CALCULATING THE ECONOMIC VALUE OF GENOMIC TECHNOLOGIES IN WILD AND FARMED COHO PRODUCTION

by

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Abstract

Even in the absence of commercial fishing, coho salmon (*Onchorhynchus kisutch)* originating from the Interior Fraser River (IFR) watershed have yet to recover from the low returns experienced since 1992. New cost-effective management tools based on genomic technology have been developed and may be implemented to address the low returns of IFR coho. Parentage based tagging (PBT) and genomic stock identification (GSI) are used to identify the origin and age of individuals caught in a mixed-stock fishery. These tools are vital in generating estimates of exploitation and survival rates of both wild and hatchery fish, at a lowered cost than the management system in place today. Here, I calculate the economic value of these technologies, and show how sampling costs could decrease while still ensuring that proper regulations are instated, using the IFR populations as a case study. Results show that genomic technologies may provide an additional $65,000 in revenues over the next 32 years, under current ocean conditions, and $953,000 to $1,226,000 over the next 32 years, in favorable ocean conditions, to southern British Columbia (BC) commercial coho fisheries.

Similarly, genomic technologies can be used to enhance certain economically important biological traits in aquaculture production, and increase the production of farmed salmon in land-based recirculating systems. Important information regarding carcass quality, disease resistance, flesh colour and growth rate, has been collected for coho and may be applied for breeding programs in BC. Marker assisted selection (MAS) and genomic selection (GS) are two tools used for selective breeding to enhance coho broodstock, based on the traits listed above. To calculate the economic value of these technologies, I estimate the difference in net present value of coho production from enhanced and un-enhanced broodstock. Results indicate that the value of the genomic technologies may be around $1,384,000 over a 10-year span at a production quantity of 115 MT. Improved flesh quality can yield the greatest change in net present value, accounting for 52% of the total change in net present value when the genomic technologies are applied for selective breeding.

Lay Summary

By comparing the net present value of wild and hatchery coho production managed with and without genomic technologies, I measure how much value the genomic technologies add to a commercial troll fishery in southern British Columbia. The same methodology is applied to the production of farmed coho, with genomic technologies enhancing selective breeding of coho broodstock. The research exemplified here can contribute to the future management and conservation of endangered coho populations. Furthermore, it reinforces the importance of an ecologically sustainable and economically viable aquaculture industry in British Columbia and may offer a means to meet the growing demand for seafood through increased production of coho salmon. This study has a high analytical value as very few similar studies have focused on coho salmon, a species facing low productivity in the wild, and is produced at low quantities in salmon farms.

Preface

This publication is original, unpublished, independent work from the author, Nathan Bendriem. It was done under the supervision of Dr. Rashid Sumaila, with contributions from Dr. Harry Nelson and Dr. William Cheung.

Both of the analytical chapters are based off of current research conducted by the project "Enhancing Production in Coho: Community, Culture, Catch" or EPIC^4. While the data I used mainly stems from published fisheries assessment reports, I received guidance on how to shape the analysis from conversations with scientists involved in the EPIC^4 project, including Dr. Terry Beacham, Dr. Willie Davidson, Dr. Michelle Crown, Dr. Ben Koop, and Dr. Jose Yañez. The models used in chapter 2 stem from the Ricker (1954) and Beverton-Holt (1957) stock-recruitment models. The economic component in Chapter 2 came from previous economic studies, including Sumaila (2004), Marsden et al. (2009), Liu (2008), Liu and Sumaila (2007), and Liu and Sumaila (2010). I performed the economic analysis myself, as well as the subsequent figures and tables in this chapter.

The aquaculture production model in Chapter 3 is from Bjørndal (1990), and the economic net present value model from Sumaila (2004). I performed the economic analysis myself, as well as created the subsequent figures and tables in this chapter.

