Space in Norwegian Aquaculture – from Local Lottery to Central Planning? Norwegain College of Fishery Science, University of Tromsø. 95p.

Tacon, A.G.J., M.R. Hasan and R.P. Subasinghe, 2006. Use of fishery resources as feed inputs for aquaculture development: trends and policy implications. FAO Fisheries Circular No.1018, Rome, FAO, 99p.

Tidwell, J.H. and G.L. Allan, 2001. Fish as food: aquaculture's contribution - Ecological and economic impacts and contributions of fish farming and capture fisheries, EMBO Rep. 2 (11): 958-963.

Tveterås, R. and A. Heshmati, 2002. Patterns of productivity growth in the Norwegian salmon farming industry. International Review of Economics and Business 3: 367-393.

Watson, R. and D. Pauly. 2001. Systematic distortions in world fisheries catch trends. Nature 414: 534-536.

Whitmarsh, D. and P. Wattage, 2006. Public attitudes towards the environmental impact of salmon aquaculture in Scotland. European Environment 16: 108-121.

Chapter 3 Estimating Pollution Abatement Costs of Salmon Aquaculture: A Joint Production Approach[7]

3.1 Introduction

Pollution is one of the environmental concerns associated with salmon aquaculture. Pollution involves uneaten feed, faeces and organic matter from salmon farms entering the marine environment. These are directly discharged into the marine environment because there are no solid and effective barriers between netcages and the surrounding environment. Pollution may potentially have negative impacts on sediments and water columns, on benthic communities and on some fishery resources (e.g., Milewski 2001; Levings *et al.* 2002; Brooks and Mahnken 2003; Naylor *et al.* 2003). For instance, pollution in the form of nitrogen and phosphorus may increase the risk of eutrophication, and alter species composition and phytoplankton density in the water column (NRE 2006). Pollution in the form of organic matter may change sediment chemistry, resulting in changes in sediment flora and fauna in affected areas (e.g., Mazzola *et al.* 2000; McGhie *et al.* 2000; Pohle *et al.* 2001).

Some impacts are measurable near-field changes in sediments and water variables that are sensitive to organic matter and nutrient additions, while some are far-field effects which are difficult to observe and measure, such as eutrophication and effects on food webs (Hargrave 2003). There is an extensive literature that documents these ecological and environmental impacts, especially in Europe, North America and Chile, where most farmed salmon are produced (e.g., Tlusty *et al.* 2000; Pohle *et al.* 2001; Levings *et al.* 2002; Brooks *et al.* 2003; Naylor *et al.* 2003). These negative impacts may be considered small at a large scale, but they can be very significant locally, especially in areas where salmon farms are concentrated.

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In the case of the Norwegian salmon aquaculture industry, pollution from fish farms together with discharge from households, industry, and agriculture have posed a potentially serious risk in coastal waters and fjords (NRE 2006). Fig. 3.1 shows that nitrogen and phosphorus from aquaculture have increased rapidly over the last two decades, and their contributions to the overall nitrogen and phosphorus production have become larger over time. Today, Norwegian aquaculture is the largest source of phosphorus, and the second largest source of nitrogen in the coastal areas of the country (NRE 2006). Although pollution has not increased at the same rate as the rapid growth of aquaculture production, it is still increasing.

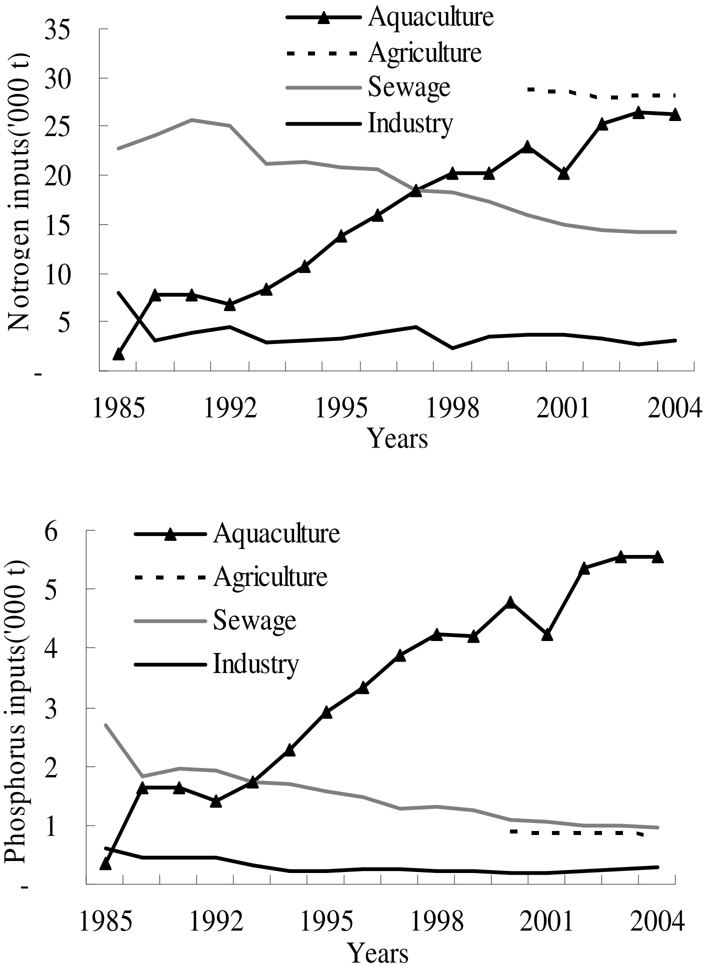

Figure 3.1. Nitrogen and phosphorus from Norwegian salmon aquaculture industry and other sources into the marine environment. (Data source: NRE 2006).

Recognizing the impacts of pollution on the environment and natural resources, salmon producers should bear the environmental costs of pollution according to the Polluter-Pays-Principle. The environmental costs can be determined either by the cost of damage caused by pollution to the environment and resource users, or by measuring abatement/prevention cost directly imposed on the production process. In most cases, the environmental costs estimated from these two approaches are not the same, especially in the case of weak environmental policies. However, due to the difficulty of directly estimating damage costs, this study focuses on pollution abatement cost, which is assumed to be a proxy for environmental cost.

A production process, such as salmon aquaculture, produces desirable or ‘good’ outputs (salmon) while simultaneously generating undesirable or ‘bad’ outputs (e.g., pollution). Bad outputs are the by-products of good outputs (i.e., good outputs cannot be produced without producing some bad outputs). Good outputs are generally marketable, while bad outputs are commonly unmarketable. In conventional production theory, the productivity and efficiency of a firm or an industry are generally measured based on good outputs. However, joint production approaches and models have been recognized and developed to incorporate bad outputs along with good outputs for measuring efficiency and productivity (e.g., Färe *et al.* 1989; Chung *et al.* 1997; Chambers *et al.* 1998; Färe *et al.* 2005 & 2007). The joint production approaches have several advantages compared to conventional production approaches. First, they can automatically capture two or more outputs, including multiple good and bad outputs. Second, the model does not require information on pollution abatement technology and its associated costs. Third, the model only requires quantitative data on inputs and outputs; no specific price data are needed (Färe *et al.*1989; Pasurka 2001; Färe *et al.* 2003).

In this study, production technology that constructs the joint production of good and bad outputs is specified based on the assumptions of strong and weak disposability for bad output. Strong disposability assumes that disposing bad outputs is free of charge, and it is viewed as unregulated technology. On the contrary, weak disposability assumes that disposing bad outputs is not free of charge, and it is viewed as regulated technology, which implies that producers face environmental regulations that limit their discarding of bad outputs, and have to engage in pollution abatement activities (Färe *et al.* 1989). Hence, abating pollution becomes a costly activity, and producers have to internalize pollution abatement cost into their production process.

The rest of the chapter is organized as follows. Section 2 presents the theoretical framework; Section 3 provides the data and describes an empirical application based on Norwegian salmon aquaculture; Section 4 reports the results; in Section 5 sensitivity analysis is conducted for some key parameters; Section 6 presents conclusions by summarizing the results, limitations of the study and suggestions for further research.

3.2 Theoretical Framework

Let us assume a production process that employs a vector of inputs $x \in R_+^n$ to yield a set of good outputs denoted by a vector $y \in R_+^m$, and bad outputs denoted by a vector $z \in R_+^j$. The technology (T) for the production process is represented by:

$$T = [(x, y, z): x \text{ can produce } (y, z)]$$

The technology illustrates all technically feasible relationships between inputs and outputs. For a given input vector x, the output set P(x) represents all feasible output vectors (y, z), that is:

$$P(x) = [(y, z) : (x, y, z) \in T]$$

The production possibility set P(x) illustrates the trade-offs between good and bad outputs along the production possibility frontier. Inputs and good outputs are assumed to be strongly disposable whereas bad outputs are weakly disposable. In other words, inputs and good outputs are assumed to be freely disposable, while bad outputs are disposed at a cost. Thus, the production possibility set P(x) is also an environmental output set (Färe *et al.* 2005 & 2007). The environmental production possibility set P(x) has the following properties:

i. $P(x)$ is convex and compact, $P(x) \in R_{+}^{n}$ and satisfies the condition of no free lunch. That is $P(0) = (0,0)$;

ii. Strong disposability of good output and of inputs: If $(y, z) \in P(x)$, then for $y' \leq y$, $(y', z) \in P(x)$, and for $x' \geq x$, $(y', z) \in P(x) \subseteq P(x')$;

iii. Null-jointness: If $(y, z) \in P(x)$ and $z = 0$, then $y = 0$;

iv. Weak disposability in good and bad outputs: If $(y, z) \in P(x)$, and $0 \leq \lambda \leq 1$, then $(\lambda y, \lambda z) \in P(x)$.

The first and second properties are standard assumptions in production theory (Shephard 1970). The first assumption implies that inactivity results in no outputs (i.e., no free lunch), and finite inputs produce finite outputs. The second assumption is strong disposability for good outputs and inputs implying that it is possible to freely dispose them (Färe *et al.* 1989, 2005 & 2007). The third assumption is null-jointness between good and bad outputs implying that if no bad outputs are produced, then good outputs will not be produced as well. The fourth assumption is weakly disposability of outputs implying that both good and bad outputs can be reduced. It is costly to reduce bad outputs because good outputs have to be reduced simultaneously in order to ensure that a new output vector $(\lambda y, \lambda z)$ is feasible (Färe *et al.* 1989, 2005 & 2007). The third and fourth assumptions are of special interest to this study. However, the last two assumptions can not hold with the second assumption at the same time. The reason why they cannot hold will be explained in Figure 3.2.

The environmental output set is illustrated in Figure 3.2. The production possibility frontier $P(x)$ is constructed from observations given input level x. The points A and B represent the combinations of good and bad outputs given a set of input (x). Since non-parametric linear programming methods are used to measure production efficiency, the production possibility frontier $P(x)$ is piecewise linear. The environmental output set is bounded by the piecewise linear segments *OABC*.

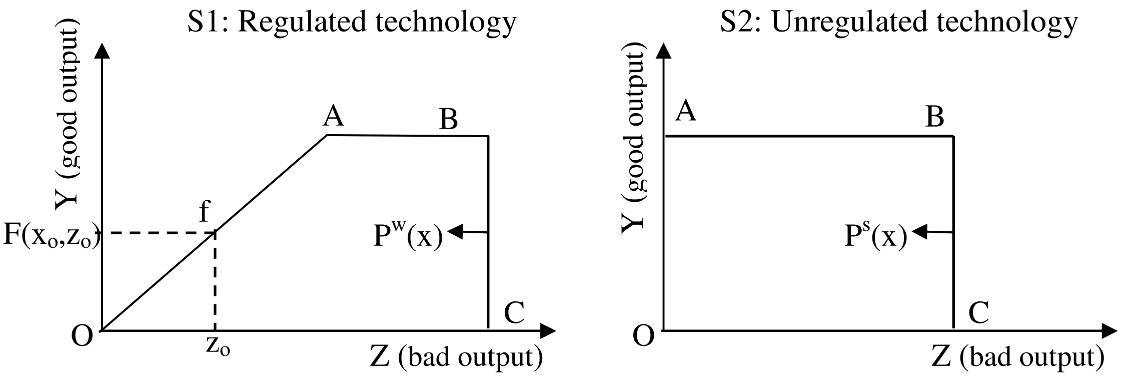

Figure 3.2. Environmental output sets. S1: regulated technology; S2: unregulated technology. (modified from Fare *et al.* 2005)

The output set *OABC* satisfies assumptions (i – iv*)*. However, if bad output is assumed to be as strongly disposable as good output, assumption iii, i.e., the null-jointness, is violated (Färe *et al.* 2005). In other words, the assumption of strong disposability for bad output abuses the physical relationship between good outputs and bad outputs. This assumption is plausible because it indicates that producers will not pay the cost of disposing bad outputs in the absence of regulations. Instead, there is a real possibility of breaking the physical relationship between good and bad outputs (Färe *et al.* 2005; Picazo-Tadeo *et al.* 2005). When environmental regulations are imposed on firms or farms, disposing bad outputs becomes a costly activity (Färe *et al.* 1989). Hence, if bad outputs are free disposal, it means that they are unregulated by the society. The positively-sloped portion (Figure 3.2 S1) implies that increasing good output production is accompanied by increasing bad output production. The vertical line segment (Figure 3.2 S1, S2) can occur when bad outputs are strongly disposable. In the case of salmon aquaculture, pollution increases when salmon production grows, everything being equal.

Based on these assumptions about inputs and outputs, a joint production approach is developed to model both good and bad outputs. It is assumed that producers attempt to maximize good outputs and minimize bad outputs if there is an environmental regulation implemented. I specify two production models with different mapping rules for outputs, known as (i) environmental production functions (EPF); and (ii) directional distance output functions (DDOF). These two models serve as the functional representation of environmental production technology. EPF is constructed for solely maximizing good output and keeping bad outputs constant in a directional vector (e.g., Färe *et al.* 2007). DDOF is formed for expanding good outputs and contracting bad outputs in a directional vector (e.g., Chung *et al.* 1997; Picazo-Tadeo *et al.* 2005; Färe *et al.* 2005 & 2007). Both models are additive, and their expansion and/or contraction take place in a directional vector. EPF is a special case of DDOF.

3.2.1 Environmental Production Function

Like traditional production functions, given the vectors of inputs and bad outputs (x, z), an environmental production possibility frontier is defined as $F(x, z)$ and constructed based on observations. I assume that $F(x, z)$ is the bounded line segments *OABC* in Figure 4.2. S1. The maximum amount of good outputs can be produced based on the production possibility frontier $F(x, z)$. Given a set of inputs and bad outputs (x^0, z^0), the maximum feasible production of good outputs is defined as $F(x^0, z^0)$. Because good outputs can be freely disposed, y is feasible if $y \leq F(x, z)$. Then, the environmental production set is defined as $P(x) = \{(y, z): y \leq F(x, z)\}$. Hence, an environmental production function is "a complete characterization of the single output environmental technology" (Fare *et al.* 2007).

There are parametric and non-parametric methods of specifying production models. The parametric method specifies a mathematical equation for a production model, for example, a quadratic function for directional distance function (e.g., Fare *et al.* 2005; Vardanyan and Noh 2006). The non-parametric method uses data envelopment analysis (DEA) technique to measure the efficiency performance of producers. DEA uses linear programming (LP) techniques that first identify the theoretically best producers based on observed data (e.g., inputs and outputs). Then, a production possibility frontier is constructed as a piecewise linear envelope of all observed outputs and inputs. The producers on the frontier are assumed to operate efficiently. Producers who are not on the frontier are regarded as inefficient. The production level due to inefficiency is calculated by comparing the performance of each producer to the best producer. Non-parametric methods have advantages over parametric methods because they can incorporate several inputs and outputs without generating different estimates. It should be noted that parametric methods (e.g., translog *vs* quadratic models) may produce different estimates. Further, they can be performed with limited datasets, and they also avoid the biases brought about by different parametric models (Fare *et al.* 1989). Therefore, in this study, a non-parametric method is adopted.

Assuming there are a sample of $k = 1 \ldots K$ producers employing a vector of inputs x_n^k, n = 1…N to obtain a vector of good output y_m^k, m =1…M, and a vector of bad outputs z_j^k, j = 1…J, θ is the maximum output that producers intend to increase. The environmental production function on the production technology T is then defined by

$$F(x, y, z; \theta) = \max[\theta : (y + \theta, z) \in P(x)] \tag{3.1}$$

Let g denote a directional vector, $g = (g_y)$ for good outputs. Where $g_y \in R_+^m$, and $g_m \neq 0$. EPF on the production technology T is defined by

$$\vec{D}_T(x, y, z; g_y) = \max_{\beta}[\theta : (y + \theta g_y, z) \in P(x)] \tag{3.2}$$

The objective function of EPF is to maximize good output by increasing quantity θ in the directional vector g_y given inputs and bad outputs. When bad outputs are unregulated, the objective function for observation k' is written as:

$$Fu(x^{k'}, y^{k'}, z^{k'}; g_y) = \max \theta^{k'} \tag{3.3.1}$$

Subject to

$$\sum_{n=1}^{N} \alpha_k x_n^k \leq x_n^{k'} \tag{i}$$

$$\sum_{m=1}^{M} \alpha_k y_m^k \geq \theta^{k'} g_y^m + y_m^{k'} \tag{ii}$$

$$\sum_{j=1}^{J} \alpha_k z_j^k \geq z_j^{k'} \tag{iii}$$

Where $x_n, y_m, z_j, \alpha_k, \theta \geq 0$, α_k are the intensity variables, which are weights assigned to each observation when constructing the production frontier. These intensity variables map out the efficient frontier. Observations on the frontier are considered efficient, while those not on the frontier are considered inefficient. Since α_k is nonnegative, constant returns to scale is imposed.

When bad outputs are regulated, the objective function for observation k' is written as

$$F(x^{k'}, y^{k'}, z^{k'}; g_y) = \max \theta^{k'} \tag{3.3.2}$$

Subject to

$$\sum_{n=1}^{N} \alpha_k x_n^k \leq x_n^{k'} \tag{i}$$

$$\sum_{m=1}^{M} \alpha_k y_m^k \geq \theta^{k'} g_y^m + y_m^{k'} \tag{ii}$$

$$\sum_{j=1}^{J} \alpha_k z_j^k = z_j^{k'} \tag{iii}$$

Where $x_n, y_m, z_j, \alpha_k, \theta$ and α_k are defined above. The right hand side of the constraints of LP problems represents the actual amounts of inputs or outputs employed or produced, while the left hand side of the constraints represents the amount of inputs or outputs used or produced by the most efficient or best producers. It should be noted that the signs of the constraints for bad outputs in two equations are different. In the 3rd constraint equation above (Eqs. iii-1 and iii-2), the equality sign means that bad outputs are weakly disposable under regulated technology, i.e., the observed amount of bad outputs equals the amount of bad outputs produced by the most efficient producers, while the inequality sign means bad outputs are strongly disposable under unregulated technology, i.e., the observed amount of bad outputs equals or is less than the amount of bad outputs produced by the most efficient producers.

3.2.2 Directional Distance Output Function

Directional distance output function (DDOF) has the quality that it can allow the expansion of good output and contraction of bad output at the same time. Let *g* denote a directional vector, $g = (g_y, -g_z)$, for good and bad outputs. Where $g_y \in R_+^m$, $g_z \in R_+^j$, and $g_{m+j} \neq 0$. DDOF on the production technology *T* is then defined by

$$\vec{D}_T(x, y, z; g_y, -g_z) = \max_{\beta}[\beta : (y + \beta g_y, z - \beta g_z) \in P(x)] \tag{3.4}$$

where β is the maximum attainable expansion of good output along the $+g_y$ direction, and largest feasible contraction of bad output along the $-g_z$ direction vector. Applying the same principles for strong and weak disposability for bad outputs as in EPF, DDOF under unregulated and regulated production technologies are written as:

The objective function under unregulated technology is:

$$\vec{D}_U(x^{k'}, y^{k'}, z^{k'}; g_y, -g_z) = \max \beta^{k'} \tag{3.5.1}$$

Subject to

$$\sum_{n=1}^{N} \alpha_k x_n^k \leq x_n^{k'} \tag{i}$$

$$\sum_{m=1}^{M} \alpha_k y_m^k \geq y_m^{k'} + \beta^{k'} g_y^m \tag{ii}$$

$$\sum_{j=1}^{J} \alpha_k z_j^k \geq z_j^{k'} - \beta^{k'} g_z^j \tag{iii}$$

The objective function under regulated technology is:

$$\vec{D}(x^{k'}, y^{k'}, z^{k'}; g_y, -g_z) = \max \beta^{k'} \tag{3.5.2}$$

Subject to

$$\sum_{n=1}^{N} \alpha_k x_n^k \leq x_n^{k'} \tag{i}$$

$$\sum_{m=1}^{M} \alpha_k y_m^k \geq y_m^{k'} + \beta^{k'} g_y^m \tag{ii}$$

$$\sum_{j=1}^{J} \alpha_k z_j^k = z_j^{k'} - \beta^{k'} g_z^j \tag{iii}$$

where, $x_n, y_m, z_j, \alpha_k, \beta \geq 0$, a_k, the input and output constraints are defined as in the case of environmental production function.

3.2.3 Pollution Abatement Costs

When bad outputs are not regulated, their disposal is free of charge for producers, and all inputs are used for producing good outputs. When environmental regulations are imposed, disposing bad outputs (pollution) becomes a costly activity because producers have to take away resources from producing good outputs to reduce/abate bad outputs. In other words, the inputs that are used to produce good outputs have to be diverted for cleaning/abating bad outputs. The reduction in bad output production comes at the cost in the form of a reduction in good output production. Hence, the cost of environmental regulation is described as pollution abatement cost (PAC), which is the lost good output related to pollution abatement activity to producers. Pollution abatement cost is also the opportunity cost of the regulation (Färe *et al.* 2005 & 2007). It is seen from the private producer's perspective, and measured by the difference of the forgone good outputs under unregulated and regulated technologies. Therefore, pollution abatement costs under two production functions are expressed as follows:

(i) environmental production function:

$$PAC = Fu(x^{k'}, y^{k'}; z^{k'}; g_y) - F(x^{k'}, y^{k'};, z^{k'}; g_y) \tag{3.6.1}$$

(ii) directional distance output function:

$$PAC = Du(x^{k'}, y^{k'}; z^{k'}; g_y, -g_z) - D(x^{k'}, y^{k'};, z^{k'}; g_y, -g_z) \tag{3.6.2}$$

Where $Fu(x^{k'}, y^{k'}; z^{k'}; g_y)$, $F(x^{k'}, y^{k'};, z^{k'}; g_y)$, $Du(x^{k'}, y^{k'}; z^{k'}; g_y, -g_z)$ and $D(x^{k'}, y^{k'};, z^{k'}; g_y, -g_z)$ are defined earlier.

It should be noted that these production models are usually used to measure technical inefficiency of producers. Given input vectors, technical inefficiency measures are determined by the ratio of actual good output to maximum potential good output. If observed data points lie on the frontier, producers are defined to be efficient, otherwise they are inefficient. The magnitude of technical inefficiency measures the distance between observed data points and the production possibility frontier.

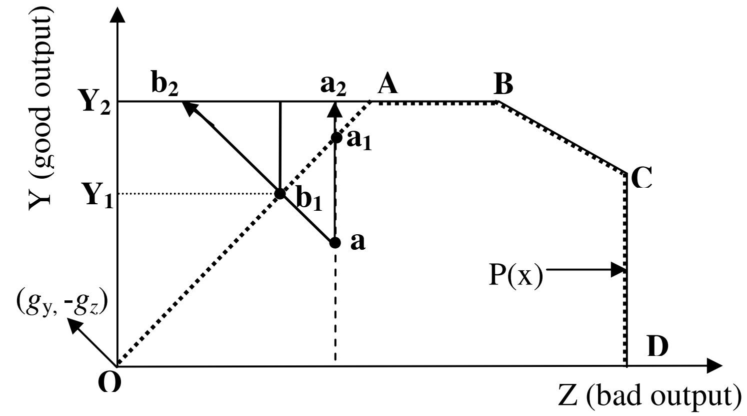

Figure 3.3. Illustration of environmental production and output distance functions.

Figure 3.3 illustrates an environmental production function and a directional distance output function. Points *A, B* and *C* are on the frontier *P*(*x*) and are efficient. Point *a* operates inside the frontier and is inefficient. Any point on or inside *P*(*x*) can be expanded and/or contracted in both (y, z). For instance, in the case of the environmental production function, keeping bad output unchanged, the producer operating at point *a* can expand its good output from *a* to a_1 with regulated technology or from *a* to a_2 with unregulated technology. Under the directional distance output function model, the producer can increase its good output and decrease bad output by moving from *a* to b_1 with regulated technology or from *a* to b_2 with unregulated technology.

Thus, pollution abatement costs can be determined by the difference between the maximum good output production associated with unregulated and regulated production technologies, or they can be determined on the loss of good output production related to technical inefficiency (Färe *et al.* 2007). As can be seen in Figure 3.3, if the environmental production function model is used, the lost output due to inefficiency is the distance between *a* and a_1 under regulated technology and between *a* and a_2 under unregulated technology; the PAC is the distance between a_1 and a_2. If the directional distance output production function is used, the lost output due to inefficiency is the distance between *a* and b_1 under regulated technology and between *a* and b_2 under unregulated technology; the pollution abatement cost is the vertical distance between b_1 and b_2, i.e., the distance between Y_1 and Y_2. Since farmed salmon are sold in the market, the potential revenue losses are calculated using average yearly market prices and potential output production losses. Therefore, pollution abatement costs also can be determined by the potential revenue losses.

3.2.4 Directional Vector

Before conducting the programming, I need to specify the directional vector $g(g_y)$ and $g(g_y, g_z)$ for the EPF and DDOF models, respectively. I choose the directional vector $g = (g_y, -g_z) = (1,0)$ for the EPF model, and $g = (g_y, -g_z) = (1,-1)$ for the DDOF model. The reason for choosing the unity directional vectors ($g_y = 1$ and $g_z = 1$) is that the unity directional vectors indicate the ‘shortest’ distance when ‘optimizing over the direction’ to reach the production frontier (Färe and Grosskopf 2000). In other words, the estimates from the two models give the maximum unit expansion in good output production and simultaneous unit contraction in bad output production. I test the effects of using different directional vectors on the pollution abatement costs in sensitivity analysis. Linear programming is used to solve the maximization problem for each functional form. The computer software General Algebraic Modeling System (GAMS) is used to perform the calculation. GAMS is a high-level modeling system for mathematical programming and optimization (GAMS[8]). The optimal solutions are achieved for unregulated and regulated production technologies for two production models based on explicitly differentiating the assumptions on the constraints regarding inputs and outputs, in particular, the constraints due to bad outputs.

3.3 The Data

Since Norway has widely-available ecological and economic data related to salmon aquaculture, I use the Norwegian salmon aquaculture industry as my empirical application of the joint production models proposed herein. Norway is the pioneer in salmon aquaculture development and production. The country has been the number one farmed salmon producer in the world since the beginning of salmon farming. However, due to the lack of farm-level data, I consider salmon aquaculture as a whole and use the data collected at an aggregated industry level on an annual basis.

In this analysis salmon aquaculture operation needs four inputs (feed, smolt, labour and capital) to produce one good output (salmon production) and two bad outputs (nitrogen and phosphorus). The quantities of salmon production and inputs are extracted from Statistics Norway and the Fisheries Directorate Norway (www.ssb.no), whereas the quantities of nitrogen and phosphorus were estimated by the Norwegian Institute for Water Research (NIVA 2005) and compiled by Natural Resource and Environment Norway (NRE 2006). Several methods are used to quantify nitrogen and phosphorus from aquaculture. The

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[8] More information about GAMS can be found at http://www.gams.com/

production parameters, such as production, feed used, nitrogen and phosphorus contents in feed and farmed salmon, treatment yield, wastewater volume, nitrogen and phosphorus concentration of samples and number of sampling periods are used for these calculations, and the detailed information can be found in OSPAR (2004). The data set ranges from 1986 to 2005, and is summarized in Table 3.1. Since both the environmental production function and directional distance output function are additive models, the measurement unit and magnitude of inputs and outputs may affect the results (Picazo-Tadeo *et al*. 2005; Färe *et al*. 2007). To avoid these problems, I scale all inputs and outputs into fractions by dividing these by their respective maximum values in the samples of inputs and outputs. In other words, the values of all the inputs and outputs are normalized between 0 and 1. However, I also run the models without normalizing the data, and it turns out the results from both analyses are the same.

Table 3.1. Summary Statistics for the Norwegian Salmon Aquaculture, 1985 - 2005.

		Units	Minimum	Mean	Maximum
Good output	Production	tonnes in thousands	44.9	286.1	582.2
Bad output	Phosphorus	tonnes in thousands	0.7	3.1	6.1
	Nitrogen	tonnes in thousands	2.5	13.7	27.3
Input	Feed	tonnes in thousands	87.3	357.4	727.6
	Labor	man-hours in millions	3.0	3.9	4.9
	Smolt	numbers in millions	27.3	96.0	160.2
	Capital	NOKs in millions	402.7	1,723.8	2,147.3

The lost good output associated with technical inefficiency is estimated for the EPF and DDOF models using the same data set. The pollution abatement costs are simply the difference between the lost good outputs resulting from technical inefficiency for unregulated and regulated production technologies. By multiplying by the price of good output, i.e. farmgate price, the losses of good outputs in terms of revenue are calculated. Hence, the pollution abatement costs are expressed in both lost production and revenue of the good output.

3.4 Results and Discussions

Table 3.2 shows the results. On average, pollution abatement costs expressed in terms of lost production and revenue are about 10.3 thousand tonnes and 472 million NOKs, respectively, over the 20 years. These comprise 3.5% and 6.5% of total farmed salmon production and revenue, respectively. On average, the PACs estimated, based on the DDOF and EPF models, are about 12.1 and 8.2 thousand tonnes, which corresponds to about 4.2%, and 2.9% of total salmon production, respectively. In terms of revenue, the costs are around 544 and 400 million NOKs, which work out to about 7.5% and 5.5% of total revenues, respectively. Out of a total of 20 observations, 8 in the DDOF model, and 10 in the EPF model do not incur pollution abatement costs. Considering that salmon producers make very low profit margins currently, these PAC estimates are quite large. If these PAC estimates are internalized into producers' production processes, the profit margins may disappear.

Table 3.2. Average pollution abatement costs associated with the two production models.

	Production		Revenue		# of years
Model	000 t	% of total	million NOK	% of total	with PAC=0
Environmental production function	8.16	2.85	400	5.53	10
Directional distance output function	12.09	4.23	544	7.52	8
Average	10.13	3.54	472	6.53	9

Without environmental regulations, farmed salmon could be increased by 3.5% in terms of tonnes of salmon production and 6.5% in terms of revenues. However, such increases in good output production will be accompanied by simultaneous increases in bad output production. This implies that these pollution abatement costs reflect trade-offs between good and bad outputs (Table 3.2).

It should be noted that pollution abatement costs show a wide variation depending on years (or producers) and production models (Figure 3.4). Over the years, PAC has shown a decreasing trend. This is because salmon aquaculture operation is getting more efficient due to the improvement of feed formulation and feeding technology, and husbandry management (Bjørndal *et al.* 2002). However, in some years PAC increased unexpectedly. For instance, in 1989, 1994 and 2002, PACs were much higher than their respective adjacent years (Fig. 3.4). These sudden increases in PACs may be caused by different factors, such as investment in production, market conditions, regulatory changes, or biophysical shocks (e.g., disease outbreak and accidents). Tveretås (1999) and Tveretås and Heshmati (2002) indicated that these factors might result in technical changes from year to year. For instance, in 1989, *Furunculosis*, a bacterial disease, became endemic in Norway, hitting the salmon aquaculture industry hard, with 189 salmon farms and wild salmon populations in 18 rivers affected (Johnsen and Jensen 1994).

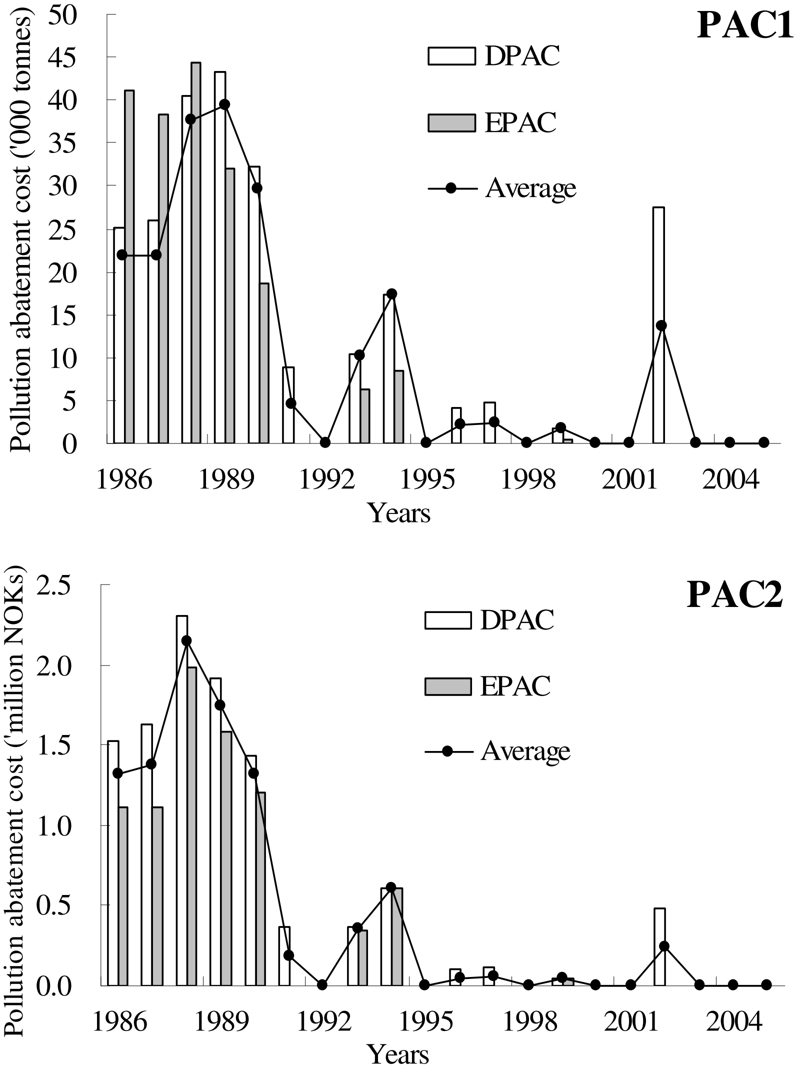

Figure 3.4. Pollution abatement costs for two production models. PAC1: PAC is expressed in terms of lost production; PAC2: PAC is expressed in terms of lost revenue. EPAC: Environmental production function; DPAC: Directional distance output function.

Between DDOF and EPF models, the former estimates higher pollution abatement cost than the latter. This is because different mapping rules for bad outputs are applied in these two models. DDOF increases good output and decreases bad outputs in a directional vector; EPF only increases good output and keeps bad outputs unchanged. In the DDOF model, some inputs have to be diverted to reduce bad outputs, while all inputs are used to increase good outputs in the EPF model.

Since pollution abatement costs are estimated based on technical inefficiency, I herein show the production losses under unregulated and regulated technologies for two models due to technical inefficiency. Under unregulated technology, the levels of production losses for the two models are very close. Under regulated technology, the level of production losses is very low in the DDOF model, while it is much higher in the EPF model. This result is consistent with the belief that salmon aquaculture operations attempt to increase their production and decrease pollution (Figure 3.5). This implies that producers who must increase good output and decrease bad output can be regarded as more technically efficient.

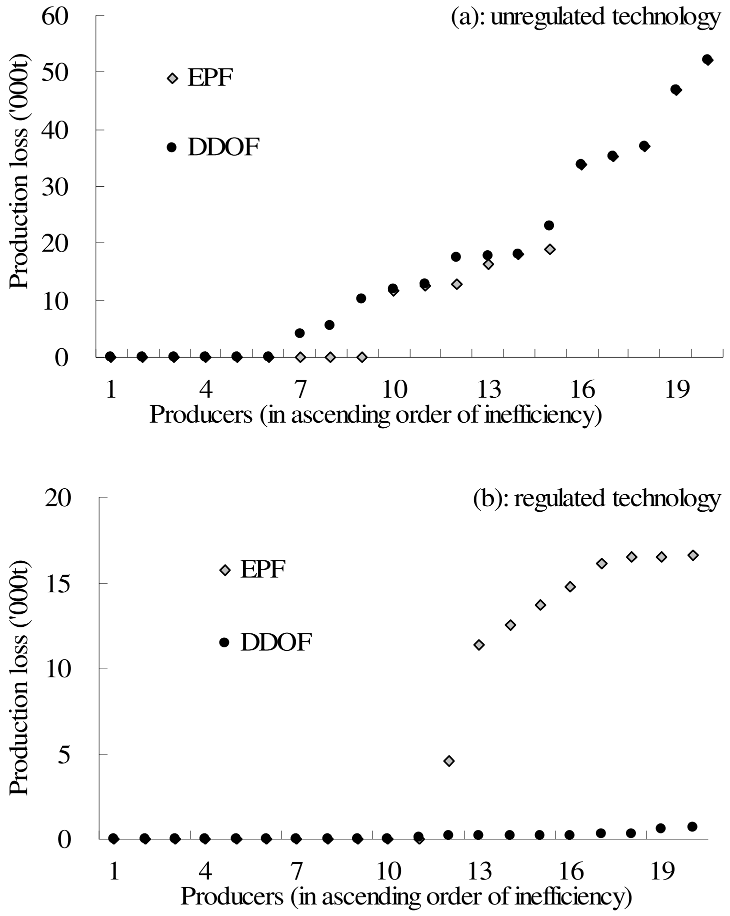

Figure 3.5. Production loss due to technical inefficiency. (a): unregulated technology; and (b): regulated technology. EPF: environmental production function; DDOF: directional distance output function.

3.5 Sensitivity Analysis

As the mapping rules for directional vectors have impacts on the estimated pollution abatement cost (e.g., Vardanyan and Noh 2006), a variety of mapping rules are applied for the two directional models – EPF and DDOF. First, it is assumed that the directional vector for bad outputs remains constant set equal to 1, and the directional vector for good output is assumed to gradually increase from a scale of 1 to 10. The results show that the estimated PACs fall with increasing directional vector for good output. This is to be expected because more inputs have to be diverted to producing good outputs. The magnitude of the decline gets smaller as the directional vector for good output gets bigger. This is the case in both models.

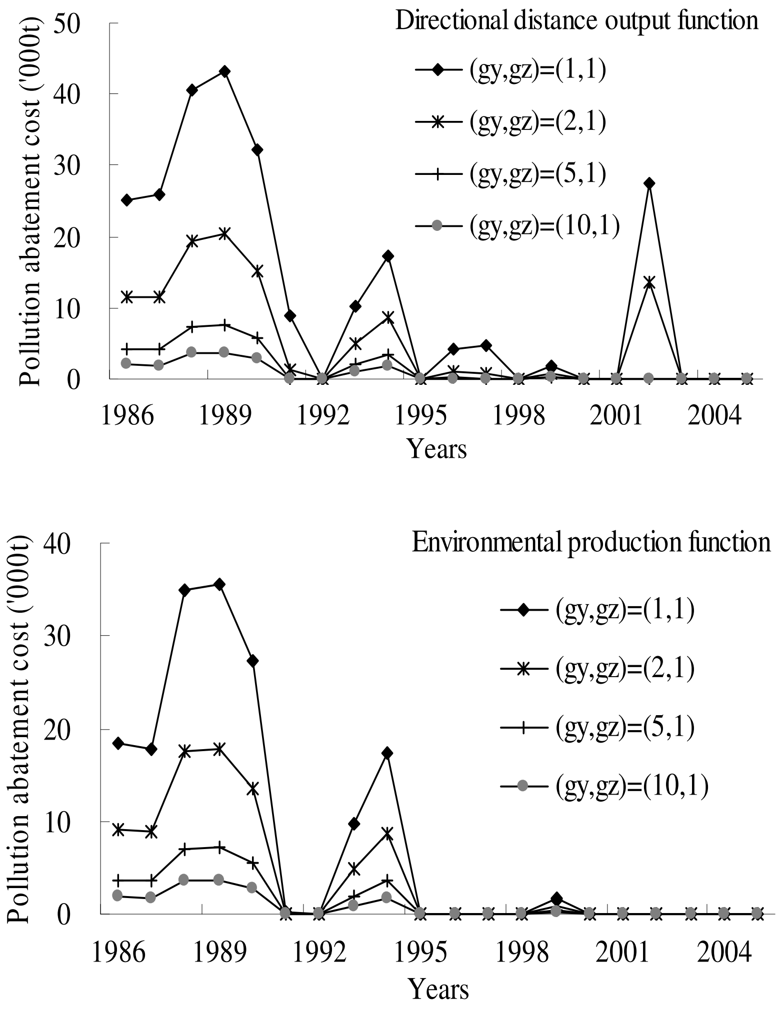

Figure 3.6. Estimated pollution abatement cost for various mapping rules. The figure on the top is directional distance output function; the figure on the bottom is environmental production function.

Second, it is assumed that regulations have no effects on input factors. Within a production process, assuming inputs are all used to produce good output when bad outputs are unregulated, some inputs have to be allocated for pollution abatement activity when bad output is regulated. However, in some cases, inputs do change depending on the resource, economy and time. For instance, the use of feed has gradually reduced with the improvement of feed formulation and feeding technology. Thus, I test the effect on PAC under an assumption of expanding good output and reducing input uses. Here, I use the DDOF to illustrate these effects on PACs. Two scenarios are performed: i) increasing good output while reducing inputs and bad outputs simultaneously $g(-g_x,+g_y,-g_z)$ = (-1,1,-1); and

ii) increasing good output while reducing inputs and keeping bad outputs constant $g(-g_x, +g_y, -g_z) = (-1,1,0)$. The results are compared with the base scenario $g(+g_y, -g_z) = (1,-1)$.

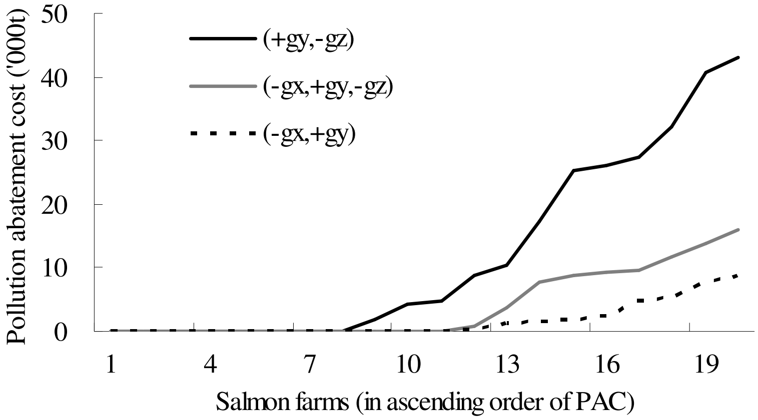

Figure 3.7. Pollution abatement costs under different mapping rules for inputs and outputs.

In Fig. 3.7, it is found that PACs decline when inputs are reduced. This indicates that directly reducing inputs may be more resource efficient than directly reducing bad outputs because pollution is reduced at source in the former case. This result may provide producers and policy makers a useful insight for formulating environmental regulations. As in the case of salmon aquaculture, it is difficult to mitigate pollution once it is discharged into the environment. This is because pollution is directly dispersed into the open ocean, given current open netcage technology. Since feed is the key input factor in contributing waste discharges, controlling feed input may be the most efficient means to regulate pollution discharges for salmon aquaculture. For instant, a feed quota program has been established in Norway since 1995. The aim of the program is to control production through controlling feed (Hjelt 2000).

3.6 Conclusions

In this study, I develop a joint production function to model both good and bad outputs from salmon aquaculture industry. This allows me to calculate pollution abatement costs from a production process and from a private producer's perspective. Two production models, environmental production function and directional distance output function are applied. Good and bad outputs are treated in an asymmetrical way in the models.

Environmental production function only maximizes good outputs and keeps bad outputs constant. Both models are appropriate in the case of salmon aquaculture because some producers are compelled to reduce bad output (pollution) such as producers in Norway, while some are not such as producers in Chile. Directional distance output function expands good outputs and contracts bad outputs. The analyses are conducted based on the assumptions of strong and weak disposability for bad outputs. Thus, unregulated and regulated production technologies are specified. The analyses are carried out on the Norwegian salmon aquaculture industry. One good output (salmon), two bad outputs (nitrogen and phosphorus), and four inputs (feed, smolt, labor and capital) are included in the analyses. The data are aggregated at the industry level, and range for a period of 20 years from 1986 to 2005. I choose a non-parametric approach to solve the maximization problem that this analysis entails. Pollution abatement costs are calculated by determining the difference between the foregone good outputs using two technologies.

Although pollution abatement cost is estimated based on a production process from a producer's perspective, it can be viewed as the costs of pollution damage on the environment and resource users. Some may argue that the damage costs estimated in this approach may be underestimated. The producers who fail to implement environmental regulations in their production decision making should be penalized. The level of penalty can be set based on the estimates of pollution abatement costs. Further, pollution abatement costs can be used as reference points to set pollution taxes that can be imposed on producers or consumers. To the best of my knowledge, this study is the first attempt to use a joint production function approach, especially directional distance output function to estimate pollution abatement costs for aquaculture, in general, and salmon aquaculture, in particular, although a joint production model has been applied earlier to estimate productivity and technical efficiency for shrimp farming in Mexico (Martinez-Cordero and Leung 2004).

The estimated pollution abatement costs are closely dependent on the model forms used. Environmental production function and directional distance output function are all joint production models, but they have different mapping rules. Joint production models, especially directional distance output function model, have gained growing interest and become the most favorite model because of its flexibility of mapping rules and clear connection to traditional production functions (e.g., Chung *et al.* 1997; Chambers *et al.* 1998; Pasurka 2001; Färe *et al.* 2005 & 2007; Verdanyan and Noh 2006). The directional distance output function model has been used to estimate shadow prices (e.g., Färe *et al.* 2006), productivities (e.g., Chung *et al.* 1997), and pollution abatement costs (e.g., Färe *et al.* 2007; Pasurka 2001; Verdanyan and Noh 2006). Further, joint production models can be used to test the economic effects of different environmental policies on different sectors (e.g., Brännlund *et al.* 1995). For instance, if the government sets a pollution level as a reduction target, we can use joint production models to test how much production, revenue or profit producers have to give up in order to meet the target. In this study, the directional distance output function is more appropriate because it fits better the goal of producers and policy makers: increasing good output and reducing bad outputs.

It should be noted that this joint production approach provides a framework to measure pollution abatement costs through technical inefficiency across farms and years. This study explores these costs for different years due to data constraints at the farm level. Ideally, a cross-sectional panel data of salmon farms is more appropriate than using a time series of data aggregated from all the salmon farms. However, in the case of salmon aquaculture, it is impossible to get such a cross-sectional panel data. Pollution abatement costs based on a time series data may be underestimated like demonstrated in Pasurka (2001). Due to data limitation, I have assumed no technical changes over 20 years, which is clearly strong assumption. However, I believe that technical changes have been incorporated into production process, such as input and output factors.

Overall, the Norwegian salmon aquaculture industry is getting more efficient over the years, in particular during the last several years, although technical efficiency and pollution abatement costs greatly differ among years. Clearly, some years are more efficient than others, and *vice versa*. This comparative difference provides a basis for future study about why some years are generally more efficient than others. In addition, these differences may reveal a pattern of variation by various factors, such as production techniques, farm characteristics, environmental regulations, market conditions, and biophysical shocks (e.g., disease outbreaks).

I assume that salmon aquaculture operates under certain forms of regulatory constraints. This means that salmon producers in Norway have engaged in pollution abatement activity. This assumption is appropriate because in fact there are some regulatory frameworks proposed and implemented for salmon aquaculture industry. It is particularly true for the Norwegian salmon aquaculture. For instance, Norway has implemented a number of regulations, such as limitations on production level, farm size, and fish density, and feed quota (Hjelt 2000; Maroni 2000). Feed is the key factor that contributes to pollution. Feed formulation and feeding technology have been greatly improved over the years. For instance, feed conversion ratio, a measure of a fish's efficiency in converting feed into increased body weight, has been greatly reduced from around 4.0 in the 1980s to about 1.2 at present (Asche *et al.* 1999; Bjørndal *et al.* 2002; Tveretås 2002). Moreover, feeding technology has improved from hand feeding to automatic feeders (Bjørndal *et al.* 2002).

Given current production technology and environmental regulations, if pollution is to be reduced, salmon production has to be reduced simultaneously. In particular, salmon farms which are clustered in some areas have to be closed down partially or fully. This has already happened in the North Sea. The North Sea Agreement declares that the pollution level in the North Sea has to be reduced to the level in 1985 for all production sectors and households in all the countries bordering the North Sea. In order to meet the target, Norwegian fish farming facilities have been prohibited in the North Sea region since 1997 (NRE 2006).

3.7 References

Asche, F., A. Guttormsen and R. Tveterås, 1999. Environmental problems, productivity and innovations in Norwegian salmon aquaculture. Aquaculture Economics and Management 3(1): 19-29.

Bjørndal, T., R. Tveterås and F. Asche, 2002. The development of salmon and trout aquaculture. In Paquotte, P., Mariojouls. C. and J. Young (Eds): Seafood Market Studies for the Introduction of New Aquaculture Products. Cahiers Options Méditerranéennes 59: 101-115.

Brooks, K.M., A.R. Stierns, C.V.W. Mahnken and D.B. Blackburn, 2003. Chemical and biological remediation of the benthos near Atlantic salmon farms. Aquaculture 219(1-4): 355-77.

Brooks, K.M. and C.V.W. Mahnken, 2003. Interactions of Atlantic salmon in the Pacific Northwest environment II. Organic wastes. Fisheries Research 62(3): 255-93.

Brännlund, R, R. Färe and S. Grosslope, 1995. Environmental regulation and profitability: an application to Swedish pulp and paper mills. Environmental and Resource Economics 6: 23-36.

Chambers, R.G., Y. Chung and R. Färe, 1998. Profit, directional distance functions and Nerlovian efficiency. Journal of Optimization Theory and Applications 98(2): 351-364.

Chung, Y.H., R. Färe and S. Grosskopf, 1997. Productivity and undesirable outputs: a directional distance function approach. Journal of Environmental Management 51(3): 229-240.

Färe, R., S. Grosskopf and W. Weber, 2006. Shadow prices and pollution costs in U.S. agriculture. Ecological Economics 56: 89-103.

Färe, R., S. Grosskopf, C.A.K. Lovell and C. Pasurka, 1989 Multilateral productivity comparisons when some outputs are undesirable. Review of Economics and Statistics 71: 90-98.

Färe, R. and S. Grosskopf, 2000. Theory and application of directional distance functions. Journal of Productivity Analysis 13(2): 93-103.

Färe, R., S. Grosskopf, D.W. Noh and W. Weber, 2005. Characteristics of a pollution technology: theory and practice. Journal of Econometrics 126: 469-492.

Färe, R., S. Grosskopf and C. Pasurka, 2003. Estimating Pollution abatement Costs: A Comparison of 'Stated' and 'Revealed' Approaches. http://ssrn.com/abstract=358700

Färe, R., S. Grosskopf, and C.A. Jr. Pasurka, 2007. Environmental production functions and environmental directional distance functions. Energy 32: 1055-1066.

Hargrave, B.T., 2003. Far-Field Environmental Effects of Marine Finfish Aquaculture. A Scientific Review of the Potential Environmental Effects of Aquaculture in Aquatic Ecosystems. Canadian Technical Report Fisheries Aquatic Science 1, Fisheries and Oceans Canada, 3-11.

Hjelt, K.A., 2000. The Norwegian regulation system and the history of the Norwegian salmon farming industry. In Liao, C.I and C. Kwei (Eds): Cage Aquaculture in Asia: Proceedings of the First International Symposium on Cage Aquaculture in Asia. Asian Fisheries Society, Quezon City, Philippines.1-17p.

Johnsen, B.O. and A.J. Jensen 1994. The spread of furunculosis in salmonids in Norwegian rivers. Journal of Fish Biology 45:47-55.

Levings, C.D., J.M. Helfield, D.J. Stucchi and T.F. Sutherland, 2002. A Perspective on the Use of Performance Based Standards to Assist in Fish Habitat Management on the Seafloor near Salmon Net Pen Operations in British Columbia. Department of Fisheries and Ocean, Vancouver, Canada, 59p.

Maroni, K., 2000. Monitoring and regulation of marine aquaculture in Norway. Journal of Applied Ichthyology 16: 192-195.

Martinez-Cordero, F.J. and P.S. Leung, 2004. Sustainable aquaculture and producer performance: measurement of environmentally adjusted productivity and efficiency of a sample of shrimp farms in Mexico. Aquaculture 241: 249-268.

Mazzola, A., S. Mirto, T. La Rosa, M. Fabiano and R. Danovaro, 2000. Fish-farming effects on benthic community structure in coastal sediments: analysis of meiofaunal recovery. ICES Journal of Marine Science 57(5): 1454-61.

McGhie, T.K., C.M. Crawford, I.M. Mitchell and D. O'Brien, 2000. The degradation of fish-cage waste in sediments during fallowing. Aquaculture 187(3-4): 351-66.

Milewski, I., 2001. Impacts of salmon aquaculture on the coastal environment: a review. In M. F. Tlusty, D.A. Bengston, H.O. Halvorson, S.D. Oktay, J.B. Pearce and J.R.B. Rheault (Eds), Marine Aquaculture and the Environment: A Meeting for Stakeholders in the Northeast. Falmouth, Massachusetts, Cape Cod Press, 35p.

NRE, 2006. Natural Resource and the Environment, Statistics Norway. http://www.ssb.no/english/subjects/01/. Access Feb., 2007.

Naylor, R.L., J. Eagle and W.L. Smith, 2003. Salmon aquaculture in the Pacific Northwest - a global industry. Environment 45(8): 19-39.

Pasurka, C.A., 2001. Technical change and measuring pollution abatement costs: an activity analysis framework. Environmental Resource Economics 18(1): 61–85.

Picazo-Tadeo, A.J., E. Reig-Martinez and F. Hernandez-Sancho, 2005. Directional distance functions and environmental regulation. Resource and Energy Economics 27: 131-142.

Pohle, G., B. Frost and R. Findlay, 2001. Assessment of regional benthic impact of salmon mariculture within the Letang Inlet, Bay of Fundy. ICES Journal of Marine Science 58(2): 417-26.

Shephard, R.W., 1970. Theory of Cost and Production Functions. Princeton University Press, Princeton, NJ, 308p.

Tlusty, M.F., K. Snook, V.A. Pepper and M.R. Anderson, 2000. The Potential for soluble and transport loss of particulate aquaculture wastes. Aquaculture Research 31(10): 745-55.

Tveterås, R. and A. Heshmati 2002. Patterns of productivity growth in the Norwegian salmon farming industry. International Review of Economics and Business 50(3): 367-394.

Tveterås, S. 2002. Norwegian salmon aquaculture and sustainability: the relationship between environmental quality and industry growth. Marine Resource Economics 17: 117-128.

Vardanyan, M. and D.W. Noh, 2006. Approximating pollution abatement costs via alternative specifications of a multi-output production technology: a case of the US electric utility industry. Journal of Environmental Management 80: 177-190.

Chapter 4 Potential Impacts of Sea Lice from Farmed Salmon on Wild Salmon Fisheries[9]

4.1 Introduction

The dramatic declines in pink salmon populations around the Broughton Archipelago, British Columbia (BC), in 2002 triggered a debate over the possible effect of sea lice (*Lepeophtheirus salmonis* and *Caligus clemensi*) originating from salmon farms on wild salmon populations. Since then, a number of studies have been conducted in both laboratory and field environments to explore the connections between farm-derived sea lice and wild salmon populations in BC (Morton *et al.* 2004; Brooks 2005; Krkošek *et al.* 2005 & 2006; Beamish *et al.* 2006). Some argue that salmon farms intensify the level of sea lice in surrounding waters, which leads to serious infection of wild juvenile pink and chum salmon, possibly resulting in increased mortality and declines in wild salmon populations (e.g., Morton *et al.* 2004; Morton and Routledge 2005; Krkošek *et al.* 2005 & 2006). Others claim that factors other than sea lice (e.g., ocean conditions) may play more important roles in the decline of wild salmon populations because these populations fluctuate widely on their own from year to year, and that sea lice are natural parasites (e.g., Noakes *et al*. 2000; Brooks 2005; Brooks and Stucchi 2006).