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List of Abbreviations

BC	British Columbia
BKD	Bacterial Kidney Disease
CBA	Cost-Benefit Analysis
CCA	Closed-containment aquaculture
CEDP	Community Economic Development Program
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CWT	Coded-wire tag
DFO	Department of Fisheries and Oceans Canada
EDS	Electronic detection system
$EPIC^4$	Enhancing Production in Coho: Community, Culture, Catch
ER	Exploitation rate
FAO	Food and Agriculture Organization
FCR	Feed conversion ratio
GS	Genomic Selection
GSI	Genetic stock identification
HSMI	Heart and skeletal muscle inflammation
IFR	Interior Fraser river
IHN	Infectious Hematopoietic Necrosis
LBA	Land-based aquaculture
MAS	Marker assisted selection
MS	Marine Survival
MT	Metric tonne
NOAA	National Oceanographic and Atmospheric Administration
NPV	Net present value
ONF	Open net farm
PBT	Parentage based tagging
PSC	Pacific Salmon Commission
PST	Pacific Salmon Treaty
QTL	Quantitative trait loci
RAS	Recirculating Aquaculture System
RMPC	Regional Mark Processing Center
SAR	Salmon Aquaculture Review
SEP	Salmonid Enhancement Program
TGC	Thermal growth coefficient
US	United States
WCVI	West Coast of Vancouver Island

Acknowledgments

I am incredibly grateful for the experience and knowledge that I have gained from my Master's thesis, coursework, and research. I would like to begin by thanking my academic advisor and research supervisor, Dr. Rashid Sumaila. Your guidance and support played a large role in my success and motivation. I cannot think of a single meeting with Rashid that has not included a hearty laugh. I would also like to thank my supervisory committee, Dr. Harry Nelson and Dr. William Cheung for their comments and guidance in shaping my research and final thesis. A big thank you to my external examiner as well, Dr. Sumeet Gulati for his contributions to the final draft.

The $EPIC^4$ teams have been a tremendous help as well, in forming my research and collecting my data, as well as for their support and questions over the numerous presentations that I have given in the past two years. A big thank you to those who helped with the questionnaires, Dr. Terry Beacham, Dr. Ben Koop, Dr. Louis Bernatchez, Dr. Jean-Sébastien Moore, Dr. Willie Davidson, Dr. Michelle Crown, and Dr. José Yañez. I am incredibly grateful for working with Raphael Roman on the $EPIC^4$ project since my first week in the office. It has been very fulfilling to be able to collaborate with someone and see my research through the end, with a helping hand every step of the way.

The Fisheries Economic Research Unit lab group at UBC has been nothing but supportive and caring since I started my Master's two and a half years ago. A big thank you to Tim Cashion, Travis Tai, Nicolas Talloni, and Rob Parker for their comments on the final presentation.

The friendships that I have made here are the reasons why my time at UBC was incredible. I want to thank the *Sea Around Us* crew for treating me as their own. The lunches, ski trips, and late board game nights created the perfect balance of work and play. I would like to thank Melanie Ang for her continuous support even after she had graduated, in helping me prepare for the final presentation. And while our bet clearly did not motivate me, her words of confirmation and advice did.

I would like to give a special thank you to my girlfriend, Maeve Winchester, who has been my support system late at night when I have too much on my plate to go to sleep. She has rehearsed my presentations with me more times than was necessary and I would never have had the confidence or peace of mind as I did at my defense without her.

And last but not least, I would like to thank my parents for their advice and encouragement, along every step of the way.

Chapter 1: Introduction

1.1 Introduction

Coho salmon (*Oncorhynchus kisutch*) have great social and economic importance in British Columbia (BC), supporting numerous types of fisheries, and playing a vital ecological and cultural role for those who call the province home. Numerous stocks of coho in southern BC experienced a sharp decrease during the early 1990s and have yet to recover (DFO, 2001). One such stock, comprising of the Interior Fraser River (IFR) populations, has exhibited low marine survival even in the absence of commercial fishing, and low improvement on returns from hatchery releases (Beamish et al., 2010; Chittenden et al., 2010a). The assessment and management of salmon populations relies on the successful identification of individuals to their rivers or hatchery of origin (PSC, 2005b). However, the current management structure has been linked with sparse data and out-dated tools, giving rise to concern coupled with an uncertainty for the future outlook of once prolific populations (PSC, 2008a, 2015; Steele et al., 2013) as well as high monetary funding requirements to remain significant (PSC, 2015).