Farmed salmon are typically reared in open netcages with no solid barriers to separate farmed salmon from the surrounding environment. It should be noted that in most cases the parasites that are found within salmon farms do not orginate there; rather, the farms amplify those that originate in the wild (Bakke and Harris 1998; Beamish *et al.* 2005). Sea lice, including *L. salmonis* and *C. clemensi,* are naturally occurring parasites in the coastal marine waters of BC (Margolis and Arthur 1979; McDonald and Margolis 1995). Returning wild adult salmon such as pink, chum, and sockeye can carry high levels of adult sea lice (Beamish *et al.* 2005), which may lead to initial infection of a farm population. The extreme density of salmon within the netcages ensures completion of the

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[9] A version of this chapter will be submitted for publication. Liu, Y., Volpe, J. and Sumaila, U.R. The Potential Ecological and Economic Impacts of Sea lice from Salmon Farms on Wild Salmon Fisheries.

lice cycle, leading quickly to amplified pathogen concentrations within the farm and increased infection risk to nearby wild salmon populations (Noakes *et al.* 2002; Morton *et al.* 2004; Krkošek *et al.* 2005 & 2006).

Several studies have attempted to examine the links between sea lice from salmon farms and the declines in wild salmonid populations at both local and regional scales. In Norway, high levels of sea lice infection are known to have profound negative effects on sea trout (*Salmon trutta*), Arctic char (*Salvelinus alpinus*), and Atlantic salmon (*Salmo salar*) smolt populations in Norwegian fjords (Finstad *et al.* 2000; Bjorn and Finstad 2002). The collapse of sea trout populations along the coast of Scotland was caused by heavy infestation of sea lice (Butler 2002; Gargan *et al.* 2002). On the west coast of Canada, sea lice production within a farm has been observed to reach four orders of magnitude (~30,000x) higher than ambient levels, triggering infection rates of wild juvenile salmon that is 73 times higher than ambient levels near the farm and a greater than normal infection level up to 30 kilometers away (Krkošek *et al.* 2005). This increased infection pressure has been shown to induce 9 - 95% mortality in exposed pink and chum salmon populations (Krkošek *et al.* 2006).

Clearly, these studies demonstrate that without appropriate management and treatments, salmon farms can harbour higher densities of sea lice than wild salmon populations. If the farms are sited close to fish migratory routes, there is a higher chance for migratory wild fish to get infected. This is especially so for migratory juveniles because they are more vulnerable to the parasites than adult fish (Morton *et al.* 2004; Beamish *et al.* 2005). Thus, sea lice from salmon farms pose a potential risk to some wild salmonid populations, although the extent of the risk varies, and the ultimate impacts of sea lice on wild salmon are yet to be fully determined. However, the literature on European and BC salmon farming demonstrate that there is a close connection between the levels of sea lice derived from salmon farm and wild salmon populations. The objective of this chapter is to examine whether sea lice from salmon farms have ecological and economic effects on wild salmon populations and fisheries, and if they do, to what extent. To address this objective, I first examine how increases in juvenile mortality caused by sea lice may affect salmon population levels, then explore how such effects impact the performance of the commercial fishing sector.

4.2 British Columbia Wild Salmon Fisheries

Pink and chum salmon are anadromous and semelparous species. That is, they reproduce and spend their early life in freshwater and their adult life in seawater, and spawn only once. Upon emergence from the gravel in spring or early summer, pink and chum salmon fry immediately migrate toward the sea, and spend about 1.5, and 2.5 - 4.5 years at sea, respectively. Then, mature adult salmon return to their spawning grounds to spawn in late summer and fall (Groot and Margolis 1991). Pink salmon have a simpler life cycle with a fixed two-year life span; thus, all pink salmon are mature at age two, and return as either odd- or even-year populations, which are genetically distinct (Heard 1991). Chum salmon mature at ages two to seven years with most maturing between ages three to five years (Salo 1991). Wild salmon may interact with salmon farms during their migration periods. Sea lice impact is measured in terms of number of lice per unit body weight, so wild salmon are at the greatest risk during the juvenile out-migration stage. For this reason, I restrict my examination to the possible effects of salmon farm-derived sea lice on wild juvenile salmon.

Both pink and chum salmon in the Broughton Archipelago have experienced wide variations in rates of return in recent years, with the numbers of returning salmon typically being below the historical average. However, the returning pink salmon population in 2002 declined remarkably, and little improvement has been made since then (DFO 2006). Pink and chum salmon are caught by the First Nations, recreational and commercial sectors. A fixed exploitation rate of about 20% for chum salmon has been implemented since 2002 (DFO 2006). This policy aims to ensure sufficient escapement levels while providing relatively stable fishing opportunities. This exploitation rate covers all user groups, and of this 20%, a fixed exploitation rate of 15% is allocated to the commercial sector and the remaining 5% is allocated to First Nations and recreational fishing. For pink salmon, there have been very limited opportunities for commercial fisheries in the last few years because of low returns (DFO 2006).

The top management priority for salmon fisheries in BC is to conserve salmon populations and their habitat to avoid overexploitation (DFO 2005). Two management policies have commonly been implemented in BC wild salmon fisheries. One is a fixed exploitation rate, and the other is a target escapement. For an overexploited population, a target escapement policy is more desirable from an ecological perspective because it will allow the populations to rebuild relatively quickly, and such a management policy will result in the largest possible average long-term catch (Walters and Korman 1999). During recovery, fishers have to reduce or stop fishing entirely for some period of time. Overexploited populations recover more slowly under a fixed exploitation rate policy, because it always allows some catch, which is less variable from year to year (Walters and Korman 1999). Here, I study the exploitation of pink and chum salmon under these two management policies. The objective is to test whether the ecological and economic effects of farm-derived sea lice on wild salmon is significantly different when the fisheries are managed under a fixed exploitation rate versus target escapement policies.

Given the complex population structure of salmon and the complexity of the fisheries, management is very challenging. Both salmon fisheries consist of a number of different stocks; fishers employ multiple fishing gears (seine, gillnet, troll); and fish are harvested by different users (commercial, recreational and First Nations). In addition, the fisheries are managed under different management goals, i.e., conservation and maximization of socioeconomic benefits. Due to lack of data for each individual stock of pink and chum salmon, I assume that pink and chum salmon fisheries are each managed as a single population. Also, the catch is assumed to be only for commercial use. Analyses are repeated for each of the two management policies.

Study Area – Broughton Archipelago

This study focuses on the Broughton Archipelago, which includes a group of islands north of Johnstone Strait and off the northeast coast of Vancouver Island. My focus is on the

Kingcome, Bond and Knight Inlets (within DFO's management area 12; see Figure 4.1). The reason for choosing this area is that the effects of farm-derived sea lice on wild salmon populations are known to be greatest here and, as a result, more data are available in the region (Morton *et al.* 2004; Brooks 2005; Morton and Routledge 2005; Krkošek *et al.* 2005 & 2006; Brooks and Stucchi 2006).

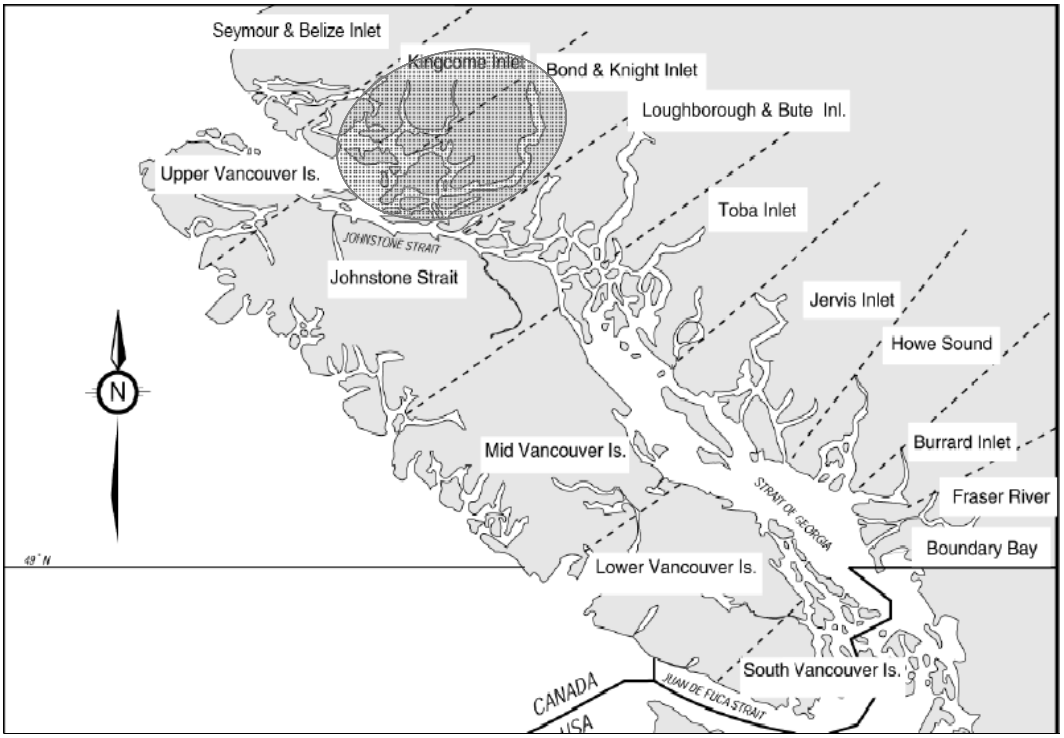

Figure 4.1. The study area (dark oval), including Kingcome and Bond to Knight Inlet. (Source: Ryall *et al.* 1999, P53).

Twenty nine licensed salmon farms were located in this area in 2007, owned by three companies: 19 by Marine Harvest Canada Inc.; 9 by Mainstream Canada; and 1 by Grieg Seafood BC. The locations of these farms are shown in Appendix 4.1. According to the British Columbia Ministry of Agriculture, Food and Fisheries (MAFF[10]), these farms are not all operational in any one year since sites need to be fallowed between production cycles. On average, about 14 - 16 salmon farms are in operation at any one time with 10 - 14 farms fallow from March to June during juvenile salmon migration period. The farmed salmon production level in this area has remained relatively stable even though the total farmed salmon production in BC has seen steady increases in recent years (MAFF[5]).

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[10] http://www.agf.gov.bc.ca/fisheries/bcsalmon_aqua.htm.

4.3 Methodology

I construct an age-structured model to capture wild salmon population dynamics with fry production modelled following a Ricker relationship (Ricker 1954). I then introduce to this a sea lice induced mortality rate. This dynamic model tracks salmon population abundance as a function of ecological parameters. To extend this ecological model to a bioeconomic one, economic components associated with fishing are added. This process is conducted under two different scenarios: i) without sea lice induced mortality; and ii) with sea lice induced mortality applied to the fry production model. The ecological effects of farm-derived sea lice are determined by the difference between the outcomes under these two scenarios, and are expressed in terms of changes in recruitment and catch of pink and chum salmon in the fishery. The economic effects are determined by the difference between the outcomes of these two scenarios in terms of the potential discounted profits to pink and chum salmon fisheries. I then compute and compare discounted profits using conventional and intergenerational discounting methods. The analyses are carried out for a time horizon of 30 years.

In addition to the deterministic population dynamic models, I also apply a Ricker stock-recruitment model with a stochastic variable to explore the effects of sea lice versus the combined effects of all factors (including sea lice). It is assumed that the stochastic variable captures the combined effects of all environmental factors and human interventions that may affect wild salmon populations.

4.3.1 Age-structured Model

A commonly-applied population assessment method for Pacific salmon is the ‘run reconstruction’ model, which uses spatial and temporal catch and escapement data to estimate salmon run sizes at different times throughout the adult reproductive migration stage. Age-structured models that do not rely on the spatial-temporal structure of catch statistics are commonly used in salmon population assessment (e.g., Kope 1987; Savereide and Quinn II 2004). However, farmed-derived sea lice have the greatest impact on wild salmon at the juvenile out-migration stage. Of interest here though is how lice-induced juvenile mortality may affect salmon populations at the adult stage, requiring an age-structured approach. Moreover, age-structured assessment models have proven most useful when addressing population level impacts of disease on wild fish populations, where impact can occur across life history stages, not just at the harvestable adult stages. Examples include assessments of fungal infections in North Sea herring (*Clupea harengus)* (Patterson 1996); herpesvirus in Australian pilchard (*Sardinops sagax*) (Murray and Gaughan 2003); and viral hemorrhagic septicaemia virus in Pacific herring (*Clupea pallasii*) (Marty *et al.* 2003). Therefore, an age-structured model is considered to be an appropriate framework for this study. Equation (4.1) illustrates an age-structured model in detail.

$$N_{0,t} = N_{t-1}^{s} e^{\alpha_j (1 - N_{t-1}^{s} / \beta_j)} \tag{4.1a}$$

$$N_{a,t} = s_a N_{a-1,t-1}(1 - m_a) \tag{4.1b}$$

$$N_{A,t} = (s_A N_{A-1,t-1} + s_A N_{A,t-1})(1 - m_A) \tag{4.1c}$$

Where, $N_{0,t}$ is the numbers of salmon at age 0, in year t, as determined by a Ricker recruitment model at the fry stage; $N_{0,0}$, the initial number of age 0 fish, is given; N_{t-1}^{s} is the number of spawning individuals in year $t-1$, α_j is a population productivity parameter at the fry stage; β_j is the unfished equilibrium population size (numbers of individuals) at the fry stage; subscript j represents the fry (juvenile) stage of wild salmon; $N_{a,t}$ is the number of fish at age a and year t; s_a is age-specific natural survival rate; m_a is age specific maturity rate; $N_{A,t}$ is the number of fish at the last age group A, in year t; $N_{A,t} \approx 0$ because I assume that all fish in the last age group mature and return to spawn (i.e., $m_A = 1$). The spawning biomass N_{t-1}^{s} is determined under our two management policies as follows:

i) fixed exploitation rate: $$N_{t-1}^{s} = \sum_{a=0}^{A} \sum_{t=1}^{T} N_{a,t-1} m_a (1 - z), \quad \forall t \tag{4.1d1}$$

ii) target escapement: $$N_{t-1}^{s} = \min(E), \quad \forall t \tag{4.1d2}$$

Where, z and E are a fixed exploitation rate and target escapement, respectively, and different for pink and chum salmon, their calculations are detailed in the following section.

I assume chum has six age classes (i.e., a =0, 1, 2, 3, 4, 5), while pink has three age classes (i.e., a = 0, 1, 2). The time horizon of the model is 30 years (i.e., t = 1, 2, 3, …, 30).

Since the farm-derived sea lice may cause the mortality of wild salmon juveniles, I introduce a sea lice induced mortality factor into the fry production model, i.e., $N_{1,t} = s_1(1-\phi)N_{0,t-1}(1-m_1)$, where ϕ is the sea lice induced mortality rate and captures the salmon farm derived sea lice induced mortality on wild salmon fry production, and occurs only in the first age class ($a = 1$).

4.3.2 Catch Function

The catch functions for pink and chum salmon under the two management strategies, a fixed exploitation rate and target escapement, are defined as follows:

Fixed exploitation rate policy: The total catch for pink or chum salmon, H_s^z, is written as:

$$H_s^z = z_p \sum_{a=1}^{A} N_a^s m_a^s w_a^s \tag{4.2}$$

Where subscript s represents pink and chum salmon, respectively; H_s^z is the total catch of pink or chum salmon; z_s is the exploitation rates for pink or chum salmon; w_a^s is the age specific weight for pink or chum salmon; N_a^s and m_a^s are as defined earlier.

Target escapement policy: The total catch for pink or chum salmon, H_s^E, is expressed as:

$$H_s^E = \sum_{a=1}^{A} N_a^s m_a^s w_a^s \left\{ 1 - \frac{\min(E_s)}{\sum_{a=1}^{A} N_a^s m_a^s} \right\} \tag{4.3a}$$

Where, H_s^E is the total catch of pink or chum salmon; E_s is a target escapement level for pink or chum; and other variables are as defined earlier.

4.3.3 Cost Function

The total cost of fishing is assumed to be a function of catch, H_t, population size, N_t and the unit cost of fishing, c: $TC_t = f(c, H_t, N_t)$. I define a specific total cost function as $TC_t = c \cdot \left(\frac{H_t}{N_t}\right) \cdot H_t$, where H_t / N_t is the catch-population ratio representing the population effect.

In theory, the cost of fishing is assumed to be a function of fishing effort $TC = cE_f$, where c is unit cost of fishing effort, and E_f is total fishing effort (Clark 1990). Based on the Schaefer production model, catch is assumed to be a function of fishing effort and fish population size ($H = E_f Nq$), where, H is catch, N is fish population and q is catchability. Thus, fishing effort, $E_f = H / qN$, which is positively related to catch and negatively related to fish population size. Further, most BC salmon fishing fleets have multiple fishing licenses, target multiple salmon species and populations, and operate across different fishing grounds. Thus, fishing effort deployed in a given period is highly variable depending on the allowable catch determined in the fishing area, other vessels' activities during the same period, and on the market price. This is especially so in the case of pink salmon because its price is so low that fishers are often unwilling to target the species. Moreover, the catch-population ratio is used when there are no detailed fishing effort data available (e.g., Laukkanen 2001; Doole 2005).

4.3.4 Profit Function

Given the catch obtained under the two management policies, the annual profits for pink or chum salmon fisheries are determined by the annual total revenue (*TR*) and total costs (*TC*). The annual total revenue is assumed to be a function of catch, H_t and market price, p, $TR = pH_t$. Where, H_t = { H_s^z or H_s^E }, and are as defined above. The annual total cost is $TC_t = c \cdot \left(\frac{H_t}{N_t}\right) \cdot H_t$, where c, H_t and N_t are as defined before.

It is assumed that the biological constraints are enforced by two management policies: fixed exploitation rate and target escapement. The profit maximization problem is written as:

i) Discounted profits, using conventional discounting is defined as follows:

$$\text{Max } \pi = \sum_{t=1}^{T} \rho_t (TR_t - TC_t) = \sum_{t=1}^{T} \rho_t \left[PH_f - c \cdot \left(\frac{H_f}{N_f} \right) \cdot H_f \right] \tag{4.4a}$$

Where ρ_t is the discount factor, $\rho_t = 1/(1+r)^t$, and r is the discount rate.

ii) Discounted profits, using intergenerational discounting:

Conventional discounting applies a single discount rate to discount all future costs and benefits (i.e., revenues) of a project or an operation, such as fishing activity over the time horizon of the project, and a net benefit is calculated. Conventional discounting works well using a social discount rate when evaluating short-term projects (e.g., 5 - 10 years). However, when it is applied to value natural resources and environmental services in the long run, there is an ongoing debate about whether or not conventional discounting is an appropriate tool to be used for generations in the far future. Some argue that the costs and benefits to current and future generations should be discounted using different social discount rates for different time periods (e.g., Weitzman 2001; Newell and Pizer 2003) because of, for instance, uncertainty about the future.

In fact, the net benefits to future generations in conventional discounting are discounted based on the current generation's time perspective, effectively meaning that future generations are given much less consideration than the current generation. In order to weight future generations equally with the current generation, I adopt the methods of Sumaila (2004) and Sumaila & Walters (2005): intergenerational discounting using different discounting clocks. They argue that the flow of net benefits should be discounted separately for each generation, using a discounting "clock" for each generation because each generation has its own life span. The net benefits to future generations from having fish protein will be discounted based on their own time perspective, not simply using the current generation's time perspective. Sumaila & Walters (2005) introduced a mathematical expression ($NPV = \sum_{t=0}^{T} \frac{NB_t}{(1+r)^t}\left(1+\frac{t}{G}\right)$, where *NPV* is net present value, *NB* is net benefit, *r* is discount rate and *G* is generation time) to deal with overlapping generations. This approach results in less discounting of future generations' flows of benefits from natural and environmental resources than in the case of conventional discounting (Sumaila 2004; Sumaila & Walters 2005). Thus, discounted profits using intergenerational discounting is defined as follows:

$$\max \quad \pi = \sum_{t=1}^{T} \rho_t (TR_t - TC_t) = \sum_{t=1}^{T} \rho_t \left[PH_f - c \cdot \left(\frac{H_f}{N_f} \right) \cdot H_f \right] \cdot \left(1 + \frac{t}{G} \right) \qquad (4.4b)$$

Where G is generation time, here assuming G = 20 years; $(1+\frac{t}{G})$ is an intergenerational discounting factor.

4.3.5 Potential Ecological and Economic Effects of Sea lice

Two scenarios are explored: i) *scenario 1_no lice,* assuming where no sea lice induced mortality occurs; and ii) *scenario 2_lice,* assuming where sea lice induced effects occur. Hence, the ecological effects of farm-derived sea lice are determined by the difference between the outcomes of these two scenarios and expressed in terms of changes in recruitment and catch. The economic effects of farm-derived sea lice are determined by the difference between the outputs of the two scenarios and expressed in terms of changes in the discounted profits. Conventional and intergenerational discounting approaches are applied to estimate these discounted profits.

4.4 The Data

Some of the data and parameters needed for this study are directly available from the literature, while other figures and parameters have to be estimated from raw data.

4.4.1 Ecological Parameters

Estimating Parameters for Chum Salmon

Productivity and equilibrium population size:

The productivity of the population at fry stage, α_j^c, is estimated based on a regression of time series data of female spawners and fry recruited[11]. α_j^c for chum salmon is estimated to be ~4.9. The unfished equilibrium population size at fry stage β_j^c is calculated based on the unfished equilibrium population size (β_a^c) at adult stage, and α_j^c. For the detailed derivation of β_j^c see Appendix 4.2.

$$\beta_j^c = \frac{\beta_a^c \alpha_j^c}{\alpha_j^c + [s_j s_1 s_2 s_3 (m_3 + m_4 s_4 + m_5 s_4 s_5)]} \tag{4.5}$$

Where, s_j, s_1, s_2, s_3, s_4, s_5 are the survival rates at the fry stage, and age 1,2,3,4 and 5, respectively; m_3, m_4 and m_5 are the proportion of mature fish at age 3, 4 and 5, respectively. Thus, β_j^c for chum salmon is estimated to be ~ 2,494,570 in numbers (Table 4.1a).

In order to get the initial data ($N_{0,0}$) for the age-structured models at year 0, I first calculate the age specific numbers based on the numbers of current spawners (e.g., chum: average 1953 - 1997; pink: 1953 - 2003), fecundity per female, egg efficiency, egg retention, age specific survival rates. Then, I run the models without fishing until the populations reach equilibrium. I use equilibrium values as the initial number of individuals at the first age class in year 0 (i.e., $N_{0,0}$ for pink salmon and chum salmon). There are two reasons for using equilibrium values instead of using current populations' numbers: *i*) lack of age specific data; and *ii*) chum and pink salmon in the Broughton Archipelago have been experiencing dramatic declines compared to historical average levels, and are both currently overexploited. Therefore, it is very difficult to examine the effects of a single factor (e.g., sea lice induced mortality) on the decline of overexploited salmon populations.

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[11] Source: Ransom Myer's database: http://fish.dal.ca/~myers/welcome.html.

Fixed exploitation rate and target escapement:

According to the management policies implemented for fisheries in the Johnstone Strait area, the target escapement in the study area set by DFO was ~546,000 (Ryall *et al.* 1999). Therefore, I use this as the target escapement. The fixed exploitation rate is estimated by using the productivity parameter α since there is a relationship between exploitation rate and productivity parameter $U_{msy} = 0.5\alpha - 0.07\alpha^2$ (Hilborn and Walters 1992). Since α is known to be $\alpha \approx 0.7$ (Luedke 1990), the fixed exploitation rate, U_{msy}, is ~32% (Table 4.1a).

Mortality rate induced by sea lice from farmed salmon

Based on 2004/2005 field data, Krkošek *et al.* (2005) developed a series of spatial transmission dynamic models of sea lice to examine the magnitude of sea lice infection from salmon farm to wild juvenile salmon. Later, combining field data with survival models and empirical lab experiments, they estimated cumulative mortality rates, ranging from 20% to 60% for chum juveniles based on estimates for the Tribune Channel and Knight Inlet datasets (Krkošek *et al.* 2006). As the mortality rate induced by sea lice from salmon farms on chum salmon varies considerably and depends on many different factors (water temperature, salinity, proximity of wild fish to farm, lice density on farm, etc.), I use a range of mortality rates for chum salmon with a lower limit of 20% and an upper limit of 60%. Mortality rates are randomly picked within this range, and are included in year one (s_1) in the age-structured models. A Monte Carlo simulation is used to simulate the mortality rates and compute the results. Each Monte Carlo run can randomly pick a number (i.e., a mortality rate) within this range and repeat simulations and computations for a thousand times (i.e. 1,000 iterations). In addition, snapshots for a series of mortality rates are simulated as part of the sensitivity analyses included in this chapter (Table 4.1a).

Table 4.1a. Parameter values for chum salmon.

Parameters	Adult	Juvenile
Productivity α	0.7	4.9
Unfished population β	1,287,822	2,494,570
Fixed exploitation rate (z)	0.32	/
Target escapement in # (E)	546,000	/
Sea lice induced mortality rate (ϕ)	/	0.2 – 0.6

The other parameters, such as age-specific natural survival rates, proportion of mature salmon, and weight are extracted or estimated from the literature. These estimates and their sources are given in Table 4.1b.

Table 4.1b. Parameter values for chum salmon.

Parameters	Age Class					Sources
	1	2	3	4	5	
Proportion mature (m_a)	0	0	0.30	0.75	1	Salo (1991); Ryall *et al.* (1999)
Weight ($w_{a,}$ kg)	0.36	2.51	3.72	4.72	5.35	Salo (1991); Bigler *et al.* (1996)
Survival rate (s_a)	0.08	0.70	0.70	0.70	0.70	Salo (1991); Ryall *et al.* (1999)

Estimating Parameters for Pink Salmon

Productivity and equilibrium population size:

The parameters α_j^p and β_j^p are estimated using the same methods and procedures as for chum salmon earlier. For pink salmon α_j^p is estimated to be ~5.2, while β_j^p is estimated to be ~4,456,618 in numbers (Table 4.2a).

Fixed exploitation rate and target escapement

There is no target escapement set in the study area for pink salmon. Thus, I have to calculate it based on some parameters estimated earlier. I use the productivity and capacity parameters α and β for adult pink salmon, and formulae for estimating optimum catch rate U_{MSY} [$U_{MSY} = 0.5\alpha - 0.07\alpha^2$] and optimum population size S_{MSY} [$S_{MSY} = \beta(0.5 - 0.07\alpha)$, Hilborn and Walters 1992]. The exploitation rate is estimated to be ~0.76, yielding a target escapement level of ~766,581 individuals. I use these two estimates as the fixed exploitation rate and target escapement for pink salmon, respectively (Table 4.2a).

Mortality rate induced by sea lice from farmed salmon

The mortality rate induced by sea lice from salmon farms for pink juveniles ranged from 20% to 80% based on estimates for the Tribune Channel and Knight Inlet datasets (Krkošek *et al*. 2006). I use a range of mortality rates for chum salmon with a lower limit of 20% and an upper limit of 80%. The running procedure is the same as for chum salmon, described earlier (Table 4.2a).

Table 4.2a. Parameter values for pink salmon.

Parameters	Adult	Juvenile
Productivity α	2.2	5.2
Unfished population β	2,228,309	4,456,618
Fixed exploitation rate (z)	0.76	/
Target escapement in # (E)	766,581	/
Sea lice induced mortality rate (ϕ)	/	0.2 – 0.8

The other parameters, such as age-specific natural survival rates, proportion of mature salmon, and weight are extracted or estimated from the literature. These estimates and their sources are given in Table 4.2b.

Table 4.2b. Parameter values for pink salmon.

	Age Class		
Parameters	1	2	Sources
Proportion of mature (m_a)	0	1	Heard (1991)
Weight (w_a)	0.52	1.43	Heard (1991); Bigler *et al.* (1996)
Survival rate (s_a)	0.06	0.50	Heard (1991); Beamish *et al.* (2005)

4.4.2 Economic Parameters

Estimating Parameters for Chum Salmon

Ex-vessel prices:

Ex-vessel price is the price received by fishers for the salmon landed at the dock. Based on total landing and landed values of chum salmon in British Columbia (DFO statistics[12]), I calculate the ex-vessel prices of chum salmon by dividing landed values by the total

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[12] http://www.dfo-mpo.gc.ca/communic/statistics/commercial/index_e.htm

landings. The ex-vessel price is $1.05 per kg for chum salmon in 2005. Based on the literature, I assume constant price through time.

Costs of fishing:

Since 1995, no systematic and complete financial surveys of BC fishing fleets have been carried out. The latest fishing cost data available are the total fishing cost for salmon fisheries in 2002[13] (GSGislason & Associates 2004). Thus, I use this total fishing cost, fishing days, and catch to estimate the fishing costs for pink and chum salmon. To calculate them, I follow the steps listed below:

- Calculate the fishing cost per day based on the total fishing cost and days fished (DFO statistics) in 2002;
- Estimate the total fishing days used for each salmon species based on the proportion of total revenue per species multiplied by the total fishing days for all the species;
- Compute the total fishing cost per species by the fishing days used for that species multiplied by the cost per fishing day based on the assumptions of no change in fishing technology between 2000 - 2005, so the fishing cost per day is also to remain constant;
- Estimate the fishing cost by dividing the total catch for each species for 2000 - 2005 by the total fishing cost; and
- Calculate the average fishing cost for the period 2000 - 2005 for each species.

From this procedure, the unit fishing cost for chum salmon is estimated to be at about 0.86 per kg.

Estimating Parameters for Pink Salmon

Ex-vessel prices:

Using the same method described for chum salmon earlier, the ex-vessel price for pink salmon is calculated at ~ $0.33 per kg in 2005.

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[13] Fishing cost here refers to the operating costs directly related to fishing, also called "noncapital cost" (Schwindt *et al.* 2000). It includes operating expenses (e.g., fuel, oil, wages and others), and fixed costs (e.g., repairs/maintenance, net, gear and others).

Costs of fishing:

The method and procedure for estimating fishing cost for pink salmon is the same as for chum described earlier. The unit fishing cost for pink is estimated to be at about $0.37 per kg. From the fishing cost and ex-vessel price estimated, it can be seen that the fishing cost is greater than the ex-vessel price for pink salmon. As rational fishers, they won't go fishing. However, fishing vessels have multiple fishing licenses and harvest at different fishing grounds. Harvesting pink salmon is not a main fishing activity for the fishers.

4.4 Results

4.4.1 Chum Salmon

Recruitment in *scenario 1_no lice* is the same under both management policies, whereas in *scenario 2_lice* recruitment is higher under a target escapement policy than under a fixed exploitation rate policy. There is virtually no catch under a target escapement because the total returning fish is less than the target escapement. The discounted profits over 30 years are greater under a fixed exploitation rate than under a target escapement. Table 4.3 shows the numbers of recruitment, escapement and catch when populations are in equilibrium, and the total discounted profits over 30 years.

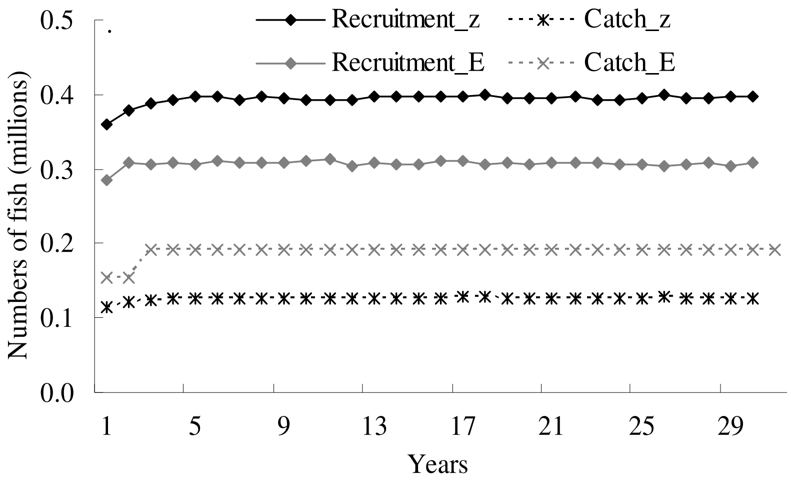
Table 4.3. Summary of recruitment, harvest, escapement and total discounted profit under a fixed exploitation rate and a target escapement policy for chum salmon.

	Under a fixed exploitation rate		Under a target escapement	
	Scenario 1_no lice	*Scenario 2_lice*[*]	*Scenario 1_no lice*	*Scenario 2_lice*[*]
Recruitment (million #)	0.74	0.35 (*47%*)	0.74	0.43 (*58%*)
Harvest (million #)	0.24	0.11 (*46%*)	0.19	0.00
Escapement (million #)	0.50	0.23 (*46%*)	***0.55***	***0.55***
Exploitation Rate	***0.32***	***0.32***	0.26	0.00
Conventional discounted profit (million $)	10.02	4.73 (*47%*)	1.98	0.00
Intergenerational discounted profit (million $)	15.40	7.24 (*47%*)	3.05	0.00

[*] The numbers in the parentheses indicate the percentage of *scenario 2_lice* to *scenario 1_no lice*.

Ecological and Economic Impacts of sea lice

The ecological and economic impacts of sea lice vary greatly under the different management policies. Under a fixed exploitation rate policy, on average, the numbers of recruits, catch and discounted profit decline by 53% when we allow for sea lice induced mortality. Under a target escapement policy, on average, the numbers of recruits decline by 42%, while the discounted profit declines by ~100% over 30 years since there is no catch. When sea lice induced mortality is incorporated into the production model, the total number of returning fish is on average less than the target escapement level. However, in terms of absolute numbers, the recruitment, catch and discounted profit under a fixed exploitation rate are higher than under a target escapement. In sum, the potential ecological impacts under a fixed exploitation rate policy are more severe than under a target escapement policy, and economic impacts under a target escapement are more severe than with a fixed exploitation rate (Figure 4.2).



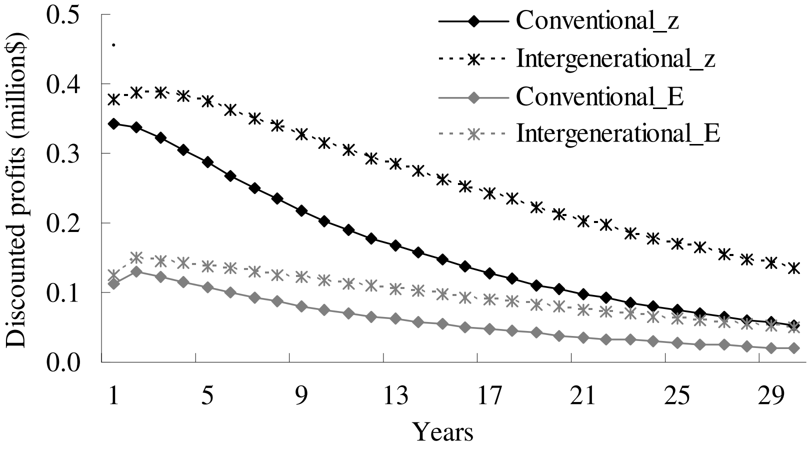


Figure 4.2. Ecological and economic impacts of sea lice on chum salmon under the two management policies. The top graph shows ecological effects in terms of recruitment and catch, while the bottom graph shows economic effects in terms of discounted profit. Legend: z and E represent under a fixed exploitation rate and a target escapement policy, respectively.

4.4.2 Pink Salmon

Under a fixed exploitation rate, the population in *scenario 2_lice* collapses after ten years, while in *scenario 1_no lice* it declines over the first several years before reaching a steady state. Thus, in *scenario 2_lice*, there are very limited catches and discounted profits in the first several years. Under a target escapement policy, the population in both scenarios reaches a steady state. Recruitment in *scenario 1_no lice* arrives at a level twice as high as that in *scenario 2_lice*. There is little catch in *scenario 2_lice* in the first few years. As a result, the discounted profits are quite different between the two scenarios. The recruitment in *scenario 2_lice* under a target escapement is slightly lower than that in *scenario 1_no lice* under a fixed exploitation rate (Table 4.4).

Table 4.4. Summary of recruitment, harvest, escapement and the total discounted profit under a fixed exploitation rate and a target escapement policy for pink salmon.

	Under a fixed exploitation rate		Under a target escapement	
	Scenario 1_no lice	*Scenario 2_lice*[*]	*Scenario 1_no lice*	*Scenario 2_lice*[*]
Recruitment (million #)	0.88	0.08 (*9%*)	1.67	0.79 (*47%*)
Harvest (million #)	0.67	0.06 (*9%*)	0.91	0.00
Escapement (million #)	0.21	0.02 (*10%*)	***0.77***	***0.77***
Exploitation Rate	***0.76***	***0.76***	0.54	0.00
Conventional discounted profit (million $)	0.63	0.10 (*16%*)	2.07	0.51 (*25%*)
Intergenerational discounted profit (million $)	0.95	0.12 (*13%*)	3.19	0.80 (*25%*)

[*] The numbers in the parentheses indicate the percentage of *scenario 2_lice* to *scenario 1_no lice*.

Ecological and Economic Impacts of sea lice

Under a fixed exploitation rate and exposed to farm-amplified lice densities, the pink salmon population collapses after several years resulting in significant ecological and economic impacts. On average, both recruitment and catch are reduced by almost 100%. The discounted profits drop by 75%. Under a target escapement policy, on average, recruitment is reduced by 53%. Since there is virtually no catch available when farm-induced lice mortality is taken into account, the discounted profits approach zero. Hence, the ecological impacts under a target escapement management are higher than under a fixed exploitation rate in terms of numbers. However, the ecological impacts are more severe under a fixed exploitation rate than under a target escapement because the population collapses under a fixed exploitation rate. In sum, both ecological and economic impacts under a fixed exploitation rate are greater than under a target escapement (Figure 4.3).

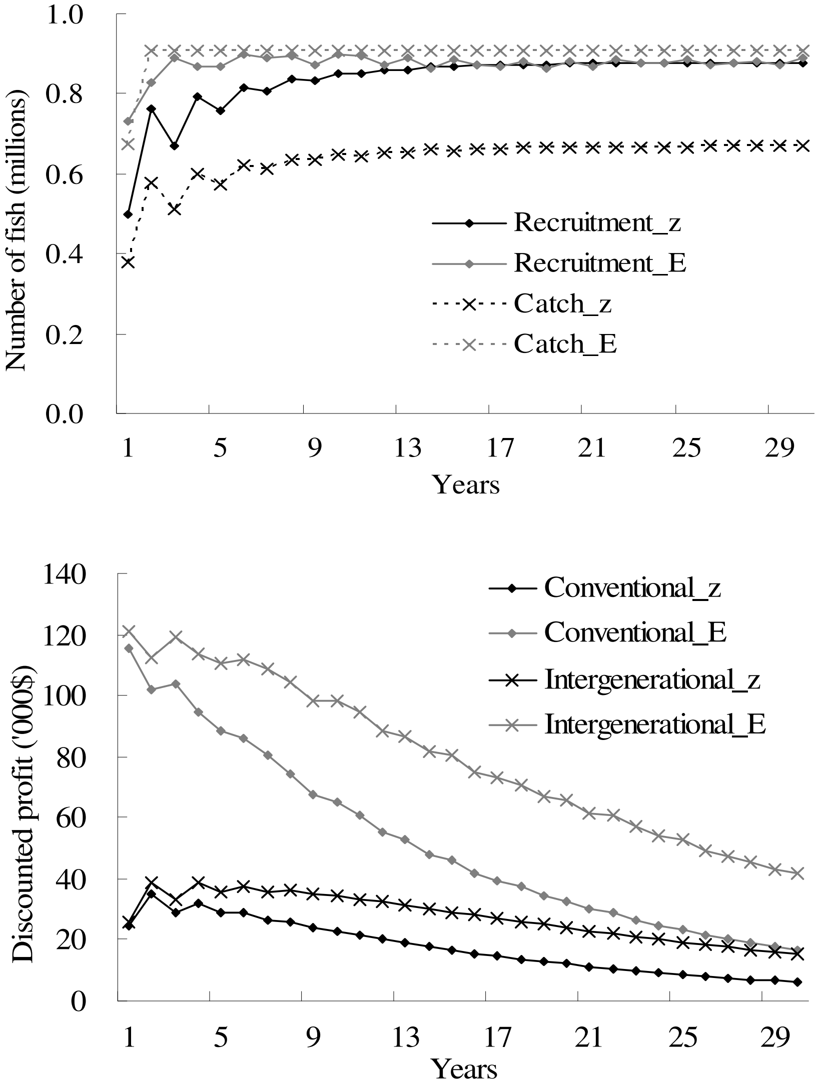


Figure 4.3. Ecological and economic impacts of pink salmon under two management strategies. The top panel represents ecological effects in terms of recruitment and catch, while the bottom panel represents economic effects in term of discounted profits. Legend: z and E represent a fixed exploitation rate and target escapement policy, respectively.

4.5 Sensitivity Analysis

There are uncertainties surrounding the values of some key parameters in these analyses, so a sensitivity analysis is carried out to estimate the robustness of the results to variations in these parameters. First, I compare the effects of sea lice induced mortality with all mortality factors combined. I then test the effects of different sea lice induced mortality rates on ecological and economic impacts. Finally, I estimate robustness of the results vis-à-vis changes in productivity and capacity parameters as well as costs and ex-vessel prices.

4.5.1 The Effects of Combined Factors

Obviously, salmon farm-derived sea lice are not the only mortality factor that negatively affects wild salmon populations. Climate change, disease, destruction of habitat and pollution are among many other significant factors. Thus, I introduce a stochastic variable that represents combined effects of environmental factors and human interventions (fishing is not included). This stochastic variable is integrated into a Ricker population-recruitment model. The stochastic variable is estimated from the standard deviation of the average recruit per spawner. The theoretical foundation and model description can be found in Appendix 4.3. I use the same Monte Carlo method to simulate the stochastic variable as introduced above. The stochastic variables used range from -0.6 to 0.0 for chum salmon, and from -2.4 to 0.0 for pink salmon. Monte Carlo simulations can pick up a random number each time from these ranges and repeat them for a thousand times. I use the changes in recruitment as an example to demonstrate how farm-induced lice factors and all combined factors affect the recruitment of chum and pink salmon under two management policies.

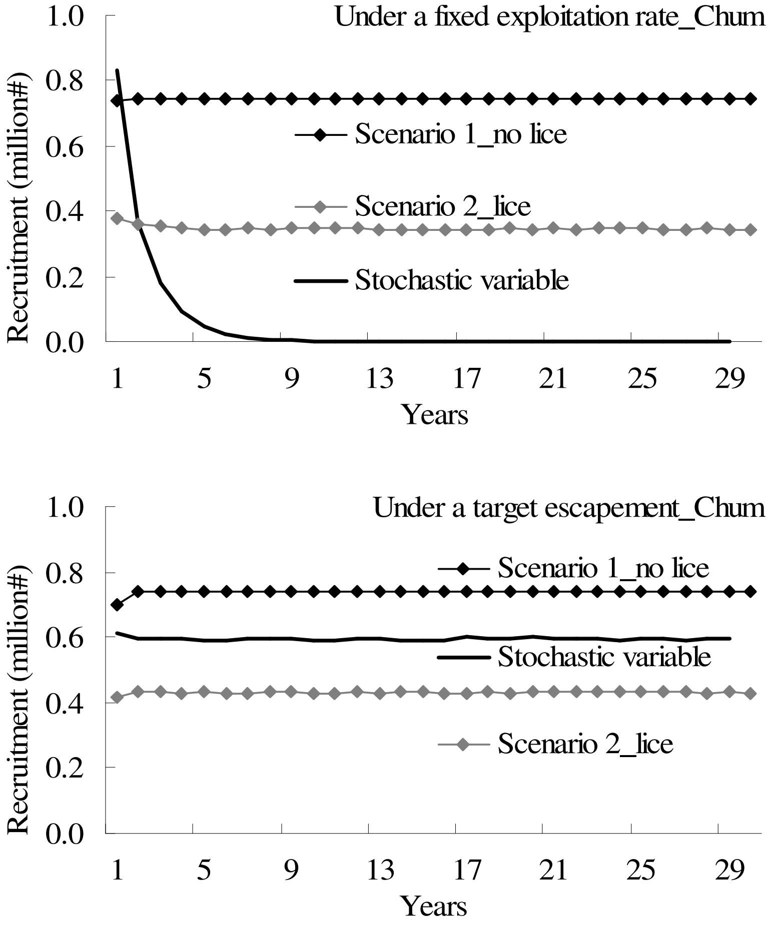


Figure 4.4. Recruitment changes under three scenarios: *scenario 1_no lice, scenario 2_lice* and combined factor (i.e., stochastic variable) for chum salmon under two management policies.

The results for both chum and pink salmon are the same (Fig. 4.4 & 4.5). The salmon population with the stochastic variable collapses under a fixed exploitation rate, while the recruitment with stochastic variable is smaller than that in *scenario 1_no lice* and larger than that in *scenario 2_lice* under a target escapement. These results for chum and pink salmon are expected under a fixed exploitation rate policy as the combined effects should have larger impacts on the populations than only disease effect. However, under a target escapement policy, the scenarios with sea lice have greater impacts on chum and pink salmon populations than the scenarios with stochastic variables. This may imply that high mortality rate incurred at the early stages of salmon populations may have stronger impacts on salmon populations than that at the late stages of salmon populations.

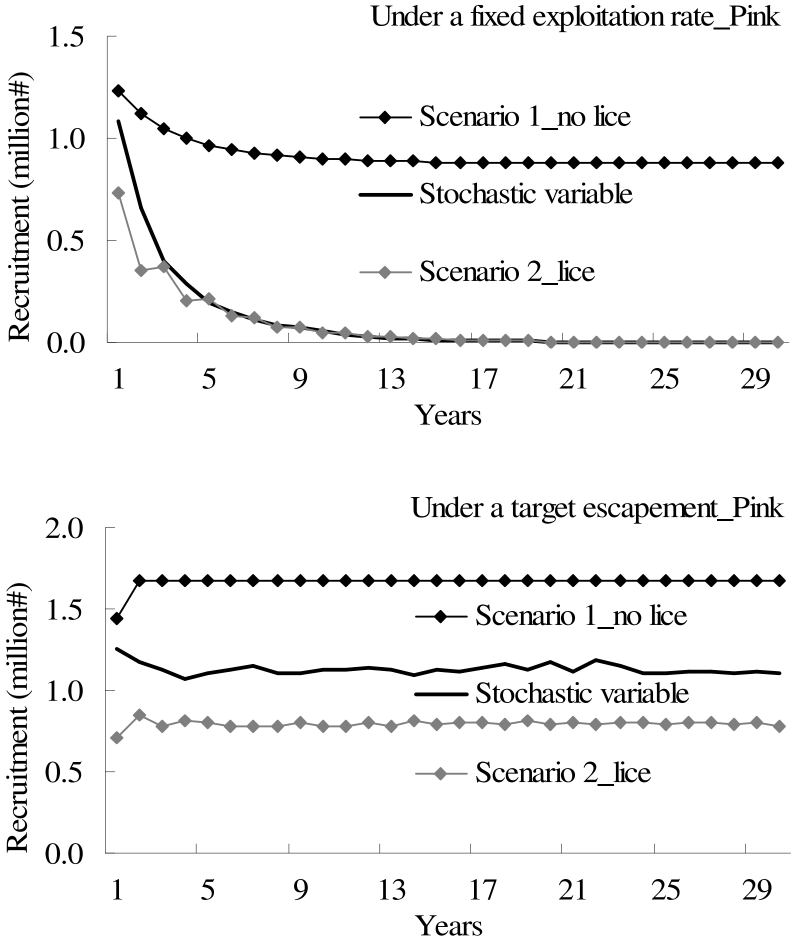


Figure 4.5. Recruitment changes under three scenarios: *scenario 1_no lice*, *scenario 2_lice* and combined factor (i.e., stochastic variable) for pink salmon under two management policies.

4.5.2 Mortality Rate Induced by Sea Lice from Salmon Farm

The exact mortality rates of wild pink and chum salmon induced by farm-derived sea lice are unknown owing to the complex interactions among potential mortality factors. In the base scenario, random mortality rates within the ranges for pink (20% – 80%) and chum salmon (20% – 60%) are used over 30 years. These mortality rates are estimates based on the datasets from two areas over a two-year period, and a series of lab experiments (Krkošek *et al.* 2006). However, I test the mortality rate from the lower limit at 10% to upper limit at 80% for both pink and chum salmon. The mortality rate is increased in increments of 10%. Each simulation uses one single mortality rate which remains constant over 30 years.

Chum salmon: Under a fixed exploitation rate the salmon population fluctuates for the first several years and reaches a steady state at all the mortality rates. The population collapses when the mortality rate > 60%. It should be noted that the higher the mortality rate, the lower the steady state. The recruitment is lower than the target escapement level when the mortality rate is above 20%. The discounted profit decreases with increasing mortality rate. It decreases by less than 20% when mortality rate is below 20%, while it decreases by more than 50% when mortality rate is more than 40% (Fig. 4.6).

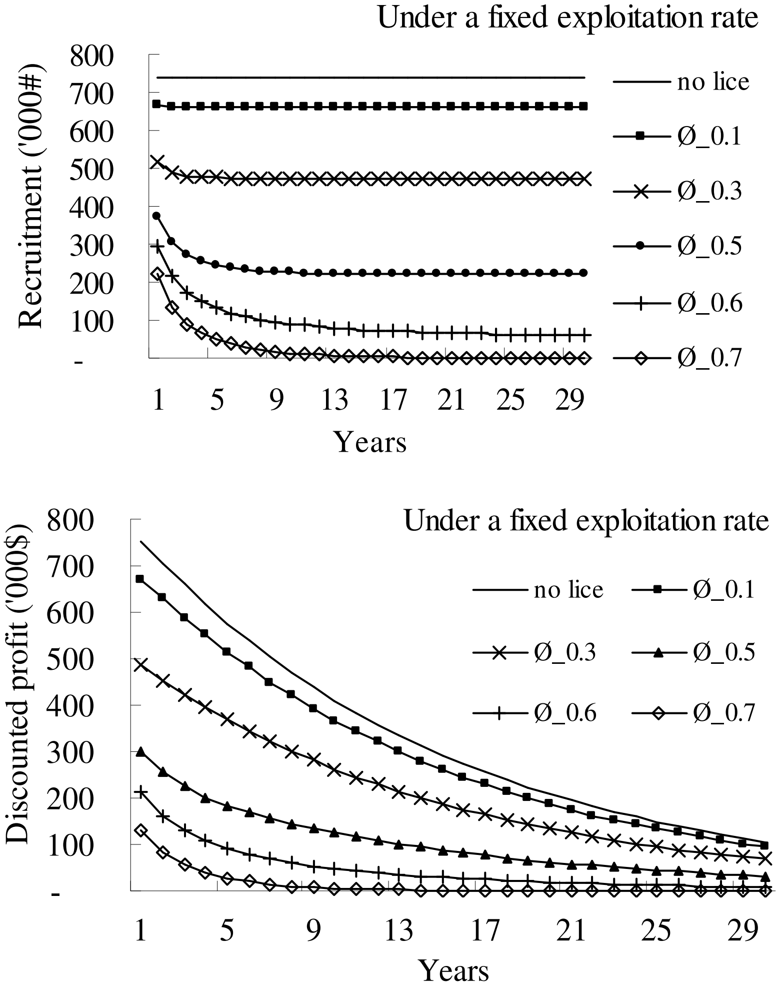


Figure 4.6. Recruitments and discounted profits at various mortality rates for chum salmon under a fixed exploitation rate policy. The top graph shows the recruitments; and the bottom graph shows the discounted profits.

Under a target escepement policy, the population also fluctuates first and then reaches a steady state across all mortality rates. Recruitments and discounted profits decline with increasing mortality rates. Recruitments are lower than the target escapement level when mortality rate is ≥ 30%. The population collapse when the mortality is > 70%. Discounted profits decrease by over 80% when mortality rate is over 20%, and is zero when mortality rate is ≥ 30% as no catch is allowed (Fig. 4.7).

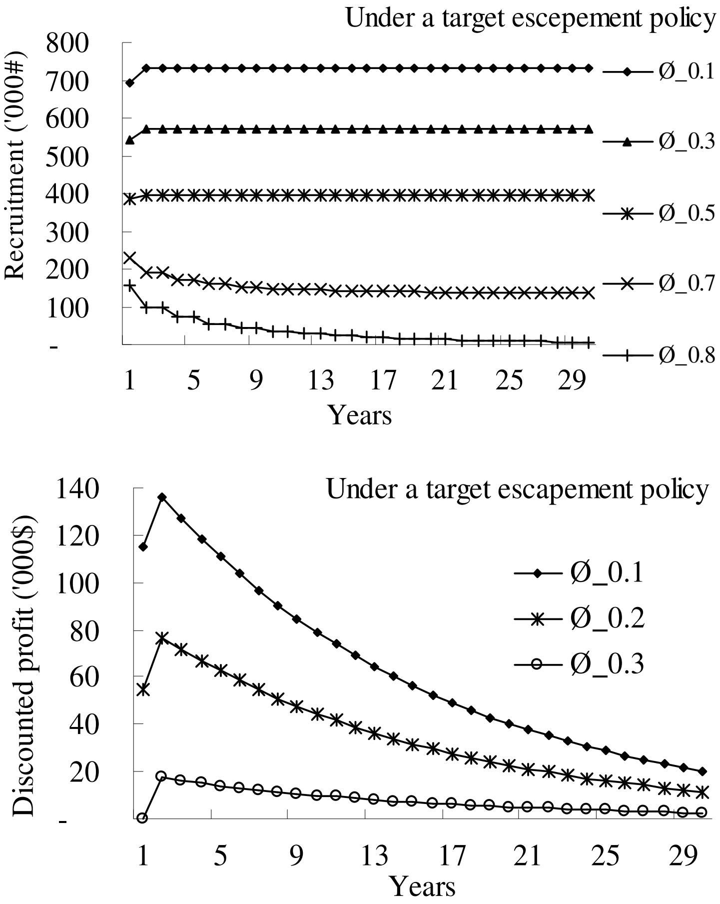


Figure 4.7. Recruitments and discounted profits at various mortality rates for chum salmon under a target escapement policy. The top graph shows the recruitments; and the bottom graph shows the discounted profits.

<u>Pink salmon</u>**:** Under a fixed exploitation rate, the pink salmon population declines at all mortality rates, and eventually reaches a steady state if the mortality rate is ≤ 20%, and the population collapses sooner or later when the mortality rate is > 20%. The higher the mortality rate, the sooner the population collapses. The discounted profits gradually improve with declining mortality rate, and decrease by 30% and 57% compared to the

discounted profits in *scenario 1_no lice* for the mortality rates of 10% and 20%, respectively. Recruitment is higher than the target escapement level only when the mortality rate is below 10% (Fig. 4.8).

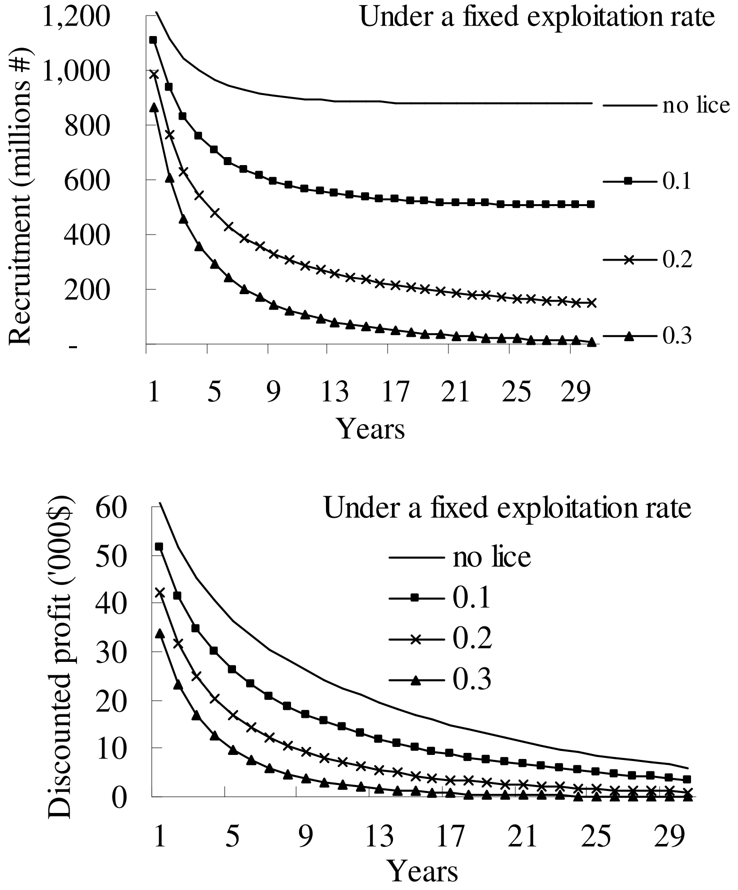


Figure 4.8. Recruitments and discounted profits at various mortality rates for pink salmon under a fixed exploitation rate policy. The top graph shows the recruitments; and the bottom graph shows the discounted profits.

Under a target escapement, the pink salmon population fluctuates initially, then reaches a steady state for all mortality rates. Recruitment is higher than the target escapement when the mortality rate is below 60%. Discounted profits decrease with increasing mortality rate (Fig. 4.9).