As the decline in wild coho survival and landed catches characterized British Columbia during the 1990s, the production of farmed Atlantic salmon rapidly grew and eventually exceeded the production of wild salmon in 1998 (DFO, 2013a). Salmon grown in open-net pens entered the global market and the number of licensed farms within the coastal seas has reached around 120. Coho salmon is produced in smaller quantities than Atlantic salmon, but the advancement of broodstock development programs may generate more interest into the production of farmed coho (Neira et al., 2014), which can be applied to land-based aquaculture farms.

The use of genomic technologies is becoming crucial to the production and management of both wild and farmed coho salmon in B.C. (Beacham et al., 2017b; Neira et al., 2014). Genetic sequencing is used to identify a wild or hatchery-reared coho to its native river with more precision, providing more accurate measures of fishery stock composition, catch allocation, and survival (Anderson & Garza, 2006; PSC, 2005a; Shaklee et al., 1999). The identification of certain genes is advantageous for selecting broodstock that is well suited for captive rearing, and may improve growth rate, mortality, and feed consumption within the industry (Dufflocq et al., 2017; Neira et al., 2004; Yáñez et al., 2016; Yáñez et al., 2013).

While genomic technologies have been successfully developed and tested in wild-capture fisheries, few studies have compared the economic viability of the new technologies with those currently in place (PSC, 2008b; Satterthwaite et al., 2015). The value of the genomic technologies extends to the salmon fisheries in BC, as proper management tools can result in maximizing commercial quotas while conserving endangered stocks. The current provisions for the Pacific Salmon Treaty are set to expire at the end of 2018, with representatives from the United States (US) and Canada providing their recommendations for ratifications (PSC, 2016b). It is important to understand the socio-ecological benefits and cost of these technologies, as there is a possibility of the genomic tools being adopted into the treaty for widespread use. I use the Interior Fraser coho populations as a case study to conduct a cost-benefit analysis comparing the current fisheries management and assessment tools against the proposed genomic-based tools.

Similarly, most studies measuring the economic feasibility of land-based aquaculture systems focus on Atlantic salmon (Bjørndal & Tusvik, 2017; Liu & Sumaila, 2007; Pinfold, 2014; Wright & Arianpoo, 2010), and indicate a low profit margin (Boulet et al., 2010). However, with the use of genomic tools to better improve broodstock, coho salmon may offer an alternative to counter the high capital and operating costs associated with the growing land-based industry. It is important to recognize the economic value of these genomic technologies and their role in meeting the growing demands for seafood (Gjedrem, 2012). I provide a cost-benefit analysis of land-based systems incorporating different biological broodstock traits meant to increase the production of farmed coho in British Columbia. By doing so, I may measure the value of the genomic-based technologies used in salmon aquaculture.

This introductory chapter reviews the downward trend in wild coho salmon as well as the rise of salmon aquaculture in British Columbia. I give an overview of the genomic technologies that comprise the focus of my study, and discuss the importance that these technologies have had on both the wild-capture and farmed coho industries. Finally, I explain the objectives and structure of this thesis.

1.2 Scope of Research

Chapter 2 focuses on the Interior Fraser River coho population as a case study. While the use of genomic technologies will be widespread and encompass several stocks of coho within BC, the economic analysis will rely on one stock and be extrapolated to a larger scale. The Interior Fraser is comprised of five different populations and a total of 11 different sub-populations (Irvine, 2002). These populations include the Fraser Canyon, Upper Fraser, as well as the Lower, North, and South Thompson River, as seen by the map below.