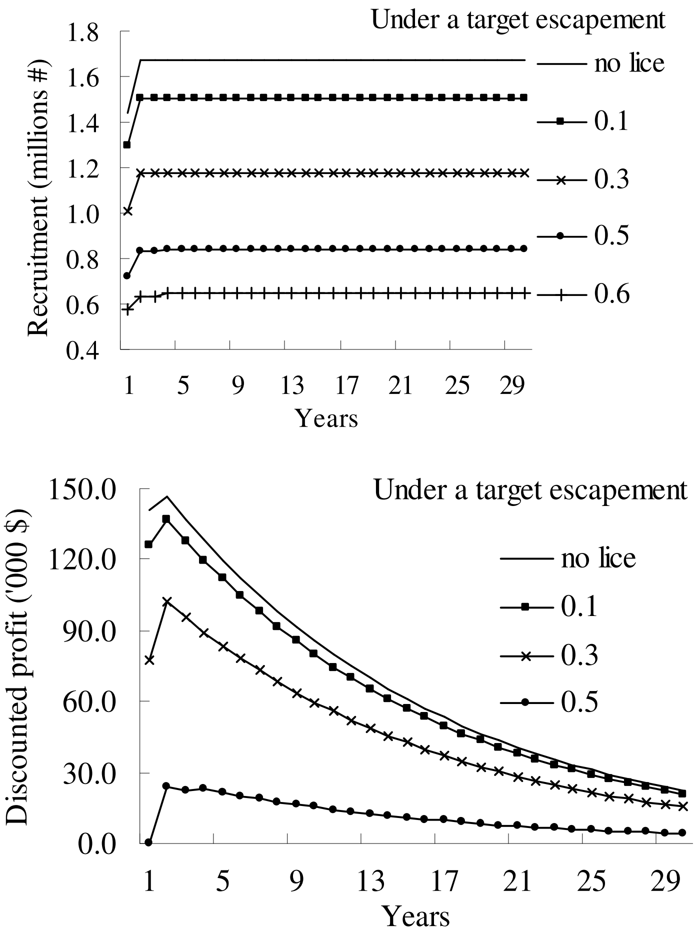


Figure 4.9. Recruitments and discounted profits at various mortality rates for pink salmon under a target escapement policy. The top graph shows the recruitments; and the bottom graph shows the discounted profits.

4.5.3 Productivity and Capacity Parameter

The productivity parameter α is presumed to be similar within a species over a defined spatial range, while the capacity parameter may vary depending on the size of area and the specific dynamics of a population (Hilborn and Walters 1992). However, recent studies indicate that ocean climate change can alter the productivity parameter of a population (Peterman *et al.* 2000; Beamish *et al.* 2004). Thus, for chum salmon, I test the robustness of our α_j estimate of 4.9 by re-running the analysis using values of 5.1 and 4.7. Similarly, for pink salmon I test α_j set to 5.0 and 5.4 rather than the base value of 5.2. I also increase and decrease the capacity parameter β_j by 10% and 20% for both salmon species. I use recruitment in *scenario 1_no lice* as an example to demonstrate these changes.

Results suggest recruitment of both species is positively related to productivity and capacity, though the magnitude of change is different. For capacity parameters, the magnitude of recruitment changes is at almost the same magnitude as capacity parameters regardless of management policies for the pink and chum salmon populations. However, for productivity parameters, the magnitude of recruitment changes is different for chum and pink salmon and different management policies. Under a fixed exploitation rate, the magnitudes of recruitment changes for pink and chum salmon are similar, ranging from 14% to 20%, as well as for chum salmon under a target escapement. But, under a fixed exploitation rate, the magnitude of recruitment change for pink salmon is great, ranging from 70% to 80%. Likewise, the ecological and economic impacts of sea lice also co-vary with productivity and capacity changes, but the magnitude of these effects in both species is minor because recruitment, catches and discounted profits change in similar magnitudes in both scenarios.

4.5.4 Costs and Price

In the base scenario, a population effect is added into the cost function using a catch-population ration term. This catch-population ratio is an arbitrary value between 0 and 1. If this population effect is removed from the cost function, the total cost is simply a function of catch since the unit cost of fishing is assumed to be constant. As a result, the discounted profits decrease proportionally for chum salmon, and they become negative for pink salmon because the unit cost of fishing is higher than the ex-vessel price. However, the economic impacts for chum salmon are almost the same since the discounted profits decrease in equal proportion for both scenarios.

It is assumed that ex-vessel prices remain unchanged over 30 years. This assumption is not likely to be true because the ex-vessel prices for pink and chum salmon have widely fluctuated over the years and trended downward gradually over the last decade due to the increasing supply of farmed salmon. However, I believe that wild salmon fisheries are price inelastic in the short term, while they may be price elastic over the long term due to economic viability of catching and processing. If a salmon management goal is to sustain escapement, the catch is determined by the total numbers of returning individuals, not by ex-vessel prices. But if fishing cost is higher than the ex-vessel price, as in the case of pink salmon, this may affect fishers' incentives to go fishing. Fishers may go out to fish if they believe that the price would be higher or they may be compensated (e.g., if there is high demand from processors), if they expect less catch of other salmon species or if they expect a subsidy. Certainly, price is a very important driver of fishing effort and catch, which may have large ecological and economic impacts on fisheries and fishers.

4.6 Discussions and Conclusions

In this study, I examine the potential ecological and economic impacts of salmon farm-derived sea lice on wild pink and chum salmon at a population level by incorporating sea lice induced mortality into age-structured models. I also explore how the combined effects of all environmental factors and human interventions may affect salmon populations and fisheries by incorporating a stochastic variable into population-recruitment models. The initial populations used are equilibrium (i.e. populations without fishing). Thus, the salmon populations do not represent the current pink and chum salmon populations in the study area. All simulations are conducted based on this fundamental assumption. The following findings are drawn from the analyses:

Salmon farm-derived sea lice have ecological and economic effects on wild salmon populations and fisheries, but to varying degrees. These effects are minor at low mortality rates (<20%), but can be substantial as mortality rates increase. For instance, populations change marginally when the mortality rate is ≥ 20% for pink and chum salmon; the population can collapse when the mortality rate is higher (60% for chum and 30% for pink). Other studies have demonstrated that the high level of lice infestation does pose a mortality risk to out-migrating salmon smolts (Bjorn and Finstad 2002; Gargan *et al.* 2002; Holst *et al.* 2003; Morton *et al.* 2004; Krkošek *et al.* 2005 & 2006). Increasing the mortality level of migratory salmon smolts could have major impacts on the size of the returning populations, contributing to overall wild salmon population declines in the region (Carr and Whoriskey 2004; McVicar 2004). The results from this study are consistent with these findings.

To fishers, the decline in (or collapse of) populations means less (or no) catches and economic returns; to society, it may mean extensive social and ecological costs because the society may need to compensate fishers for their losses, as well as bear the costs for restoring the collapsed populations. The exact costs are unknown, but certainly it will be significant if populations collapse. Additionally, current pink and chum populations in the study area are in decline. The increased mortality due to salmon farm-derived sea lice may accelerate these declines, especially for some small and/or weak stocks when they are managed as one single mixed population.

The ecological and economic effects of sea lice from farmed salmon on wild pink and chum salmon are similar to those attributable to the combined effects of all factors, including sea lice. This indicates that sea lice may have significant impacts on wild salmon than other factors. Wild salmon populations in BC have fluctuated considerably over time, and have seen dramatic decline since the late 1980s. The decline, nevertheless, is believed to be due to a combination of factors, including overfishing, climate change (Mueter *et al.* 2005; Pyper *et al.* 2001&2002; Brooks 2005; Beamish *et al.* 2005 & 2006), destruction of freshwater habitats (Bradford and Irvine 2000), and salmon farming (e.g., Noakes 2002; Krkošek *et al.* 2005). These factors have various degrees of importance in contributing to the decline of different wild salmon populations. This study reveals that on average the combined factors have greater impacts on pink and chum salmon populations than just the sea lice induced mortality factor. However, impacts can be severe when the sea lice induced mortality rate is high. A high rate of return in the adult spawning population cannot be attained with very low survival at the early stage, regardless of survival at the adult stage.

The ecological and economic effects of sea lice vary greatly under different management policies. A target escapement policy is more ecologically promising than a fixed exploitation rate because its priority is to ensure sufficient recruitment. A fixed exploitation rate can drive an overexploited population to collapse although it may provide benefits to fishers over the short term. In stable populations, both strategies may be appropriate. However, given uncertainties with population assessment, environment change, and time-area-gear control, a fixed exploitation rate policy may be a more appropriate policy than a target escapement management policy (Walters and Parma 1996; Grout and Cass 2006). To an overexploited population, a target escapement management policy is more desirable from an ecological perspective than a fixed exploitation rate policy because overexploited populations can rebuild quickly to reach the target escapement level. Moreover, it can also result in the largest possible average catch over the long term. The exploitation rate used in this study for pink salmon is very high compared to management implemented in the current fisheries, in which there is virtually no commercial fishing, and the priority is given to aboriginal and recreational fishing (DFO 2006).

Changing the productivity parameter, α, and capacity parameter, β, have slight ecological and economic effects on pink and chum salmon. Recent studies suggest that ocean conditions (e.g., temperature, current) exhibit a strong influence on salmon survival and productivity (Peterman *et al.* 2000; Beamish *et al.* 2004). Increasing productivity and capacity can enhance recruitment to some extent. However, in this study, the changes of these parameters have marginal ecological and economic effects because recruitment increases simultaneously in both cases.

Varying fishing cost and ex-vessel price may have extensive impacts on pink and chum salmon through changing fishers' behaviour. Chum salmon have a relatively high ex-vessel price, which exceeds the cost of fishing, thus, fishers make a positive economic return from fishing, and therefore fishing will continue. On the other hand, pink salmon have an ex-vessel price that is lower than fishing cost, thus, fishers have no incentive to go fishing. Population size may change fishing cost to some degree, but a large catch is not necessary to generate a high economic return.

Pink salmon is more sensitive to the changes of parameter values and management policies than chum salmon. Compared to chum salmon, pink salmon population changes dramatically when sea lice induced mortality and combined environmental factors are incorporated. This is because pink salmon have a two year life cycle, and any change in mortality can extensively alter their population dynamics. However, because of this, pink salmon are also capable of rebuilding from overexploitation faster than chum salmon (Walters and Korman 1999).

This study is the first attempt to examine the ecological and economic impacts of farm-derived sea lice on wild salmon from a population level. We have to recognize that the high mortality rate induced by sea lice has considerable ecological and economic impacts on salmon populations and fisheries. There is no doubt that the debate over the impacts of sea lice on wild salmon will continue, and salmon farming is unlikely to alter its development, at least over the short term. What should we do and what can we do? Salmon aquaculture in BC is a relatively new industry, thus, policy makers and the salmon industry should learn from the failed and succeed experiences of their counterparts in other jurisdictions. The precautionary principle should be adopted and an appropriate management scheme and policy strategy should be developed in order to improve the husbandry practice of salmon farming, and minimize sea lice problem stemming from salmon farms. As mentioned earlier, this study is based on a number of simplifying assumptions because the data are very limited both in accuracy and in scale, and the simulations are based on populations at equilibrium, not current salmon populations in the study areas – making findings conservative.

4.7 References

Bakke, T.A. and P.D. Harris, 1998. Diseases and parasites in wild Atlantic salmon (*Salmo salar*) populations. Canadian Journal of Fisheries and Aquatic Sciences 55(Sup. 1): 247-266.

Beamish, R. J., J.T. Schnute, A.J. Cass, C.M. Neville and R.M. Sweeting, 2004. The influence of Climate on the Population and Recruitment of Pink and Sockeye Salmon from the Fraser River, British Columbia, Canada. Transactions of the American Fisheries Society 133:1396–1412.

Beamish, R.J., S. Jones, C-E. Neville, R. Sweeting, G. Karreman, S. Saksida and E. Gordon, 2006. Exceptional marine survival of pink salmon that entered the marine environment in 2003 suggests that farmed Atlantic salmon and Pacific salmon can coexist successfully in a marine ecosystem on the Pacific coast of Canada. ICES Journal of Marine Science 63: 1326-1337.

Beamish, R.J., C.M. Neville, R.M. Sweeting and N. Ambers, 2005. Sea lice on adult Pacific salmon in the coastal waters of Central British Columbia, Canada. Fisheries Research 76: 198-208.

Bigler, B.S., D.W. Welch and J.H. Helle, 1996. A review of size trends among North Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 53(2): 455-465.

Bjorn, P.A. and B. Finstad, 2002. Salmon lice, *Lepeophtheirus salmonis (*Kroyer), infestation in sympatric populations of Arctic char, *Salvelinus alpinus* (L.), and sea trout, *Salmo trutta* (L.), in areas near and distant from salmon farms. ICES Journal of Marine Science 59:131-139.

Bradford, M.J. and J.R. Irvine, 2000. Land use, fishing, climate change, and the decline of Thompson River, British Columbia, coho salmon. Canadian Journal of Fisheries and Aquatic Sciences 57: 13-16.

Brooks, K.M, 2005. The effects of water temperature, salinity, and currents on the survival and distribution of the infective copepodid stage of sea lice (*Lepeophtheirus salmonis*) originating on Atlantic salmon farms in the Broughton Archipelago of British Columbia, Canada. Reviews in Fisheries Science 13(3): 177-204.

Brooks, K.M. and D.J. Stucchi, 2006. The Effects of Water Temperature, Salinity and Currents on the Survival and Distribution of the Infective Copepodid Stage of the Salmon Louse (*Lepeophtheirus salmonis*) Originating on Atlantic Salmon Farms in the Broughton Archipelago of British Columbia, Canada (Brooks, 2005) – A Response to the Reubttal of Krkosek *et al.* (2005). Review of Fishery Science 14**:**13-23.

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

Carr, J. and F. Whoriskey, 2004. Sea lice infestation rates on wild and escaped farmed Atlantic salmon (Salmo salar L.) entering the Magaguadavic River, New Brunswick. Aquaculture Research 35(8): 723-729.

Chen, D.G., and J.R. Irvine, 2001. A semiparametric model to examine population-recruitment relationships incorporating environmental data. Canadian Journal of Fisheries and Aquatic Sciences 58: 1178-1186.

Clark, C.W., 1990. Mathematical Bioeconomics : the Optimal Management of Renewable Resources. 2nd edition. New York : J. Wiley. 386p.

Costello, C.J., R.M. Adams, and S. Polasky, 1998. The value of El Nino forecasts in the management of salmon: a stochastic dynamic assessment. American Journal of Agricultural Economics 80(4): 765-777.

DFO, 2005. Canada's Policy for Conservation of Wild Pacific Salmon. Fisheries and Oceans Canada, 57p. http://www-comm.pac.dfo-mpo.gc.ca/publications/wsp/wsp_e.pdf.

DFO, 2006. South Coast Integrated Fisheries Management Plan. Fisheries and Oceans Canada, 115p. http://www-ops2.pac.dfo-mpo.gc.ca/xnet/content/MPLANS/plans06/Salmon/southcoast/Salmon%20IFMP.SC.2006.pdf

Doole, G.J., 2005. Optimal management of the New Zealand longfin eel (*Anguilla dieffenbachia*). The Australian Journal of Agricultural and Resource Economics 49: 395-411.

Finstad, B., P.A. Bjorn, A. Grimnes and N.A. Hvidsten, 2000. Laboratory and field investigations of salmon lice [*Lepeophtheirus salmonis* (Kr_yer)] infestation on Atlantic salmon (*Salmo salar* L.) post-smolts. Aquaculture Research 31: 795-803.

Gargan, P.G., O. Tully, and W.R. Poole, 2002. The Relationship between sea lice infestation, sea lice production and sea trout survival In Ireland, 1992-2001. In: Mills, D. (Ed): Salmon on the Edge. Chapter 10: 119-135.

Groot, C. and L. Margolis, 1991. Pacific Salmon Life Histories. Vancouver, Canada: University British Columbia Press. 564p.

Grout, J and A.Cass, 2006. Workshop to assess population dynamics of cyclic Fraser River sockeye and implications for management. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2006/004.

GSGislason & Associates, 2004.British Columbia Seafood Sector and Tidal Water Recreational Fishing: A Strengths, Weaknesses, Opportunities, and Threats Assessment. Prepared for BC Ministry of Agriculture, Food and Fisheries, Victoria, BC. 308p.

Heard, W.R., 1991. Life history of pink salmon (*Oncorhynchus gorbuscha*). In: Pacific Salmon Life Histories. C. Groot and L. Margolis, (eds.).Vancouver, Canada: University British Columbia Press. pp. 119-230.

Hilborn, R. and C.J. Walters, 1992. Quantitative fisheries population assessment: choice, dynamics, and uncertainty. New York: Chapman and Hall, 570p.

Holst, J.C; P. Jakobsen, F. Nilsen, M. Holm, L. Asplin, J. Aure, 2003. Mortality of seaward-migrating post-smolts of Atlantic salmon due to salmon lice infection in Norwegian salmon populations. Salmon at the Ege. pp. 136-137.

Kope, R.G., 1987. Separable virtual population analysis of Pacific salmon with application to marked chinook salmon, *Oncorhynchus tshawytscha*, from California's Central Valley. Canadian Journal of Fisheries and Aquatic Sciences 44: 1213-1220.

Koslow, J.A., A.J. Hobday and G.W. Boehlert. 2002. Climate variability and marine survival of coho salmon (Oncorhynchus kisutch) in the Oregon production area. Fisheries Oceanography 11(2): 65-77.

Krkošek, M., M.A. Lewis and J.P. Volpe, 2005. Transmission dynamics of parasitic sea lice from farm to wild salmon. Proceedings of the Royal Society of London Series B 272: 689-696.

Krkošek, M., M.A. Lewis, A. Morton, L.N. Frazer and J.P. Volpe, 2006. Epizootics of wild fish induced by farm fish. Proceedings of the National Academy of Sciences of the USA 103(42): 15506-15510.

Laukkanen, M., 2001. A bioeconomic analysis of the Northern Baltic salmon fishery: coexistence versus exclusion of competing sequential fisheries. Environmental and Resource Economics 18: 293-315.

Luedke, W.H., 1990. Optimal Catch Policies in Salmon Gauntlet Fisheries: Terminal Versus Mixed Population Fishery Catch. Masters Thesis, University of British Columbia.124p.

Margolis, L. and J.R. Arthur, 1979. Synopsis of the parasites of fishes of Canada. Bulletin of the Fish Res. Bd. of Canada No. 199. Department of Fisheries and Oceans, Ottawa, Ontario, Canada. 269 pp.

Marty, G. D., T.J. Quinn II, G. Carpenter, T.R. Meyers and N.H. Willits, 2003. Role of disease in abundance of a Pacific herring (*Clupea pallasi*) population. Canadian Journal of Fisheries and Aquatic Sciences 60: 1258-1265.

McDonald, T.E., and L. Mrgolis. 1995. Synopsis of the parasites of fishes of Canada: Supplement (1978-1993). Canadian Special Publication of Fisheries and Aquatic Sciences No. 122. National Research Council of Canada, Ottawa, Ontario, Canada. 265 pp.

McVicar, A., 2004. Management actions in relation to the controversy about salmon lice infections in fish farms as a hazard to wild salmonid populations. Aquaculture Research 35(8): 751-758.

Morton, A. and R. Routledge, 2005. Mortality rates for juvenile pink *Oncorhynchus gorbuscha* and chum *O. keta* salmon infested with sea lice *Lepeophtheirus salmonis* in the Broughton Archipelago. Alaska Fisheries Research Bulletin 11: 146-152.

Morton, A., R. Routledge, C. Peet and A. Ladwig. 2004. Sea lice (*Lepeophtheirus salmonis*) infection rates on juvenile pink (*Oncorhynchus gorbuscha*) and chum (*Oncorhynchus keta*) salmon in the nearshore marine environment of British Columbia, Canada. Canadian Journal of Fisheries and Aquatic Sciences 61:147-157.

Mueter, F.J., R.M. Peterman, B.J. Pyper. 2002. Opposite effects of ocean temperature on survival rates of 120 populations of Pacific salmon in northern and southern areas. Canadian Journal of Fisheries and Aquatic Sciences 59: 456-463.

Murray, A.G., D.J. Gaughan, 2003. Using an age-structured model to simulate the recovery of the Australian pilchard (*Sardinops sagax*) population following epidemic mass mortality. Fisheries Research 60(2): 415-426.

Newell, R,G. and W.A. Pizer, 2003. Discounting the Distant Future: How Much Do Uncertain Rates Increase Valuations? Journal of Environmental Economics and Management 46: 52-71.

Noakes, D.J., R.J. Beamish and M.L. Kent, 2000. On the decline of Pacific salmon and speculative links to salmon farming in British Columbia. Aquaculture 183 (3): 363-386.

Noakes, D.J., R.J. Beamish and R. Gregory, 2002. British Columbia's Commercial Salmon Industry. Dept. of Fisheries and Oceans, Sciences Branch - Pacific Region, Pacific Biological Station, Nanaimo, British Columbia, Canada. NPAFC Doc. No. 642, 13 p.

Patterson, K.R., 1996. Modelling the impact of disease-induced mortality in an exploited population: the outbreak of the fungal parasite *Ichthyophonus hoferi* in the North Sea herring (*Clupea harengus*). Canadian Journal of Fisheries and Aquatic Sciences 53: 2870–2887.

Peterman, R.M., B.J. Pyper, and J.A. Grout, 2000. Comparison of parameter estimation methods for detecting climate-induced changes in productivity of Pacific salmon (*Oncorhynchus* spp.). Canadian Journal of Fisheries and Aquatic Sciences 57: 181-191.

Pyper, B.J., F.J. Mueter and R.M. Peterman. 2002. Spatial covariation in survival rates of Northeast Pacific Chum Salmon. Trans. Am. Fish. Soc. 131: 343-363.

Pyper, B.J., F.J. Mueter, R.M. Peterman, D.J. Blackbourn and C.C. Wood, 2001. Spatial covariation in survival rates of Northeast Pacific pink salmon (*Oncorhynchus gorbuscha*). Canadian Journal of Fisheries and Aquatic Sciences 58: 1501-1515.

Ricker, W.E., 1954. Stock and recruitment. Journal of Fisheries Research Board Canada 11: 559-623.

Ryall, P., C. Murray, V. Palermo, D. Bailey and D. Chen, 1999. Status of Clockwork Chum Salmon Population and Review of the Clockwork Management Strategy. Canadian Population Assessment Secretariat Research Document 99/169. Fisheries and Oceans Canada. 134p.

Salo, E.O. 1991. Life history of chum salmon (*Oncorhynchus keta*). In Groot, C. and L. Margolis (eds.), Pacific Salmon Life Histories. Univ. B.C. Press, Vancouver, B.C., Canada. p. 231-309

Savereide, J.W. and T.J. Quinn II, 2004. An age-structured assessment model for chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 61: 974-985.

Schwindt R,A. Vining and S. Globerman, 2000. Net loss: A cost-benefit analysis of the Canadian Pacific salmon fishery. Journal of Policy Analysis and Management 19(1): 23-45.

Sethi, G., C. Costello, A. Fisher, M. Hanemann and L. Karp, 2005. Fishery management under multiple uncertainty. Journal of Environmental Economics and Management 50: 300-318.

Sumaila, U.R., 2004. Intergenerational cost benefit analysis and marine ecosystem restoration. Fish and Fisheries 5: 329-343.

Sumaila, U.R. and C.J. Walters, 2005. Intergenerational discounting: A new intuitive approach. Ecological Economics 52: 135-142.

Tully, O. and D.T. Nolan, 2002. A review of the population biology and host–parasite interactions of the sea louse *Lepeophtheirus salmonis* (Copepoda: Caligidae). Parasitoloy 124: 165-182.

Walters, C. and J. Korman, 1999. Salmon Populations. Vancouver, BC: Pacific Fisheries Resource Conservation Council. 42p.

Walters, C. and M. Parma, 1996. Fixed exploitation rates strategies for coping with effects of climate change. Canadian Journal of Fisheries and Aquatic Sciences 53: 148-158.

Walters, C., 1986. Adaptive Management of Renewable Resources. MacMillan Publishing, New York, 374p.

Walters, C., 1975.Optimal catch strategies for salmon in relation to environmental variability and uncertainty about production parameters. J. Fish. Res. Board Can. 32: 1777-1784.

Weitzman, M.L, 2001. Gamma discounting. American Economic Review 91(1): 260-271.

Chapter 5 Economic Analysis of Netcage Versus Sea-bag Production Systems for Salmon Aquaculture in British Columbia[14]

5.1 Introduction

Conventional open netcage systems for salmon aquaculture are under scrutiny and criticism partly because they are believed to generate environmental problems, such as waste discharge, spread of disease, and escaped fish. Such problems could have potential impacts on other resource users and on the surrounding marine environment (SAR, 1997; Volpe *et al.,* 2000 & 2001; Naylor *et al.,* 2003; Morton *et al.,* 2004; Naylor *et al.,* 2005; Krkošek *et al.,* 2006). In a netcage system, there are no solid barriers between the cages and the surrounding environment. Therefore, it can be difficult to effectively mitigate or prevent these environmental or ecological problems. Enclosed systems, such as land-based and sea containment systems, have been proposed and promoted for salmon aquaculture in response to the criticism of conventional open netcage systems. These enclosed systems physically isolate cultured fish from the surrounding environment. Some environmental problems created by netcage systems mentioned earlier can be prevented or minimized. For example, the solid waste could be collected and treated, and wastewater could be filtered before released into the environment.

In British Columbia, a few trials using enclosed systems for salmon aquaculture have been conducted since 2003. These operations are directed by the British Columbia Provincial Government and supported by the Federal Government with tax credits given by the Canadian Customs and Revenue Agency (CCRA, 2004) under the program of Scientific Research and Experimental Development. The results from the first cycle of these trials were mixed. On the one hand, enclosed systems appear to be biologically, environmentally,

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and technically promising; on the other hand, they are financially demanding due to the high initial capital and operational costs entailed.

A prerequisite for a successful aquaculture venture is the ability to generate sufficient economic returns to cover all costs, including repayment of capital investment. It should also satisfy producer's expectations. For instance, the goal of a subsistence aquaculture activity is to sustain the farmer's livelihood, while a commercial aquaculture operation, like salmon aquaculture, aims to maximize its profits. In general, commercial producers will not engage in an operation that does not make a positive net economic return. Aquaculture operations require natural and human resources to generate outputs and services, while they also have potential to impose environmental costs on the environment and natural resources. If these environmental costs are not incorporated into their production making process, the society as a whole has to bear them. Therefore, evaluating the feasibility of an aquaculture venture should also account for these environmental costs. In other words, a successful aquaculture operation should not only be financially profitable to an aquaculture producer, but it should also be socially and environmentally benign. Like any economic activity, both open netcage and sea-bag systems for salmon aquaculture potentially create environmental costs. However, anecdotal evidence suggests that enclosed systems impose less external costs on other resource users and the surrounding environment than netcage systems in terms of waste, diseases, escapees and interaction with marine mammals, even though this system has higher initial capital and operating costs. Thus, this research examines the profitability of netcage and sea-bag systems with and without environmental costs embedded on salmon aquaculture practice in BC.

5.2 Materials and Methods

5.2.1 Salmon Aquaculture Systems

At present, two culture systems for salmon aquaculture are employed: open netcage and enclosed systems, including sea-bag and land-based systems. Almost all commercially farmed salmon worldwide are produced in open netcage systems. However, enclosed systems have received increasing interest for the last decade. Small- or experimental scale operations in have been carried out, such as land-based systems in Iceland and sea-bag systems in Australia, Canada and the United States (pers. comm.: Clark, Future Sea Technologies Ltd; Gústavsson, Holar University, Iceland; and Meilahn, MariCulture Ltd; SAR 1997). Land-based systems for the salmon grow-out stage have been shown to be economically unfeasible in British Columbia due to considerably high capital costs (SAR, 1997; Walker, AgriMarine Industries Inc. pers. comm.). Thus, land-based systems are excluded, and I only consider open netcage and sea-bag systems in this study.

Open Netcage System

A typical open netcage system is made up of a steel or HDPE (High Density Polyethylene) frame, over which treated nets are stretched. A bird net covers the top of the netcage in order to prevent birds from diving for fish, and a predator net is strung beneath and around the cage in order to deter marine mammals from attacking fish. Cages are arranged in double rows, typically in sets of 6, 10, and 16, and they are anchored in the shelter inlets and bays near shore. The sizes of cages vary, ranging from 15 x 15 x 15 m to 40 x 40 x 20 m, depending on production capacity, stage of operation and availability of operating capacity. The small cages (15 x 15 x 15 m) are preferred for the early stage and transition period, while larger cages (30 x 30 x 15 m) are preferred for the grow-out stage.

Sea-bag Systems

The sea-bag system analyzed in this study is designed and produced by Future Sea Technologies Inc. based in BC (http://www.futuresea.com/). The systems use soft ("non-ridged") bags, which float on the sea surface. A typical module of a sea bag system includes four bags (2,000 m^3 each), a walkable flotation collar, 12 kWh electric pumps, 20 m intake depth, waste treatment (including four waste traps and one concentrator), four bag oxygen monitoring systems, bird nets and one harvest device (Clark, pers. comm.). Deep water is continuously pumped into the bags for replenishing oxygen, with additional oxygen injected when large amounts of fish are confined. Solid waste is collected in the waste traps for disposal. Soluble wastewater is discharged into the sea hundreds of meters away from the systems, mostly without treatment. Each aquaculture operation can have one or more modules of sea-bag systems dependent on production capacity. However, sea-bag systems are still in the early stages of development for salmon grow-out in the open waters, and more trials on large commercial scales are needed to test their viability.

5.2.2 Production Capacity/Farm Size

Based on salmon aquaculture operations in British Columbia, I simulated salmon aquaculture practices with three different production capacities (small, medium and large). The size of the cage for netcage system is different from the size of the bag for sea-bag systems. Assuming the size of netcage systems is about 12,000 m^3 (30 x 30 x 15 m) per cage, and the size of the sea-bag system is 2,000 m^3 per bag. The average fish density through the whole grow-out stage is assumed to be approximately 10 - 12 kg/m^3 for netcage systems, and 30 - 35 kg/m^3 for sea-bag systems. The density assumptions are conservative for netcage systems because some salmon farmers operate at higher fish densities. Nevertheless, aquaculture operations face lower risks of susceptibility to disease problems at lower fish densities. Based on the sizes of cage and bag and fish density assumed, on average, the production level of netcage systems is estimated at about 120 tonnes per cage, while the production level of the sea-bag system is set at about 60 tonnes per bag. Hence, the respective production capacities of the designed farm sizes from small, medium to large are 720, 1,200 and 1,920 tonnes, which correspond to 6, 10, and 16 cages and the number of sea-bag modules of 3, 5 and 8, respectively. A single farmed salmon growth cycle is estimated to be between 16 - 24 months dependent on location, temperature and feeding (Bjørndal, 1990). For the analysis herein, I assume that a single marine growth cycle is 20 months (including fallowing period) for both systems, which implies that the two systems operate 12 cycles within a 20-year time horizon. Twenty year is the average tenure for an aquaculture licence in British Columbia. I assume that smolts are released into cages or sea bags at the same time in Year t, and salmon are harvested after each growth cycle. In fact, farmers prefer to release smolt and harvest salmon at different times of the year in order to take advantage of high market prices.

5.2.3 Economic Analysis

I use capital budgeting and investment appraisal analyses to compare the financial performance of the two systems. These approaches are widely used in aquaculture economic studies (e.g., Hatch and Tai, 1997; Engle *et al.*, 2005; Pomeroy *et al.*, 2006; Whitmarsh *et al.*, 2006). First, I construct a capital budget analysis of both systems using biological and physical components of salmon aquaculture in the two systems, and financial data associated with the costs and prices of farmed salmon. Due to the physical structural differences of the two systems, the capital costs differ between them. Then, I apply investment appraisal analysis to examine the financial feasibility of the two systems using the net present value (NPV) criteria. The aquaculture operation bears costs and yields revenues over time, and the future revenues and costs must be discounted into present values. The net present values (NPVs) from the aquaculture operations are determined based on the expected revenues and the costs incurred over the time horizon of the project. In NPV analysis, a discount rate which is the minimum desired rate of refund for the project is used. If the NPV is positive, it indicates that the project is financially worthwhile, and *vice versa*. Further, I also construct projected cash flow analysis to check the cash into and out of the operation in each growth cycle. Since some capital costs are replaced periodically, capital costs vary in different growth cycles.

In addition to NPVs, other financial/economic indicators, such as internal rate of return (IRR), break-even analysis (i.e., break-even price and production) are also applied. IRR calculates the break-even rate of return from a capital investment. In other words, it is the rate when the NPV equals zero. If the discount rate used for calculating NPVs is below IRR, it indicates that the NPV is positive, *vice versa*. The higher an IRR, the more desirable it is to invest. Break-even analysis usually calculates production level and sales price at the break-even point at which sales revenues equal production costs. Any production level or sales price which is above break-even values represents increased profits. Some key variables in our analyses face different degrees of uncertainties; therefore, sensitivity analyses are carried out to examine the robustness of the results of these variables. The following section will describe the estimates of initial capital costs, annual operating costs and revenues of both systems for each farm size.

Costs

Licensing and Leasing Costs

To get a salmon aquaculture license in British Columbia, a number of fees must be paid. These fees include a tenure application fee, an aquaculture license fee, environmental assessment and public consultation fee, and a fee for leasing and licensing crown land. The single biggest expense is environmental assessment and public consultation fee, which ranges from $50,000 to $500,000 (Matthews, Seafood Development Branch, British Columbia Ministry of Agriculture, Food & Fisheries, and Williams, Land and Water British Columbia Inc., pers. comm.). All the values in this paper are in Canadian dollars unless otherwise specified. This study assumes an average fee of $300,000. The estimates of other costs are based on the new British Columbia policy for finfish aquaculture that came into effect on April 1, 2004 (http://lwbc.bc.ca/02land/tenuring/aquaculture/finfish/). On average, the total cost of obtaining a salmon aquaculture license is estimated at about $315,386; $327,644 and $342,163 for the production capacities of 720, 1,200 and 1,920 tonnes, respectively. The same guidelines and application procedures are applied to both open netcage and sea-bag cultured systems (Matthews and Williams, pers. comm.). Thus, I assume that netcage and sea-bag systems face the same licensing and leasing costs at the same production capacity. A five-year licence is issued initially until the site is determined to be viable by the Provincial Government, and then a 20-year lease is offered which is the standard term for a lease (LWBC, 2004).

Initial Capital Costs

The capital investment costs include the costs of farm facilities on land and in the sea and associated supporting facilities. The facilities in the sea consist of netcage/sea bag systems, treated nets/bags, predator nets for marine mammals and sea birds, mooring or installation systems, feeding and monitoring systems, barge (floating house), storage, dock; while land facilities include the administration and general service building, storage building for nets and feed, and office supplies (e.g., telephone, computer, printer). The associated supporting facilities include boats, pumps, generators, and diving equipments. I applied 2004 prices for raw materials. A 10% contingency is included in the capital cost to account for the uncertainty of cost items, in particular, the price fluctuation of components for the facilities.

This is the lower end of the 10 - 35% contingency proposed for land-based aquaculture facility (SAR, 1997). The data sources for cost estimations are very diverse, including government documents, survey reports, personal interviews, and consultation with experts, and these are detailed in the notes under Table 5.1 & 5.2. These costs are incurred in Year 0 and replaced periodically based on their useful life. I assume that salvage values of cost items at the end of the project are zero.

Table 5.1. Estimated capital investment costs and annual depreciation for netcage systems by different cost items.

Cost item	Cost by size ($)			Useful life (yrs)	Annual depreciation by size ($)		
	720 t	1,200 t	1,920 t		720 t	1,200 t	1,920 t
Netcage system[1]	450,000	750,000	1,200,000	10	45,000	75,000	120,000
Treated nets/bags[2]	75,000	135,000	236,000	4[a]	18,750	33,750	59,000
Predators nets[3]	35,000	64,000	126,000	4[a]	8,750	16,000	31,500
Anchor[4]	26,000	52,000	98,000	10	2,600	5,200	9,800
Mooring/Installation[5]	42,000	63,000	95,000	10	4,200	6,300	9,500
Feeding system[6]	125,000	150,000	180,000	10	12,500	15,000	18,000
Monitoring system[7]	10,000	15,000	25,000	10	1,000	1,500	2,500
Barge (floating house)[8]	50,000	50,000	50,000	20	2,500	2,500	2,500
Storage building (floating)[9]	30,000	30,000	30,000	20	1,500	1,500	1,500
Boats[10]	32,000	32,000	32,000	20	1,600	1,600	1,600
Boat motors[11]	13,000	13,000	13,000	10	1,600	1,600	1,600
Water pumps[12]	4,000	4,000	4,000	10	1,300	1,300	1,300
Generators[13]	14,000	21,000	28,000	10	400	400	400
Diving/lab equipment[14]	20,000	20,000	20,000	10	1,400	2,100	2,800
House/storage (on land)[15]	60,000	60,000	60,000	20	2,000	2,000	2,000
Office supplies[16]	20,000	20,000	20,000	5	3,000	3,000	3,000
Contingency (10%)	100,000	148,000	222,000		4,000	4,000	4,000
Grand Total	**1,106,000**	**1,627,000**	**2,439,000**		**112,100**	**172,750**	**271,000**

[1] The costs of netcage systems are estimated using the information from WaveMaster Canada Ltd., and the costs of sea bag systems are estimated using the information from Future Sea Technologies Inc.;

[2 & 3] The costs of treated/predator nets are estimated using the information from Cards Aquaculture Products Ltd.;

[4] Anchor estimate is determined using information from WaveMaster Canada Ltd.;

[5] Mooring/installation estimate is determined by using information for netcage systems from G_3-Consulting (2000) and for sea-bag systems from Future Sea Technologies Inc.;

[6 & 7] Feeding and monitoring system estimates are determined using information provided by the Norcan Electrical Systems Inc.;

[7-16] The other estimates are based on data in BCACFB (1989) and adjusted with an increase of 10-20% of original values;

[a] These items are replaced every two growth cycles (about 3.3 years) in netcage systems.

Table 5.2. Estimated capital investment costs and annual depreciation for sea-bag systems.

	Cost by size ($)			Useful life (yrs)	Annual depreciation ($)		
Cost item	720 t	1,200 t	1,920 t		720 t	1,200 t	1,920 t
Sea-bag system[1]	2,112,000	3,440,000	5,312,000	8[b]	264,000	430,000	664,000
Mooring/Installation[5]	56,000	70,000	83,000	8[b]	7,000	8,750	10,375
Feeding system[6]	125,000	150,000	180,000	10	12,500	15,000	18,000
Monitoring system[7]	10,000	15,000	25,000	10	1,000	1,500	2,500
Barge (floating house)[8]	50,000	50,000	50,000	20	2,500	2,500	2,500
Storage building (floating)[9]	30,000	30,000	30,000	20	1,500	1,500	1,500
Boats[10]	32,000	32,000	32,000	20	1,600	1,600	1,600
Boat motors[11]	13,000	13,000	13,000	10	1,300	1,300	1,300
Water pumps[12]	4,000	4,000	4,000	10	400	400	400
Generators[13]	28,000	42,000	56,000	10	2,800	4,200	5,600
Diving/lab equipment[14]	20,000	20,000	20,000	10	2,000	2,000	2,000
House/storage (on land)[15]	60,000	60,000	60,000	20	3,000	3,000	3,000
Office supplies[16]	20,000	20,000	20,000	5	4,000	4,000	4,000
Contingency (10%)	256,000	395,000	588,000				
Grand Total	**2,816,000**	**4,341,000**	**6,473,000**		**303,600**	**475,750**	**716,775**

[1] The costs of netcage systems are estimated using the information from WaveMaster Canada Ltd., and the costs of sea bag systems are estimated using the information from Future Sea Technologies Inc.;

[2 & 3] The costs of treated/predator nets are estimated using the information from Cards Aquaculture Products Ltd.;

[4] Anchor estimate is determined using information from WaveMaster Canada Ltd.;

[5] Mooring/installation estimate is determined by using information for netcage systems from G$_3$-Consulting (2000) and for sea-bag systems from Future Sea Technologies Inc.;

[6 & 7] Feeding and monitoring system estimates are determined using information provided by the Norcan Electrical Systems Inc.;

[7-16] The other estimates are based on data in BCACFB (1989) and adjusted with an increase of 10-20% of original values;

[b] Replaced at the growth cycle of 5 and 10 (about 8.3 and 16.7 years, respectively), and only one fourth of system, including sea-bag, pumps, waste management device, etc are replaced, not the whole sea-bay system.

Annual Operating Costs

Operating costs are expenses incurred during aquaculture operations each year. They include variable and some elements of fixed costs. Variable costs consist of feed, smolts, labour, energy, maintenance/repairs, drugs and transportation; while fixed costs include overhead (administrative and general service), asset insurance premiums, depreciation, annual land leasing and licensing fee. Due to commercial confidentiality and lack of records, it is very difficult to get first-hand data on operating costs directly from salmon aquaculture producers. However, Statistics Canada has been conducting an annual experimental survey nationwide since 1997, and its reported value added data are used to estimate annual operating costs for netcage systems. These data cover all aquaculture sectors, including finfish and shellfish aquaculture, and sources of output and product inputs. However, salmon aquaculture dominates the BC aquaculture industry accounting for 90 - 95% of the total values and production (DFO, 2005).

The survey data show that total operating costs declined from 1997 – 2002, and increased in the years 2003 and 2004 (Figure 5.1). The declining trend seen from 1997 – 2002 was mainly because of increased efficiency of feeding and feed conversion ratios, increased supply of smolts, increased efficiency in fish processing and distribution, economies of scale and better management practices (Bjørndal, *et al.,* 2002 & 2003). It should be noted that the cost of feed, labour, therapeutants and depreciation showed increasing trends during the last few years. The reason for the increasing cost of feed may be the increasing demand of fish feed for finfish aquaculture worldwide, which has been growing dramatically. The reason for the increasing costs of other factors may be associated with growing risks associated with operations. For instance, disease and parasite occurrence has been increasing and this has become one of the limiting factors for the development of salmon aquaculture.

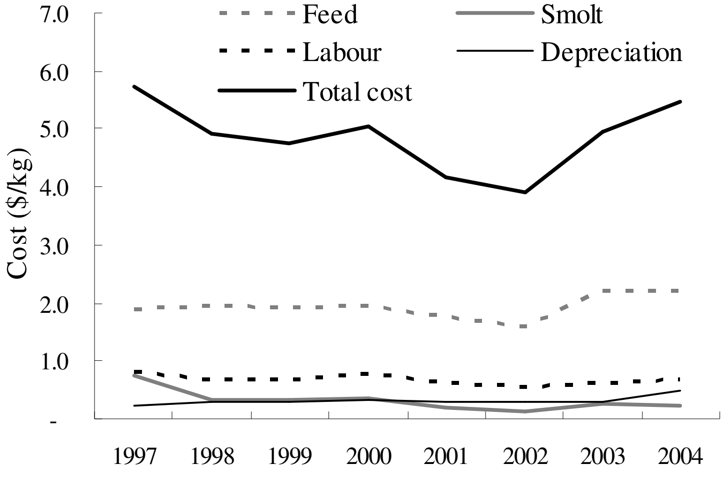

Figure 5.1. Nominal costs of some input factors for salmon aquaculture in British Columbia from 1997 – 2004.

Based on production inputs and total production, I calculated the cost per kg of production for each input item. Among production inputs, the costs of feed and smolts are determined by using the production of finfish aquaculture, and the rest is estimated by using the production of all aquaculture, including finfish and shellfish. The average cost of each item from 1997 – 2004 is calculated and assumed to be the operating costs of netcage systems.

The operating costs of sea-bag systems are estimated based on a couple of data sets and related information, including a pilot project and operations for other species (e.g., trout) in other geographic locations. The pilot project was a joint operation between Future Sea Technologies and Marine Harvest for salmon grow-out in Salt Spring Island, BC. The results from the first cycle of operation showed a lack of technical efficiency with little economic promise due to logistics and technical difficulties (Clark, pers. comm. and Dubreuil, 2003). A second operation is underway. However, the sea-bag system has been successfully used for trout farming and finfish hatcheries in Chile and Eastern Canada, as well as a full grow-out for salmon aquaculture in Tasmania (G_3-Consulting, 2000). Further, the operating costs between cage systems and sea bag systems for Coho salmon in the Kisutch Inlet, British Columbia has also been assessed (G_3-Consulting, 2000).

Based on these data and the estimated capital costs, I differentiate the costs between both systems in order to estimate the operating costs for sea-bag systems: i) depreciation is estimated based on the capital investment for sea-bag systems; ii) labour cost is estimated to be 10% higher in sea-bag systems than those in netcage systems reflecting increased person-hours for cleaning the bags, pumps, waste collections and maintaining other facilities; iii) the amount of interest paid on loans for sea-bag systems is around 2.3 times that for netcage systems based on the ratio of capital costs for netcage and sea-bag systems; iv) energy use in sea-bag systems is assumed to be five times higher than in netcage systems because of oxygen consumption and fuel consumption for pumping (oxygen & electricity) in sea-bag systems; it could be even higher if there is an inadequate supply of oxygen; and v) other inputs are assumed to have the same costs as netcage systems. Table 5.3 summarizes annual revenues and operating costs for both systems.

Table 5.3. Summary of the enterprise budget over a single production cycle of netcage and sea-bag production systems.

	Netcage system			Sea-bag system		
Production (tonnes)	720	1,200	1,920	720	1,200	1,920
Revenue @$4.47/kg ('000$)	3,218	5,364	8,582	3,218	5,364	8,582
Cost items ('000$)						
Variable cost						
Feed	1,416	2,360	3,776	1,416	2,360	3,776
Smolt	222	369	591	222	369	591
Labor	489	815	1,304	538	897	1,435
Insurance	61	101	162	61	101	162
Energy	51	85	137	256	427	684
Maintenance	117	195	313	117	195	313
Professional	53	88	141	53	88	141
Therapeutants	54	91	145	54	91	145
Others	223	372	595	223	372	595
Total variable cost	2,686	4,476	7,164	2,940	4,900	7,842
Fixed cost						
Interest	93	156	249	215	358	572
Leasing/licensing	12	22	37	12	22	37
Depreciation	111	172	270	128	189	274
Total fixed cost	216	350	556	532	857	1,327
Environmental cost (EC)	39	55	78	-	-	-
Grand Total cost without including EC	2,902	4,826	7,720	3,472	5,757	9,169
Grand Total cost with including EC	2,941	4,881	7,798	3,472	5,757	9,169

I have acknowledged that it would be more useful if the operating costs are estimated based on the quantity used and their market prices. As it is almost impossible to do so, I have to use the operating costs estimated based on the financial surveys for the analyses. However, for the benefit of readers in the future, I have estimated the costs of major items, such as feed, smolt and labor, based on the quantity used and their price/wage (see Table 5.4 – 5.6) I assumed. The costs for smolt and feed are very close between the two estimates, but there is a bigger difference for labor cost. In the financial survey, labor cost is about 18% of total variable cost, on average, which is reasonable. In this estimate, I calculated labor cost based on the possible number of employees, their weekly wages, and benefits paid for employees (15% of total wages). I divided employees into five categories: general worker, site supervisor, administrator, manager and consultants. Their wages are estimated based on the study conducted by Ralph Matthews (unpublished). In the analyses below, these estimates for feed, smolt and labor are not used because their estimates were based on a number of assumptions, which are difficult to validate in BC. Instead, I had to use the results from annual surveys conducted by the government.

Table 5.4. Estimated Feed cost based on the quantity used and price

Production capacity	Quantity* (tonnes)	Price ($/t)	Cost** ('000$)
720	900	1,200	1,350
1,200	1,500	1,200	2,250
1,920	2,400	1,200	3,600

* The quantity of feed is estimated based on feed conversion ratio, 1.25;

** Additional 25% of feed cost is included as transport, temporary storage and special feed need, such as medicated feed and dyed feed.

Table 5.5. Estimated smolt cost based on quantity used and price

Production capacity	quantity ('000#)	Price ($/smolt)	Cost* ('000$)
720	270	~1.0	270
1,200	450	~0.9	405
1,920	720	~0.8	576

* It is estimated based on survival rate (90%), weight at harvest (3kg) and smolt weight (0.5kg/smolt).

Table 5.6. Estimated labour cost based on the numbers of employee assumed and their weekly wages.

Production capacity	Type of employee	quantity (#)	Wage ($/week)	Cost ('000$)
720	Worker	6	500	179
	Supervisor	2	700	84
	Administrator	2	500	60
	Consultant@2,000/month			24
	Manager	1	900	54
	Total			401
1,200	Worker	8	500	239
	Supervisor	2	700	84
	Administrator	2	500	60
	Consultant@2,000/month			24
	Manager	1.5	900	81
	Total			487
1,920	Worker	9	500	269
	Supervisor	2	700	84
	Administrator	2	500	60
	Consultant@2,000/month			24
	Manager	2	900	108
	Total			544

Price and Revenue

Over the years, the average prices for farmed salmon have fluctuated, with a steady decline mainly due to increasing supply and declining costs of production worldwide (Figure 5.2) (Bjørndal *et al.,* 2002; Knapp, 2005). The decline has accelerated in recent years with dramatically increasing supply from Chile (Bjørndal *et al.,* 2003; Sumaila *et al.*, 2007). It is predicted that the price for farmed salmon will continue to decline if farmed salmon production continues to increase while the cost of production keeps declining (Knapp, 2005). It should be noted that Chile is planning to double its current production level over the next five years. However, in addition to the production level and production cost, the market price of farmed salmon is also affected by other factors, such as wild salmon landings and development in international markets.

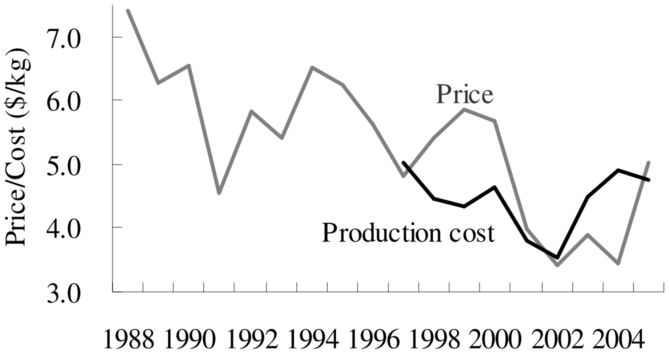

Figure 5.2. Nominal production cost and price of salmon aquaculture in British Columbia from 1988 – 2005.

BC accounts for less than 5% of the total world farmed salmon production, and most of BC's salmon products are exported to US markets. Thus, BC alone has no power to influence world prices for farmed salmon; in contrast, prices for farmed salmon in BC are determined by other larger players, such as Norway and Chile. Atlantic salmon (*Salmo salar)* is the dominant farmed species in BC, and it generally obtains slightly lower prices than native farmed Pacific salmon. In this study, the average market price for farmed salmon in BC from 1997 – 2004 is estimated and used, which is about $4.47 per kg in live weight. The market price is calculated by dividing the farmgate production with the farmgate value each year (DFO, 2005). The reason for using this average price instead the current price is that current price is lower than operating cost, therefore is no need to conduct any further analysis. However, a sensitivity analysis using different prices is conducted. I assume that the market price for salmon will remain constant because it is difficult to predict the price changes in the future.

Environmental Costs

Like any economic activity, both systems potentially generate environmental costs that may be imposed on other resource users and the environment. In general, the major problems causing environmental costs in netcage systems are waste discharge, escaped fish, spread of disease and interactions with marine mammals, while sea-bag systems have little or none of these problems because of the distinct confinement. The types and magnitudes of these environmental costs vary depending on a number of factors, such as location, production level, topography and management practice. It is difficult to directly capture these environmental costs due to the complexity of the impacts and the lack of market mechanisms. Several studies have estimated the environmental costs related to the waste discharge from netcage systems for salmon and from flow-through systems for trout (e.g., Folke *et al*., 1994; Smearman *et al.,* 1997; EPA, 2002a&b). These studies indicated that the environmental costs ranged widely, from the highest, at US$1.35, to the lowest, at US$0.032 per kg of production. These estimates applied different economic methods, which generated different results. Some results, however, are debatable (e.g., Black *et. al.,* 1997; Folke *et al*., 1997).

Instead of using environmental costs directly estimated from the damages associated with environmental problems, I use treatment or compliance costs of implementing environmental regulations designed by the authorities as a proxy in this study. For example, the US Environmental Protection Agency (EPA) proposed a series of technical and practical options as regulatory requirements and/or guidance to minimize and/or prevent wastes from netcage systems for salmon aquaculture being produced in the natural environment. These regulatory requirements include feed management – best management plans (including solid), drugs and chemical best management plans and active feed monitoring. The cost of implementation of these requirements consists of capital costs (e.g., underwater camera with computer interfaces), one-time costs (e.g., professional service and training), and operational and management costs (e.g., extra labour and time). The methodology and process of cost estimation can be found in EPA (2002a & 2002b). There is no regulation and cost for the facilities for salmon production less than 215 tonnes (i.e., < 475,000 pounds), and for the production levels larger than 215 tonnes, there are regulations and associated costs applied (EPA, 2002b).

The compliance cost changes with different production capacities. For instance, Engle *et al.* (2005) revealed that the different farm sizes bear different treatment costs. However, based on the information provided and costs estimated in the EPA's report, I have identified and estimated capital and operational costs for different production capacities. The environmental costs are estimated to be about \$0.054, \$0.046 and \$0.041 for the production capacities of 720, 1,200 and 1,920 tonnes, respectively (EPA, 2002b; Naylor *et al.*, 2003). These costs are about 1% - 1.4% of total production costs. As mentioned earlier, sea-bag systems include waste collection and treatment devices and require a high level of maintenance, thus, sea-bag systems should also have environmental costs, for instance, implementing BMP plans. If I calculate environmental costs for sea-bag system based on the estimates for netcage system, the environmental costs for sea-bag systems are negligible relative to their very high production costs. Therefore, I have to make another strong assumption: there is zero compliance cost for sea-bag systems in terms of waste matter.

5.3 Results

Tables 5.7&5.8 list the projected cash flows of selected growth cycles which represent the capital replacement costs. Projected 20-year (i.e., 12 cycles) cash flows indicate that netcage systems at all production capacities have positive profit gains except when capital investment cost is first incurred or replaced in Cycles 1 and 6 (equivalent to Years 1 and 10, respectively). Sea-bag systems have net losses during Cycles 1, 5, 6 and 10 (roughly equivalent to Years 1, 8-10, 16), and they have positive profit gains in other cycles. Further, the magnitude of positive profit gains is relatively small compared to net losses in sea-bag systems. The higher production capacities have larger profit gains or losses than lower production capacities (Tables 5.7&5.8).

Table 5.7. Summary of projected 20-year cash flows in thousand Canadian dollars for netcage production systems

	Cycle 1 (yr1-2)	Cycle 3 (yr 5)	Cycle 5 (~yr8)	Cycle 6 (yr 10)	Cycle 9 (yr 15)	Cycle 12 (~yr 20)
(i) projected 20-year cash flow for netcage system with a production level of 720 tonnes						
Beginning cash balance	0	-569	+427	+317	+427	+317
Capital equipment purchase	-1,422	-129	-109	-723	-129	0
Cash receipts/sale income	+3,218	+3,218	+3,218	+3,218	+3,218	+3,218
Cash outflow/operating expenses	-2,792	-2,792	-2,792	-2,792	-2,792	-2,792
Ending cash balance	-995	+297	+317	-296	+297	+427
(ii) projected 20-year cash flow for netcage system with a production level of 1,200 tonnes						
Beginning cash balance	0	-535	+790	+510	+709	+510
Capital equipment purchase	-1,953	-219	-199	-1,091	-219	0
Cash receipts/sale income	+5,364	+5,364	+5,364	+5,364	+5,364	+5,364
Cash outflow/operating expenses	-4,655	-4,655	-4,655	-4,655	-4,655	-4,655
Ending cash balance	-1244	+490	+510	-381	+490	+709
(iii) projected 20-year cash flow for netcage system with a production level of 2,000 tonnes						
Beginning cash balance	0	-512	1,133	+772	+1,133	+772
Capital equipment purchase	-2,779	-382	-362	-1682	-382	0
Cash receipts/sale income	+ 8,582	+ 8,582	+ 8,582	+ 8,582	+ 8,582	+ 8,582
Cash outflow/operating expenses	-7,449	-7,449	-7,449	-7,449	-7,449	-7,449
Ending cash balance	-1,646	+752	+772	-548	+752	+1,133

Table 5.8. Summary of projected 20-year cash flows in thousand Canadian dollars for sea-bag production systems

	Cycle 1 (yr1-2)	Cycle 3 (yr 5)	Cycle 5 (~yr8)	Cycle 6 (yr 10)	Cycle 9 (yr 15)	Cycle 12 (~yr 20)
(i) projected 20-year cash flow for sea-bag system with a production level of 720 tonnes						
Beginning cash balance	0	-3,030	-2,947	-3,497	-3,544	-3,994
Capital equipment purchase	-3,133	-20	-584	-219	-20	0
Cash receipts/sale income	+3,218	+3,218	+3,218	+3,218	+3,218	+3,218
Cash outflow/operating expenses	-3,167	-3,167	-3,167	-3,167	-3,167	-3,167
Ending cash balance	-3,081	-32	-533	-167	+32	+52
(ii) projected 20-year cash flow for sea-bag system with a production level of 1,200 tonnes						
Beginning cash balance	0	-4,500	-4,353	-5,199	-5,212	-5,911
Capital equipment purchase	-4667	-20	-930	-263	-20	0
Cash receipts/sale income	+5,364	+5,364	+5,364	+5,364	+5,364	+5,364
Cash outflow/operating expenses	-5,280	-5,280	-5,280	-5,280	-5,280	-5,280
Ending cash balance	-4,584	+64	-864	-179	+64	+84
(iii) projected 20-year cash flow for sea-bag system with a production level of 2,000 tonnes						
Beginning cash balance	0	-6550	-6305	-7584	-7504	-8538
Capital equipment purchase	-6,815	-20	-1411	-317	-20	0
Cash receipts/sale income	+8,582	+8,582	+8,582	+8,582	+8,582	+8,582
Cash outflow/operating expenses	-8,450	-8,450	-8,450	-8,450	-8,450	-8,450
Ending cash balance	-6,682	+112	-1,279	-185	+112	+132

The NPVs reported herein are the net present values before tax. The discount rate is assumed to be 7%. The reason for choosing this rate is because Nature Resources Canada generally uses a real discount rate ranging from 5% to 10%, and with a most frequently used rate of 7% for its analyses. Table 5.7 & 5.8 summarizes the financial performance of the two systems. For netcage systems, the NPVs at all production capacities are positive except the NPV is negative at the production capacity of 720 tonnes when environmental cost is included. The NPVs are greater at higher production capacities. For sea-bag systems, all the NPVs are negative. The reasons for the differences in NPVs between two systems are because netcage system has a relatively low capital cost, and the market price is greater than its annual operating cost; while sea-bag system has a very high capital cost, and the market price is lower than its annual operating cost. When environmental costs are included, the NPVs for netcage systems are considerably reduced, but most are still positive. It indicates that the investment in netcage systems is still financially worthwhile when environmental costs are incorporated.

Furthermore, netcage systems have lower breakeven prices and production levels than sea-bag systems regardless of whether environmental costs are incorporated or not. These results are consistent with their respective annual operating costs and the market price. Thus, sea-bag systems need to obtain higher market prices to cover their high operating costs, or higher production levels for covering the capital costs. All the IRRs for netcage systems are positive and greater than the discount rate (7%) except the IRR is lower than 7% at the production capacity of 720 tonnes when environmental cost is included. The IRRs are lower when environmental costs are included. The IRRs are higher at larger production capacities. Sea-bag systems incur negative IRRs at all production capacities.

In summary, the results from NPVs, break-even, IRR and cash flow analyses demonstrate that open netcage systems have better economic performance than sea-bag systems whether environmental costs are incorporated or not. They further suggest that the investment in netcage system is financially worthwhile, and the higher financial benefits are achieved at higher production capacities. In contrast, the investment in sea-bag system is not financially worthwhile at any production capacity.

Table 5.9. Financial performance of netcage and sea-bag systems.

	Production capacity (tonnes)					
	720 t		1,200 t		1,920 t	
Economic indicators	Netcage	Sea-bag	Netcage	Sea-bag	Netcage	Sea-bag
NPV without EC (million$)	0.23	-4.62	0.93	-6.84	2.08	-9.90
NPV with EC (million$)	-0.08	-4.62	0.49	-6.84	1.46	-9.90
Breakeven price without EC ($/kg)	4.03	4.82	4.02	4.80	4.02	4.77
Breakeven price with EC ($/kg)	4.09	4.82	4.07	4.80	4.06	4.77
Breakeven production without EC (t)	649	737	1,080	1,224	1,727	1,952
Breakeven production with EC (t)	658	737	1,092	1,224	1,744	1,952
IRR without EC (%)	10.1	-	15.8	-	20.5	-
IRR with EC (%)	5.9	-	11.8	-	16.8	-

5.4 Sensitivity Analysis

Salmon aquaculture is a relatively complex economic activity, which involves biological, environmental and economic factors. Thus, there are a number of uncertainties involved with these factors. Although salmon aquaculture producers have a lot of control over the production process, there are still certain factors that are beyond their control. For instance, feed price, salmon price, environmental impacts, and unforeseen diseases are difficult to predict or control. Some parameters are crucial and may have substantial impacts on aquaculture investments and operations, such as operating costs, market prices, discount rates and environmental costs. As mentioned earlier, since I have made some assumptions in the analyses, I therefore undertook sensitivity analyses to test the robustness of the results to key parameter changes.

5.4.1 Discount Rate

Choosing an appropriate discount rate is crucial in using the NPV method for investment feasibility analysis because the future economic returns on the investment have to be discounted into present values in order to capture the time value and risks of investments. When discount rates are higher, the NPVs decline considerably because high discount rates value future benefits less than low discount rates (Sumaila and Walters, 2005). I find that no matter what discount rate is used, the NPVs for sea-bag systems are always negative because of high capital costs. The NPVs for netcage systems are higher at lower discount rates. The NPVs are higher for larger production capacities under the same discount rates. The differences in NPVs between production capacities become smaller when the discount rates increase. The NPVs become negative faster at lower production capacities, and *vice versa*. The NPVs are approaching zero at the discount rates of 10.1%, 15.8% and 20.5% for respective production capacities of 720 t, 1,200 t and 1,920 t (Figure 5.3). These discount rates are consistent with the IRRs mentioned earlier. In general, aquaculture producers adopt a higher discount rate because investment in this sector is very risky, and therefore they require a risky premium. However, there are many ways to capture risk factors, and the use of discount rates in aquaculture investment is one of these ways.

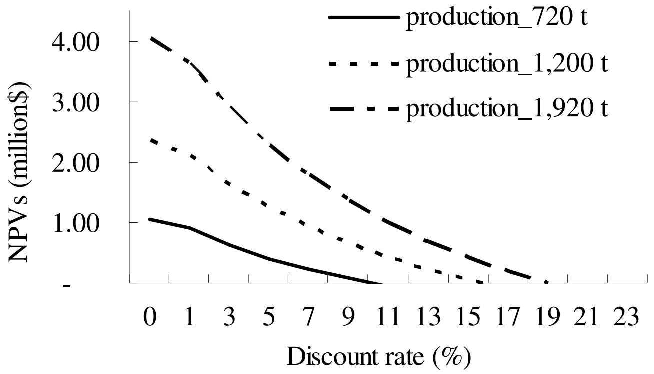

Figure 5.3. Net present values for netcage systems at different discount rates for different production capacities.

5.4.2 Feed Costs

Due to increased demand for fishmeal and fish oil and the stagnant availability of the resources used for these products, fishmeal and fish oil prices are expected to rise in the future. A 3%, 5%, 10%, 15% and 20% increase in the feed cost was simulated while the costs of other inputs remained constant. In contrast, due to the technological improvement of feed formulation, fishmeal and fish oil have been replaced at a smaller amount by non-fish protein, such as soy beans (Tacon, 2004). Some believe that the use of non-fish protein sources in feed may decrease feed costs. Thus, a 1%, 3%, 5%, 10% and 20% decrease in feed cost was also performed.

For netcage systems, the results show that the NPVs remain positive when the feed cost increases by less than 3%. When increased by 3%, 5% and 10%, the NPV turns negative at the production capacities of 720, 1,200 and 1,920 tonnes, respectively. NPVs increase slowly when feed costs decrease by less than 5%, and increase dramatically when feed cost decreases by over 5%. Overall, increases or decreases in feed cost have considerable effects on the financial performance of netcage systems, as expected because feed cost is the single greatest cost for salmon aquaculture, and it accounts for 40% -45% of total operating cost. Further, the increases or decreases in feed cost have much larger impacts on lower production capacities than on higher production capacities (Figure 5.4). For sea-bag systems, NPVs are still negative when feed cost decreases by 20%. It indicates that the gains from decreases in feed cost do not offset the high capital and operating costs for sea-bag systems.

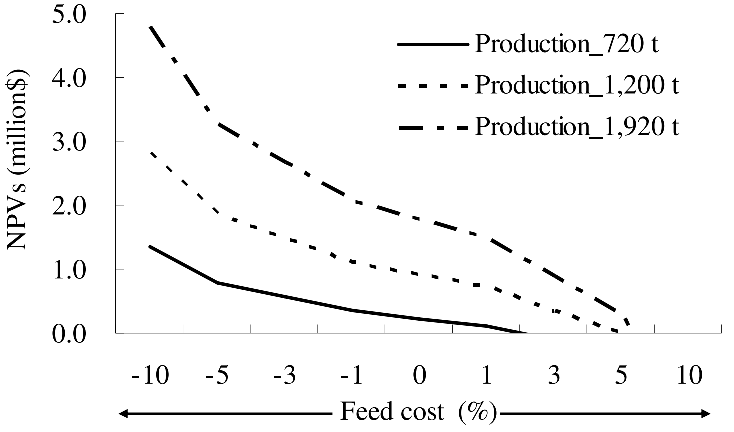

Figure 5.4. Net present values for netcage systems when feed costs increase and decrease in the percentage of feed cost for different production capacities.

5.4.3 Environmental Costs

Assumed environmental costs of \$0.054, \$0.046 and \$0.041 per kg are used in the base analyses for netcage systems, which is about 1.2% of the total production costs, on average. Because I have not estimated environmental costs directly from salmon aquaculture, I apply a series of environmental costs of \$0.05, \$0.07, \$0.10, \$0.13, \$0.15, \$0.20, \$0.25 and \$0.30 per kg of farmed salmon for netcage systems. In terms of proportion of operating cost, these comprise 1.2%, 1.7%, 2.5%, 3.2%, 3.7%, 5.0%, 6.2%, and 7.4% of total operational costs, respectively. The results reveal that all NPVs for netcage systems decline when environmental costs increase. The NPVs turn negative when environmental costs increase to \$0.05/kg (1.2%) for a production capacity of 720 tonnes, and \$0.10/kg (2.5%) for production capacity of 1,200 tonnes and \$0.13 (3.2%) for the production capacity of 1,920 tonnes. It implies that an environmental cost of 3.0% of total production cost will make salmon production economically infeasible (Figure 5.5).

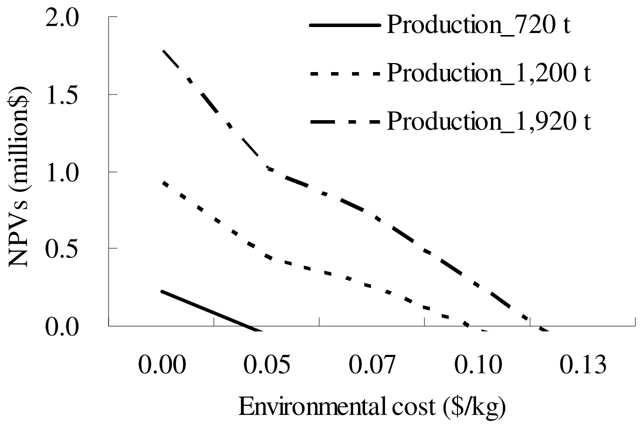

Figure 5.5. Net present values for netcage systems under different environmental costs for different production capacities.

5.4.4 Market Price

In the base analysis, I assumed that both systems obtain the same market price for their products. However, some consider the salmon produced in enclosed systems as environmentally friendly products, which may command a price premium (Sumaila *et al.*, 2007). For instance, the salmon produced in the land-based facility at Cedar, BC was labelled as 'Eco-Salmon', for which some consumers were willing to pay a price premium, 10% to 20% higher than the market prices achieved by salmon produced in netcage systems (Walker, pers. comm.). Therefore, I assume that salmon produced in sea-bag systems can also command a price premium. To test this effect, I ran our models under the assumptions of prices 10%, 15% and 20% higher than market price for sea-bag produced salmon, or prices of $4.92, $5.14, and $5.37 per kg, respectively. The results revealed that the NPVs for sea-bag systems are still negative when a less than 15% price premium is assumed, but the NPVs turn positive when a 20% price premium is achieved. The NPVs are greater at high production levels under the same price premium. Therefore, for sea-bag systems to achieve positive NPVs, a price premium of at least 20% higher than the market price for netcage systems would need to be obtained (Table 5.10).

As mentioned earlier, the salmon price used in the base analysis is price averaged across the period of 1997-2004. The yearly price during this period is either higher or lower than this averaged price, but always within ± 10%. Thus, I reduced the market price by 10% for netcage systems, to $4.02/kg, which is lower than the break-even price. The results show that, under these assumptions all NPVs turn negative whether environmental costs are included or not.

5.4.5 Feed Conversion Ratio and Survival Rate

Compared to open netcage systems, closed sea-bag systems could theoretically improve feed conversion ratio (FCR) and survival rate due to the improved environment for salmon growth and management according to the producer's suggestions (Clark, pers. comm.). Thus, I assume that the FCR for sea-bag systems is around 1.20 compared to 1.25 for netcage systems; survival rate is 92% for sea-bag systems compared to 90% for netcage systems. There currently are no data from commercial farmers to substantiate this assumption. However, trout farmers from Chile provided some positive results in the freshwater environment (Clark, 2004, pers. Com). I evaluated this scenario by adjusting the feed cost and smolt cost for sea-bag systems based on the assumed FCR and survival rates. The NPVs for sea-bag systems improved slightly compared to the results in the base analysis, and were still negative. Thus, the improved levels of FCR and survival cannot compensate for the lower NPVs (Table 5.10).

5.4.6 Growth Cycle

In the base case analysis, I assumed that the growth cycles were 20 months for both systems. Salmon in sea-bag systems may have short growth cycles without the need for that longer fallowing period required in open netcage systems. Here, I assume that sea-bag systems reduce their growth cycles from 20 months to 18 months. The results showed that the NPVs for sea-bag systems are even lower than in the base analyses (20 months). This is expected because their operating costs per unit production (kg or tonne) are higher than the market price (Table 5.10).

Table 5.10. Net present values under different values of input factors for sea-bag systems.

Value changes of inputs	Production capacity (tonnes)		
	720 t	1,200 t	1,920 t
The base NPVs at the market price ($4.47/kg)			
Netcage without EC	0.23	0.93	2.08
Netcage with EC	-0.08	0.49	1.46
Sea-bag	-4.62	-6.84	-9.90
(i) Price premium for sea-bag system			
10% ($4.92/kg)	-2.31	-2.62	-3.13
15% ($5.14/kg)	-0.83	-0.49	0.28
20% ($5.37/kg)	0.45	1.64	3.69
(ii) FCR/ survival rate			
1.20/0.92	-4.14	-6.03	-8.60
(iii) Growth cycle			
18 month	-4.66	-6.89	-9.96
(iv) Combination (FCR + survival rate + growth cycle + price premium)			
10% ($4.92/kg)	-1.45	-1.55	-1.42
15% ($5.14/kg)	-0.11	0.69	2.17
20% ($5.37/kg)	1.24	2.93	5.75

5.4.7 A Combination of Input Factors

Input factors for sea-bag systems were combined into a new scenario as follows: (i) the FCR is improved from 1.25 to 1.20; (ii) survival rate increases from 0.90 to 0.92; (iii) growth cycle is shortened from 20 months to 18 months; and (iv) the price premium for sea-bag products are 10%, 15% and 20% higher than the market price received by netcage systems. Table 5.10 summarizes the results of changing different input factors (i.e., price, FCR, survival rate and growth cycle). The NPVs are still negative with those combined factors. When a 15% price premium is assumed together with other factors, the NPVs for sea-bag systems are close to those for netcage systems when environmental costs are included. When a 20% price premium is assumed along with the improved FCR, survival rate and growth cycle, the NPVs at all production capacities turn positive, and they become much higher than the NPVs for netcage systems when environmental costs are not incorporated (Table 5.10).

Fish Density

The fish density used in the base analysis was 10-12 kg per cubic meter for netcage systems. This density assumption may be a lower that used by some producers who operate at higher fish densities. Thus, I tested the effects when fish densities increased to 20 kg/m^3. As a result, the capital investment cost decreased by 15%, 23% and 25% for the production capacities of 720, 1,200 and 1,920 tonnes, respectively. The NPVs increased by 65%, 49% and 39% for the production capacities of 720, 1,200 and 2,000 tonnes, respectively.

5.5 Discussions and Conclusions

In this study, I have compared the economic performance of open netcage and sea-bag systems with and without incorporating environmental costs. The main economic indicators used included the NPV, IRR, cash flow, break-even price and production level. I also conducted a sensitivity analysis for some key variables to test the robustness of the results. The key findings from this study are:

- Under the same operating conditions, netcage systems have much better financial performance than sea-bag systems;
- The NPVs for netcage systems decreased considerably when environmental costs are included; and netcage systems perform better economically than sea-bag systems when moderate environmental costs (<$0.13/kg) are included;
- The higher the production capacity, the better the economic performance of netcage systems;
- Market prices have substantial impacts on the NPVs for both systems; when the price of salmon declines by 10%, netcage systems achieve negative NPVs at all production capacities, sea-bag systems achieve positive NPVs when they enjoy at least a 20% price premium;
- Feed cost, fish density, environmental cost and discount rate have great effects on the economic performance of net-cage systems;
- Feed conversion ratio, survival rate, and growth cycle have minor effects on the financial performance of sea-bag systems.

To summarize, investment in netcage systems is more financially worthwhile than in sea-bag systems when environmental costs are modest. Investment in sea-bag systems is worthwhile only when the price premium is at least 15% higher than the base price. When the market price declines by 10%, investment in netcage systems is also not financially worthwhile. Given current slumping market prices for farmed salmon, it is difficult to achieve positive financial returns for either system. For instance, in 2002, 2003 and 2004, salmon prices were below the operating costs. Sea-bag systems may be more environmentally friendly than netcage systems, but they are more financially demanding given the high capital and operating costs. Salmon farmers have no incentive to adopt sea-bag systems without regulatory and market incentives. Sea-bag systems are still in the early developmental stage, with more trials and research needed, in particular, on large commercial scale closed systems. Open netcage systems are well established, and are still widely used for salmon aquaculture worldwide.

It should be noted that this research is based on data from salmon aquaculture operations in British Columbia, some assumptions had to be made where data were unavailable. Although this study has significance to other salmon producers and finfish enterprises in general, the quantitative results may be extrapolated only with careful assessment of assumptions to other operations in other geographical areas. However, this study does have some common implications/conclusions, which may be applicable to salmon farming in other jurisdictions, even for other finfish aquaculture.

5.6 References

BCACFB, 1989. Estimated Costs and Returns for Chinook Salmon Production in the Campbell River Area. Aquaculture and Commercial Fisheries Branch, British Columbia Ministry of Agriculture and Fisheries, Victoria, BC, 25p.

Black, E., R. Gowen, H. Rosenthal, E. Roth, D. Stechy and F.J.R. Taylor, 1997. The costs of eutrophication from salmon farming: implications for policy—a comment. Journal of Environmental Management 50(1):105-109.

Bjørndal, T., 1990. The Economics of Salmon Aquaculture. Blackwell Scientific Publications, London, 118p.

Bjørndal, T., G.A. Knapp, and A. Lem, 2003. Salmon: a study of global supply and demand. SNF/Centre for Fishery Economics Series/Report no.: 92. 154p.

Bjørndal, T., R. Tveterås and F. Asche, 2002. The development of salmon and trout aquaculture. In Paquotte, p., C. Mariojouls and J. Young (Eds): Seafood Market Studies for the Introduction of New Aquaculture products. Cahiers Options Méditerranéennes 59: 101-115.

CCRA, 2004. Scientific Research and Experimental Development Program: Supporting Canadian Innovation. Canada Revenue Agency, available at http://www.cra-arc.gc.ca/taxcredit/sred/menu-e.html, accessed in August 2004.

DFO, 2005. Statistical Services - Aquaculture. Fisheries and Oceans Canada, available at http://www.dfo-mpo.gc.ca/communic/statistics/aqua/index_e.htm, accessed in November 2005.

Dubreuil, M., 2003. Economic Performance of Atlantic Salmon in the Sea System II Relative to Conventional Netcages. Future Sea Ltd and Ministry of Agriculture, Food and Fisheries Province of British Columbia, 3p.

Engle, C.R., S. Pomerleau, G. Fornshell, J.M. Hinshaw, D. Sloan and S. Thompson, 2005. Englehe economic impact of proposed effluent treatment options for production of trout *Oncorhynchus mykiss* in flow-through systems. Aquacultural Engineering 32(2): 303-323.

EPA, 2002a. Development Document for Proposed Effluent Limitations Guidelines and Standards for the Concentrated Aquatic Animal Production Industry Point Source Category. Engineering & Analysis Division Office of Science and Technology, Environmental Protection Agency, United States, Washington, DC., 571p.

____ ,2002b. Economic and Environmental Impact Analysis of the Proposed Effluent Limitations Guidelines and Standards for the Concentrated Aquatic Animal Production Industry. Environmental Protection Agency of the United States, 293p. Available at http://www.epa.gov/guide/aquaculture/ea/complete.pdf, accessed at December 12, 2003.

Folke C, N. Kautsky and M. Troell, 1997. Salmon farming in context: response. Journal of Environmental Management 50 (1): 95-103.

Folke, C., N. Kautsky and M. Troell, 1994. The costs of eutrophication from salmon farming - implications for policy. Journal of Environmental Management 40(2): 173-82.

G_3-Consulting, 2000. Salmon Aquaculture Waste Management Review & Update. Environment & Resource Management, Pollution Prevention & Remediation Branch, BC Ministry of Environment, Lands and Parks, Burnaby, BC, 141p.

Hatch, U. and C.F. Thai, 1997. A survey of aquaculture production economics and management. Aquaculture Economics and Management 1(1): 13-27.

Knapp, G., 2005. Implications of aquaculture for wild fisheries: the case of Alaska wild salmon. Presentation for the Bevan Sustainable Fisheries Lecture Series, University of Washington, Seattle, Washington, Feb. 10. Available at http://www.iser.uaa.alaska.edu/iser/people/knapp/Knapp_UW_Bevan_Series_Salmon_Lecture_050210.pdf

Krkošek, M., M.L. Lewis, A. Morton, L.N. Frazer and J.P. Volpe, 2006. Epizootics of wild fish induced by farm fish. Proceedings of the National Academy of Sciences 103: 15506-15510.

LWBC, 2004. Aquaculture Policy. Land and Water British Columbia Inc., 116p.

Morton, A., R. Routledge, C. Peet, and A. Ladwig, 2004. Sea lice (*Lepeophtheirus salmonis*) infection rates on juvenile pink (*Oncorhynchus gorbuscha*) and chum (*Oncorhynchus keta*) salmon in the nearshore marine environment of British Columbia, Canada. Canadian Journal Fishery and Aquatic Science 61: 147-157.

Naylor, R.L., J. Eagle and W.L. Smith, 2003. Salmon Aquaculture in the Pacific Northwest - a Global Industry. Environment 45(8): 19-39.

Naylor, R., K. Hindar, I.A. Fleming, R. Goldburg, S. Williams, J.P. Volpe, F. Whoriskey, J. Eagle, D. Kelso and M. Mangel, 2005. Fugitive salmon: Assessing the risks of escaped fish from net-pen aquaculture. Bioscience 55(5): 427-437.

Pomeroy, R.S., J.E. Parks, and C.M. Balboa, 2006. Farming the reef: Is aquaculture a solution for reducing fishing pressure on coral reefs? Marine Policy 30: 111-130.

SAR, 1997. Salmon Aquaculture Review. Environmental Assessment Office, Victoria, BC, Canada, Vol 3, 201p.

Smearman, S.C., G.E. D'Souza and V.J. Norton, 1997. External costs of aquaculture production in West Virginia. Environmental and Resource Economics 10(2): 167-75.

Sumaila, U.R., 2005. Differences in economic perspectives and the implementation of ecosystem-based management of marine resources. Marine Ecology Progress Series 300: 279-282.

Sumaila, U.R. and C. Walters, 2005. Intergenerational discounting: a new intuitive approach. Ecological Economics 52 (2): 135-142.

Sumaila, U.R., J.P. Volpe, and Y. Liu, 2007. Potential economic benefit from sablefish farming in British Columbia. Marine Policy 31(2): 81-84.

Tacon, A.G.J, 2004. Use of fish meal and fish oil in aquaculture: a global perspective. Aquatic Resources, Culture and Development 1(1): 3-14.

Volpe, J.P., B.R. Anholt and B.W.Glickman, 2001. Competition among juvenile Atlantic salmon (*Salmo salar*) and steelhead (*Oncorhynchus mykiss*): relevance to invasion potential in British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 58(1): 197-207.

Volpe, J.P., E.B. Taylor, D.W. Rimmer and B.W. Glickman, 2000. Evidence of natural reproduction of aquaculture-escaped Atlantic salmon in a coastal British Columbia river. Conservation Biology 14(3): 899-903.

Whitmarsh, D.J., E.J. Cook and K.D. Black, 2006. Searching for sustainability in aquaculture: an investigation into the economic prospects for an integrated salmon-mussel production system. Marine Policy 30(3): 293-298.

Chapter 6 Conclusions, Policy Implications and Recommendations[15]

6.1 Summary

This dissertation has addressed issues related to the management and economics of salmon aquaculture with an emphasis on environmental impacts. The overall objectives of this dissertation are to examine the economic consequences of environmental issues associated with salmon aquaculture, and to explore policy implications and recommendations for reducing environmental impacts and the future development of salmon aquaculture. A number of analyses associated with salmon aquaculture are conducted. In chapter 1, salmon aquaculture and its associated environmental and economic impacts are reviewed. The economic concept of externality and methods or techniques for measuring environmental costs are also discussed. Chapter 2 assesses whether salmon aquaculture can continue growing at the current pace as many have optimistically predicted. Chapter 3 estimates pollution abatement costs from a production economic perspective. In Chapter 4, whether sea lice from salmon farms have ecological and economic impacts on wild salmon populations and fisheries is examined. A comparative analysis of netcage *vs* sea-bag production systems for salmon aquaculture is conducted in Chapter 5. Together, these analyses yield a relatively comprehensive picture of salmon aquaculture.

In the last chapter of this dissertation, first current environmental management strategies and policies for reducing environmental impacts are described; then key findings for each of the previous chapters are summarized, and policy implications and recommendations emerging from the findings in each chapter are explored; and finally conclusions are drawn based on the findings and policy implications derived from the previous chapters.

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[15] A version of this chapter will be submitted for publication. Liu, Y., Chuenpagdee, R. and Sumaila, U.R. Salmon Aquaculture and the Environment: Economic Perspectives for Policy Development.

6.2 Current Environmental Management Strategies and Policies

Current environmental management strategies and policies for salmon aquaculture are in the forms of a series of environmental regulations, management planning and monitoring procedures. The formulation and implementation of these environmental regulations are complex. Ecological, environmental, social-economic and political aspects must be balanced during the formulation process. Aquaculture, in general and salmon aquaculture, in particular is managed and governed by multi-layered authorities, including international, national, provincial or state, regional and local agencies.

At the international level, the Food and Agriculture Organization of the United Nations (FAO) is the leading agency. The *Code of Conduct for Responsible Fisheries* in Article 9 specifically presents guidelines for the development and management of aquaculture. Regional organizations such as the North Atlantic Salmon Conservation Organization (NASCO) and the European Union (EU) have also given specific guidance on salmon farming. For instance, NASCO signed the famous ‘Oslo Resolution’ in 1998, aiming *the Resolution by the Parties to the Convention for the Conservation of Salmon in the North Atlantic Ocean to Minimize Impacts from Salmon Aquaculture on the Wild Salmon Stocks.* The EU has implemented special requirements for aquaculture in its *Common Fisheries Policy*. However, salmon aquaculture is directly regulated at national, provincial and local levels, involving different government agencies.

At the national and regional level, the authorities involved in managing and regulating the salmon aquaculture industry may include the Ministry of Fisheries (or Department of Fisheries and Oceans Canada), the Ministry of Environment, the Ministry of Agriculture, and other departments associated with salmon aquaculture. These authorities are responsible for making aquaculture regulations and laws. *Fishery Acts* and *Aquaculture Acts* are the main legislative instruments for formulating most regulations and laws for salmon aquaculture (FAO 2007).

Although different countries and regions have their own regulations, monitoring procedures and guidelines, they all have concentrated on the same environmental issues or problems, including: i) siting criteria; ii) waste management and regulation; iii) escape prevention and response plan; and iv) disease and parasite prevention and control, and uses of chemicals and drugs.

Siting Criteria: First, the sites must be physically suitable for salmon aquaculture. For instance, water quality, tide, current, access to the freshwater and roads need to be met. Second, a guideline describing a number of environmental and social criteria or requirements is used to determine whether to issue a license or allow aquaculture operation to continue. In the case of British Columbia, such environmental criteria include minimum distance from First Nation's reserves, salmon streams, herring spawning grounds, shellfish beds, intensive areas for marine mammals, ecological reserves, protected parks and areas and existing farms. A farm also cannot be sited in an important commercial and recreational fishing ground, and/or a cultural or heritage significant area (MAFF 2003a). In Norway, a number of the National salmon watercourses and fjords have been established to protect wild salmon stocks. New licenses cannot be located in or existing salmon farms have to be relocated from these salmon watercourses and fjords (Sønvisen 2003; Porter 2005).

Waste Management and Regulation: The waste control regulations may include waste discharge standards, stocking requirements, domestic sewage requirements, best waste management practices, monitoring and reporting, remediation, fees and penalties. There are also requirements for reporting quantities and types of feed, chemicals and drugs used. Amongst these, regular monitoring (or inspection) and reporting are mandatory for all producers (Dow 2004). Different countries and regions have specific requirements for these regulations and monitoring. For instance, Norway has developed and implemented a *Modelling-Ongrowing fish farms-Monitoring* system (MOM) since 1997 (Maroni 2000). The frequency of monitoring depends on the environmental quality in the sediments under the farms and water body near the farms. Further, Norway also imposes limitations on fish density per production and water volume per licence (Dow 2004).

Escapees: The management and regulation for escapees include installation and maintenance of all facilities and staff training, prevention plan (i.e., site inspection), recording, best management practice plan and response plan for escape prevention (MAFF 2002). Fines may be charged if salmon farms violate the regulations or laws. For serious cases, licenses may be suspended. In addition an intensive monitoring and inspection program is needed (Dow 2004).

Disease and Parasite: Disease and parasite prevention and control include special guidelines or standards to deal with disease prevention, dead fish, risk factors, monitoring, recording and responding disease and hygiene, uses of drugs and chemicals. In British Columbia, a Fish Health Management Plan has been developed based on federal and provincial regulations/policies directly related to fish health management (MAFF 2003b). This plan serves as a principle or a template. Individual farms have to develop their own facility management plans following this plan (MAFF 2006). In Norway, a Fish Disease Act is created to specially manage and regulate disease and parasite problems. In order to reduce or minimize the risks, Norway also has limits on fish density, farm size, and length for fallowing, as well as requirements for slaughtering and bleeding. The amount and type of drugs and chemicals are only administered by veterinary prescription. Antibiotics are mainly administered through feed. There are withdrawal times for all therapeutants. The sale of medicated feeds and drugs are monitored. In the case of sea lice, there are special regulations on the numbers of sea lice per farmed fish allowed in different seasons. Also, regularly sampling farm sites are required to monitor the level of sea lice. If the level of sea lice exceeds the required level, immediate treatments must be carried out with prescribed drugs. The drugs for treating sea lice are either administered through feed or 'bath' treatments.

In sum, current management strategies and environmental policies are guidelines and standards. Some are mandatory, while some are voluntary. They can be categorized as input and output controls. Input controls include limited entry, feed quota, feed conversion ratio, quantity and type of drugs and chemicals, while output controls include limitations on the levels of production and pollutants. Although environmental management and policies have become more comprehensive, covering more areas, and some impacts have reduced, environmental problems, such as disease, continue to occur, and some problems have not been solved. Some strategies and policies are not very efficient in reducing or minimizing environmental impacts because they fail to provide incentives to salmon farmers.

6.3 Key Findings, Policy Implications and Recommendations

In this section, policy implications and recommendations are explored based on the analyses conducted in different chapters of this dissertation. They are organized chapter by chapter.

6.3.1 The Growth of Salmon Aquaculture

Chapter 2 examines whether salmon aquaculture can continue to expand at the current pace. Based on time series farmed salmon production, a 5-year moving average growth rate is computed in four leading producing countries and the world as a whole. Further, the growth rates of all finfish aquaculture and capture fisheries is compared. The results show that the year-to-year growth rate of salmon production quickly reaches a peak, and then begins sliding down towards zero. The growth rates of all finfish aquaculture and capture fisheries have followed the same trend. The conclusion of this analysis is that the ability of salmon aquaculture to keep growing at its current pace is doubtful. This analysis implies that aquaculture in general, salmon aquaculture, in particular may not continue growing at its current pace as many have optimistically predicted, and the convenient assumption by many that the world need not worry about the pending demise of capture fisheries may be unfounded. A key policy recommendation from this analysis is that let’s manage our wild fish stocks as best we can while we develop sustainable and sensible aquaculture to compliment. The idea that aquaculture can take over is simply a pipe dream.

In addition, to make salmon aquaculture a long term sustainable industry, a comprehensive analysis should be carefully conducted before an aquaculture license is issued or an operation is launched. For those who are already in the business, further assessment should be carried out before expansion is made. Salmon aquaculture is a commercial activity, and driven by profit-making, hence, salmon aquaculture has to be a profitable operation. Further, salmon aquaculture also generates environmental impacts and social conflicts to the environment and society, therefore, it has to be socially acceptable and environmentally sustainable. A number of factors such as market, production inputs, consumer awareness and environmental concerns may affect salmon aquaculture production and development. To foster a sustainable salmon industry in the long term, a comprehensive assessment of a salmon aquaculture is needed. Given current slumping market price for farmed salmon, production cost and strong environmental concerns, the profit margin is very thin. Salmon producers have little incentive to expand their production. Chile may be an exception because it has the lowest production cost and less environmental regulations than its counterparts. In addition, although the amount of seafood supply from aquaculture is increasing, major seafood supply still comes from capture fisheries. As this analysis suggests that aquaculture is unlikely to continue to grow at its current rate, the dependence on wild capture fisheries for seafood supply will carry on in the future, thus, concerted efforts to sustain and rebuild depleted wild fish stocks need to continue.

6.3.2 Pollution Abatement Cost

In Chapter 3, pollution abatement costs of salmon aquaculture are estimated. I develop and apply a joint production function approach to model good output (salmon production) and bad outputs (pollution) simultaneously. Two environmental production technologies are proposed, namely, regulated and unregulated technologies. Two production function models with different mapping rules are used in the analysis. Pollution abatement costs are estimated based on a series of data from the Norwegian salmon aquaculture industry. The results reveal that pollution abatement costs vary among observations and models. On average, pollution abatement cost is 2.6% in terms of total farmed salmon production and 4.6% in terms of total revenue of farmed salmon.

The analyses indicate that pollution from salmon aquaculture can impose environmental costs on salmon aquaculture producers. However, salmon aquaculture has operated relatively efficiently in the last several years. Hence, reducing pollution means that salmon production has to be reduced at the same time. The policy recommendations for salmon producers and policy makers from this analysis are stated below:

To salmon producers: The development of innovative technologies may be the top priority to reduce pollution. This analysis suggests that reducing the amounts of production inputs is the cost-efficient means to reduce pollution. For instance, feed is the single largest production cost and source of pollution. Over the last decade, feed formula and feeding technology have greatly improved. The feed conversion ratio, for example, has been reduced dramatically from around 4.0 in the early 1980s to about 1.2 at present (Asche *et al*. 1999; Bjørndal *et al*. 2002; Tacon 2006). Feeding technology has also improved from hand feeding to timely automatic feeders. The improvement of feed and feeding has been incorporated into salmon production decision making. As a result of technological innovations in feed, waste discharges have been reduced per unit of production. However, further technological development in feed and feeding is needed.

To policy makers: Environmental tax/charge needs to be used as an economic instrument to reduce pollution. According to the Polluter-Pays-Principle, an environmental tax is a fee levied on a producer. In principle, it should be equal to the environmental damages caused by the activity, e.g., salmon aquaculture. Environmental taxes/charges can encourage producers to reduce their pollution to the point at which the marginal abatement cost (i.e., tax/charge) equals the marginal damage cost. Sylvia *et al.* (1996) indicated that an emission tax can be an effective tool to reduce emissions from salmon aquaculture. Setting a tax is a very challenging task because it requires a full understanding of the sources of an environmental problem and its associated impacts and costs. In most cases, marine water pollution is non-point source pollution, that is, pollution comes from multiple sources. The revenues collected from the tax imposed on producers can be used to mitigate the negative effects or compensate for pollution damages by redistributing them between polluters and pollutees. The estimates of pollution abatement costs in Chap. 3 could be used as a reference point to establish an environmental tax/charge level. Recently, some lawmakers in Chile file a bill to tax salmon producers about 5% of monthly profit to cover the environmental costs caused by salmon farming (Carvajal 2007).

6.3.3 Impacts of Sea Lice on Wild Salmon Populations and Fisheries

Chapter 4 examines whether sea lice from salmon farms have ecological and economic impacts on wild salmon populations and fisheries. Age-structured salmon dynamic and bioeconomic models are applied. Pink and chum salmon in the Broughton Archipelago, British Columbia are used as case studies. It is shown that recruitments, catch and discounted profits have declined when sea lice induced mortality is incorporated into the production models of wild salmon. The populations collapse when sea lice induced mortality is assumed to be high. Pink population collapses faster than chum, and discounted profits are lower for pink salmon fisheries than for chum salmon fisheries due to the low market price for pink salmon.

These analyses imply that sea lice from farmed salmon can have ecological and economic effects on salmon populations and fisheries. These effects are minor when sea lice induced mortality rate is low (<20%), and the effects can be severe if sea lice induced mortality is high (>30%). Sea lice have greater ecological and economic impacts on pink salmon than on chum salmon. These effects are greater under a fixed exploitation rate than under a target escapement policy. Policy recommendations drawn from the analyses are:

To salmon producers: To prevent outbreaks of sea lice, better farm husbandry management is needed. Current management practice and design should be updated or revised in response to the best available knowledge and technologies. For instance, farm maintenance, fish husbandry and inspections should be carried out on a regular basis. Treatment should be applied immediately when an outbreak occurs. Biological treatment approaches instead of medicine should be considered and developed. For example, Wrasse (*Ctenolabrus rupestris*) has been successfully used to treat sea lice in Norway and Scotland

(Rae 2002). Salmon farmers in British Columbia should consider the use of this kind of biological approach to treating sea lice rather than depending on medicines.

To policy makers: Stringent management practice and regulations are needed. For instance, setting maximum production/fish density allowed for salmon farms, the timing and period of fallowing, number of sea lice per fish, types and quantities of medicines and drugs allowed for treating disease; relocating farms and separating age classes are all needed. In some very important water corridors or passageways, salmon farms should be forbidden. For instance, Norway has established a number of watercourses and fjords to protect wild salmon stocks from salmon farms (Sønvisen 2003; Porter 2005).

6.3.4 Open Netcage *vs* Sea-bag Production Systems

In Chapter 5, the economic performances of open netcage and sea-bag production systems for salmon aquaculture are compared. Capital budget and investment appraisal analyses are used to compare the profitability of the two production systems. For sea-bag systems, on average, the capital investment costs are 2.6 times, and operating costs are 1.2 times higher than for open netcage systems. Projected 20-year cash flows showed that sea-bag systems produce negative gains in more growth cycles than netcage systems, and the magnitude of positive gains is relatively small compared to net losses in sea-bag systems. For netcage systems, the net present values are all positive except for one production capacity, while for sea-bag systems, the net present values are all negative. Netcage systems have lower breakeven prices and production levels than sea-bag systems. All the internal rates of return for netcage systems are positive and greater than the discount rate except at the production capacity of 720 tonnes. Sea-bag systems produce negative internal rates of return at all production capacities.

Netcage production systems appear to be more economically profitable than sea-bag systems when environmental costs are either not or only partially considered. Sea-bag systems are not financially feasible because of their high capital investment and operating costs. They can be financially profitable only when they produce fish that achieve a price premium. Sensitivity analyses reveal that the market price has the most important impact on the profitability of both systems; changes in discount rates, fish density, feed costs, and environmental costs also have large impacts on the profitability of netcage systems. Policy recommendations emerging from the analyses are presented below:

To salmon producers: Salmon producers should be instructed to label their products. Eco-labeling is a market-based instrument to direct consumers' purchasing behavior. It creates market-based incentives for environmentally friendly seafood, and takes into account product attributes other than price (Cochrane and Willmann 2000). Seafood with an eco-label in general, can command a price premium because it has been shown that consumers are willing to pay a higher price to compensate for the higher production costs that it entails. Eco-labeling has been advanced as an effective way to provide consumers' awareness about the seafood they buy (Naylor *et al.* 2003). To the best of my knowledge, there are currently no eco-labeled farmed salmon products in the market. However, farmed salmon products produced in land-based systems in British Columbia, Canada were labeled as "Eco-salmon", which was self-named by the producers. This was accepted by the retailers, and some consumers were willing to pay a price premium for it. However, this land-based system operation is currently out of business. There is a growing demand for markets for eco-labeled seafood products as consumers are more aware of environmental problems and food safety issues.

To policy makers: As an alternative to levying a pollution tax on producers to correct the negative externalities of salmon aquaculture, a subsidy programs may be used to create positive externalities. Since enclosed production systems can reduce environmental impacts associated with salmon aquaculture, establishing a subsidy program may motivate producers to adopt such technologies. Some may argue that you cannot use general taxpayers' money to subsidize a small group of individuals who happen to be salmon farmers. So, we first collect taxes from producers who use open netcage production systems, and then we can use these tax revenues to subsidize producers who are willing to adopt enclosed technologies. For instance, a subsidy program such as tax credits was established and supported by both the Federal and Provincial government agencies in British Columbia, Canada in 2004, some producers have taken this subsidiary offer to adopt enclosed production systems in small-scale experiments. Since salmon aquaculture continues its development, adopting cleaner and innovative technologies to reduce environmental problems is one of the approaches and options that can produce overall long term benefits for both private producers and society.

6.4 Conclusions

Based on the key findings of the previous chapters, conclusions are made: i) salmon aquaculture cannot keep growing at the current pace; ii) pollution abatement costs are significant; iii) sea lice from farmed salmon have various ecological and economic impacts on wild salmon populations and fisheries; and iv) enclosed production technology is a promising solution to reduce environmental impacts, but it is very economically demanding.

Currently, environmental policies have been the main measures to regulate salmon aquaculture to reduce or minimize environmental impacts. Most of them are in the form of guidelines, standards and management practices. Such environmental policies do not necessarily guarantee outcomes with great environmental or social benefits. However, the control of environmental impacts can be achieved by a number of approaches and options from the industry, the public and authorities (Naylor *et al*. 2003). Some environmental management strategies and policies, such as, improved husbandry management, pollution tax, subsidy, eco-labeling and enclosed production systems, have been proposed based on this study.

In most cases, environmental impacts are highly uncertain and complex, and the type and extent of environmental impacts vary over time and space, hence, it is very challenging to design an appropriate environmental policy. The standards and guidelines have been widely used, and can be relatively easily adjusted. Technological innovation is the top choice, but it has to be feasible to be adopted by producers. Economic-based instruments can be used when an accurate environmental cost is known. There is no single environmental management option that can regulate salmon aquaculture in an effective and efficient way. A combination of technological innovations and environmental policies is required. Sound environmental management and policy should be formulated, implemented and enforced. Environmentally friendly technologies need to be developed and popularized into sound farm management practices and legislations under the context of a coastal zone management.

To develop a sustainable aquaculture industry, a comprehensive long-term cost-benefit analysis should be conducted before any aquaculture investment is approved. Sustainable development of aquaculture should be established on three defined and interrelated dimensions: environmental, social and economic. From an economic perspective, salmon farms have to be financially profitable. From a social perspective, it has to be socially fair and environmentally acceptable from society’s point of view. That is, different stakeholders’ concerns in a community need to be taken into consideration, including relevant Government agencies, aquaculture industry and allied associations, commercial and recreational fishing sectors, non-governmental organizations (NGOs), local residents, First Nations, secondary supporting sectors and the general public. From an environmental perspective, it should harmonize with the surrounding environment and natural resources. All costs and benefits should be identified and assessed before a new aquaculture operation is launched.

Although this study has focused on salmon aquaculture, results and policy implications can be adopted for other types of aquaculture, in particular industrialized aquaculture of carnivorous species within a similar context. This dissertation provides some insights and understandings to salmon producers, policy makers and the general public regarding the development of salmon aquaculture and the environmental impacts associated with it. However, salmon aquaculture is a relatively young industry, and more research needs to be conducted to support its sustainable development into the future.

6.5 References

Asche, F., A. Guttormsen, and R. Tveterås, 1999. Environmental problems, productivity and innovations in Norwegian salmon aquaculture. Aquaculture Economics and Management 3(1): 19-29.

Bjørndal, T., R. Tveterås and F. Asche, 2002. The development of salmon and trout aquaculture. In Paquotte, P., C. Mariojouls and J. Young (Eds): Seafood Market Studies for the Introduction of New Aquaculture products. Cahiers Options Méditerranéennes 59: 101-115.

Carvajal, p., 2007. Chile seeks tax on salmon profits. Intrafish, p39.

Cochrane, K. and R. Willmann 2000. Eco-labelling in Fisheries Management. Proceedings of the 2000 Conference by the Centre of Ocean Law and Policy, University of Virginia, and FAO on Current Fisheries Issues and the Food and Agriculture Organization of the United Nations. Rome, Italy, 16-17 March. 18p.

Dow, A., 2004. Norway vs. British Columbia: A Comparison of Aquaculture Regulatory Regimes. The Environmental Law Centre Society, University of Victoria. Victoria, BC, Canada. 35p.

FAO, 2007. National Aquaculture Legislation Overview – Canada and Norway. Available at http://www.fao.org/fi/website/FISearch.do?dom=legalframework, access May 2007.

Naylor, R.L., J. Eagle and W.L. Smith, 2003. Salmon aquaculture in the Pacific Northwest - A global industry. Environment 45 (8): 18-39.

Maroni, K., 2000. Monitoring and regulation of marine aquaculture in Norway. Journal of Applied Ichthyology 16: 192-195.

MAFF, 2002. Preventing Escapes to Support a healthy Aquaculture Industry. British Columbia Ministry of Agriculture, Food and Fisheries. 9p.

MAFF, 2003a. Guide to Information Requirements for Marine Finfish Aquaculture Applications. Aquaculture Development Branch, British Columbia Ministry of Agriculture, Food and Fisheries. ISBN 0-7726-4994-4. 76p.

MAFF, 2003b. Required Elements of a Fish Health Management Plan for Public and Commercial Fish Culture Facilities in British Columbia. British Columbia Ministry of Agriculture, Food and Fisheries. 11p.

MAFF, 2006. Template for Development of Facility – Specific Fish Health Management Plans. British Columbia Ministry of Agriculture, Food and Fisheries. 63p.

Porter, G. 2005. Protecting Wild Atlantic Salmon from Impacts of Salmon Aquaculture: A Country-by-Country Progress Report 2nd Edition. World Wildlife Fund and Atlantic Salmon Federation. 58p.

Rae, G.H., 2002. Sea louse control in Scotland, past and present. Pest Management Science 58: 515-520.

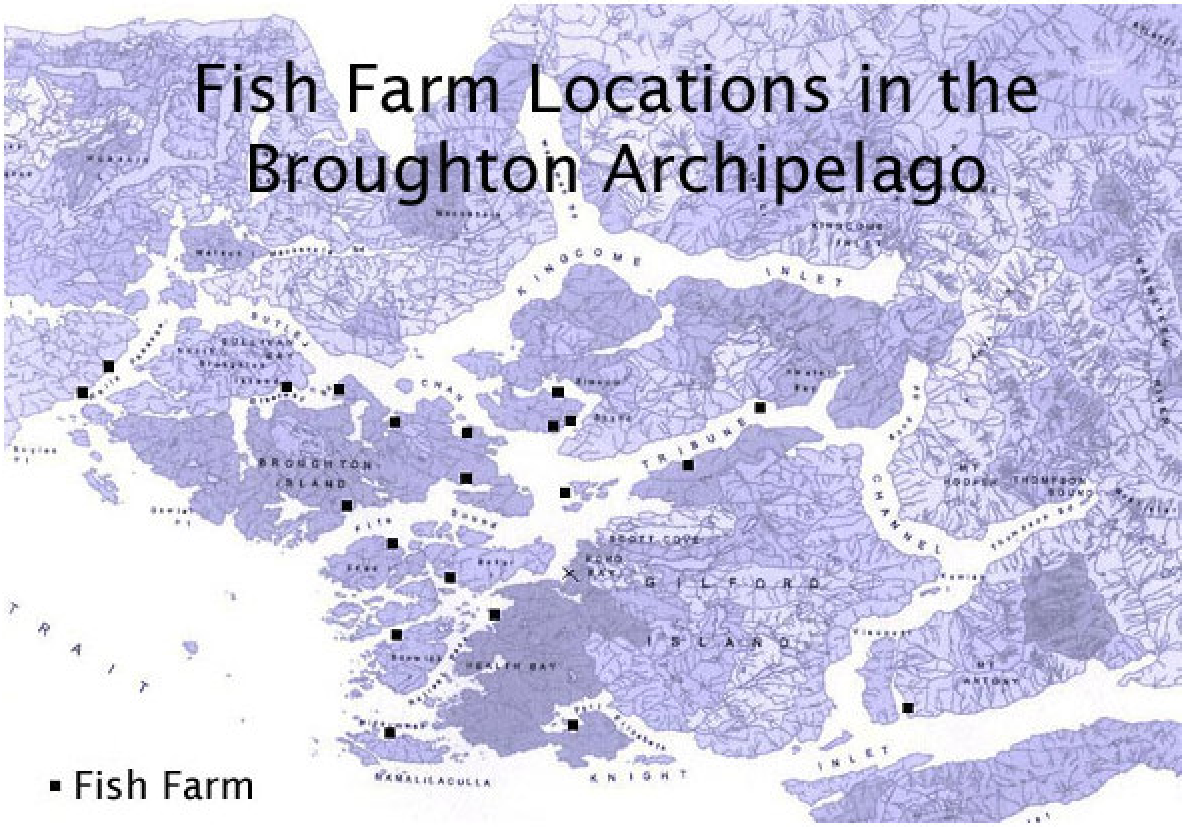
Sønvisen, S.A., 2003. Integrated Coastal Zone Management (ICZM): the Allocation of Space in Norwegian Aquaculture – from Local Lottery to Central Planning? Norwegian College of Fishery Science, University of Tromsø. 95p.

Sylvia, G., J.L. Anderson, D. Cai, 1996. A multilevel, multi-objective policy model: the case of marine aquaculture development. American Journal of Agricultural Economics 78 (1): 79-88.

Tacon, A.G.J., M.R. Hasan and R.P. Subasinghe, 2006. Use of fishery resources as feed inputs for aquaculture development: trends and policy implications. FAO Fisheries Circular No.1018, Rome, FAO, 99p.

Appendix 4.1. Location of Salmon Farms in Broughton Archipelago Area

(Source: raincoast society: http://www.raincoastresearch.org/graphics/images/broughton-watersheds.jpg)



Appendix 4.2. Calculation of the Population Capacity at Chum Salmon Juvenile Stage.

When a chum salmon population is in equilibrium, the number of fish recruits is determined as:

$$N = m_3 N_{t-3} + m_4 N_{t-4} + m_5 N_{t-5} \tag{a}$$

Where, $m_{(.)}$ is the age mature rate.

The numbers of fish recruits at ages 3, 4 and 5 are defined, respectively, as follows:

$$N_{t-3} = Ne^{\alpha_j^c (1-N/\beta_j^c)} s_j s_1 s_2 s_3 \tag{b}$$

$$N_{t-4} = Ne^{\alpha_j^c (1-N/\beta_j^c)} s_j s_1 s_2 s_3 s_4 \tag{c}$$

$$N_{t-5} = Ne^{\alpha_j^c (1-N/\beta_j^c)} s_j s_1 s_2 s_3 s_4 s_5 \tag{d}$$

Where, $s_{(.)}$ is age specific survival rate.

Substitute Equations b, c and d into Equation a:

$$N = Ne^{\alpha_j (1-N/\beta_j)} s_j s_1 s_2 s_3 (m_3 + m_4 s_4 + m_5 s_4 s_5) \tag{e}$$

When a chum salmon population is in equilibrium, $N = \beta_a^c$. Solving Equation 2, β_j^c is:

$$\beta_j^c = \frac{\beta_a^c \alpha_j^c}{\alpha_j^c + [s_j s_1 s_2 s_3 (m_3 + m_4 s_4 + m_5 s_4 s_5)]}$$

Appendix 4.3. Ricker Population-recruitment Model with Stochastic Variable

It is well accepted that populations are self-regulated by density-dependent biological systems (e.g., Ricker model). Recent studies have increasingly shown that salmon populations are also controlled by exogenous environmental forces, such as sea surface temperature, climate change, logging and construction of dams (e.g., Walter and Param 1996; Ryall *et al.* 1999; Bradford and Irvine 2000; Pyper *et al.* 2001; Koslow *et al.* 2002; Pyper *et al.* 2002; Mueter *et al.* 2002; Beamish *et al.* 2004). These factors have different impacts on the survival rates at different development stages of salmon populations (Ryall *et. al.* 1999; Beamish *et al,* 2004). The impacts vary considerably from year to year, from population to population and from development stage to stage. Also, the survival rates may be caused by a combination of environmental factors and human interventions. It is difficult to separate the effect of one factor from another in most cases. In the literature, some studies use stochastic rather than deterministic variables to represent these effects (Luedke 1990; Costello *et al.*1998; Sethi *et al.* 2005). Based on this principle, I will apply a Ricker recruitment model to integrate stochastic variations representing the combined effects of environmental forces.

$$R_t^A = B_{t-1} e^{\alpha_A (1 - B_{t-1} / \beta_A) + \varepsilon} \qquad (1.2)$$

Where, R_t^A represents recruitment at adult stage at year t, B_{t-1} is spawners at year $t-1$, α_A is the productivity of the population in adult stage, β_A is the unfished equilibrium population size at adult stage, ε is a stochastic variable to represent combined effects of environmental factors on survival, including disease induced mortality.

Walters (1986) provided a theoretical explanation for this stochastic variable. He pointed out that e^{ε} can be viewed as a random survival resulting from several independent and multiplicative environmental factors operating in series. Thus, ε represents a sum of several random factors and should be normally distributed according to the central limit theorem (Luedke 1990). In the literature, ε is either assumed to be the residual error term that is normally distributed based on time series data of recruitment and spawners (Ryall *et al.* 1999; Pyper *et al.* 2001 & 2002), or assumed to be a normally-distributed random variable that is estimated based on identified environmental factors, such as sea surface temperature (Chen and Irvine 2001; Mueter *et al.* 2002). The ratio of recruit-spawner implies the survival rate of a population, and log Ricker model shows that log recruitment to spawner is a linear relationship with ε. Therefore, the magnitude of ε is determined by the standard deviation of an average recruit per spawner. Because the factors such as disease, destruction of habitat and pollution mainly have negative impacts on wild salmon populations, the stochastic variables ranging from -0.6 to 0.0 for chum salmon and from -2.4 to 0.0 for pink salmon are used.

Parameters of population recruitment and stochastic variables

The parameters for population productivity and capacity, and stochastic variables are needed in order to use the models for simulations. Based on time series of recruitment and escapement data, I estimate the standard deviations for pink and chum salmon populations, respectively. I assume that these standard deviations are the stochastic variables in the analysis. On average, the stochastic variables ε are estimated to be 0.60 and 2.41 for chum salmon and pink salmon, respectively. The ε for chum salmon is very close to the estimate ($\varepsilon = 0.5$) by Luedke (1990). Since stochastic variable can be any value in certain ranges, I use the same Monte Carlo method to simulate the stochastic variable as introduced earlier.

<u>Chum salmon:</u> the productivity of the population, α_a, is extracted from Luedke (1990); the unfished equilibrium population size (capacity) β_a is the average of two estimates: $S_{opt} = (0.5 - 0.07\alpha)\beta$ (Hilborn and Walters 1992), and $\beta = 2.5E_{opt}$ (Luedke 1990 cited Walters 1975); I assume that $S_{opt} = E_{opt}$, which is the target escapement (~ 546,000) set by DFO for the areas of Kingcome Inlet and Bond to Knight Inlet (Ryall *et al.* 1999).

<u>Pink salmon:</u> α_a and β_a are estimated based on the regression of time series data of recruitment and escapement in DFO Area 12.

Appendix. Table 5.1. The recruitment parameters and stochastic variables for chum and pink salmon.

	Chum	Pink
α	0.7	2.2
β	1,287,822	2,228,309
ε	[+0.36, 0, -0.36]	[+2.41, 0, -2.41]