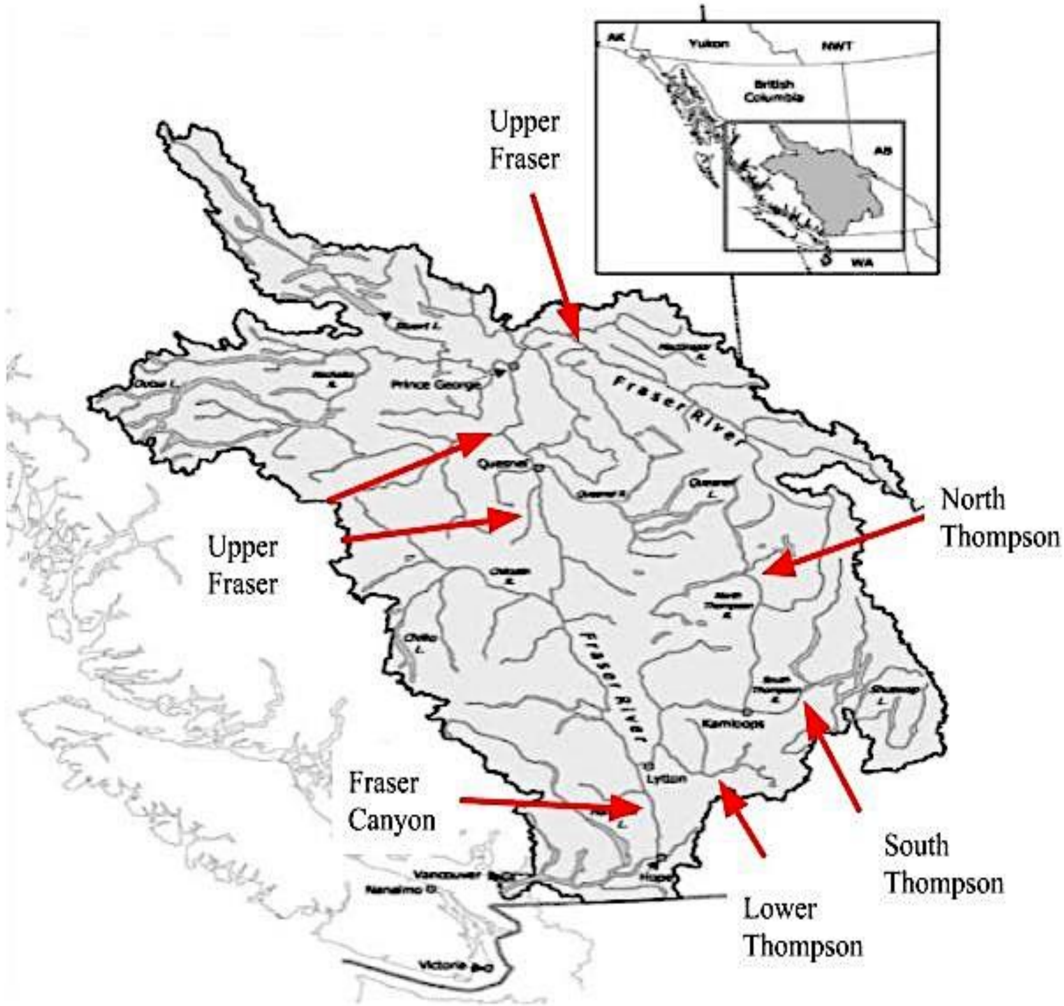

Figure 1.1: Map of Fraser River and it's tributaries, indicating the five Interior Fraser coho populations. Source: Akenhead et al., 2016

The Fraser River is BC's largest salmon bearing river, with a watershed that encompasses the greater half of the province's southern region. Coho originating from this river migrate out to sea after 18 months in freshwater (Sandercock, 1991). Their migration routes are found either through the Strait of Georgia or the Strait of Juan de Fuca and up towards northern BC and the Gulf of Alaska (DFO, 2001).

Chapter 3 does not have a defined study area, as the use of land-based salmon farms is common throughout Vancouver Island and the lower mainland of British Columbia. The improved broodstock may be applied to any of these locations with necessary inputs such as land and a source for pumping water.

1.3 Decline in Interior Fraser coho

Towards the end of the 1980s, populations of coho salmon from the IFR watershed started experiencing record low returns, suffering sharp drops in escapement and thus raising conservation concerns amongst environmentalists and fisheries scientists (Decker, et al., 2014; DFO, 2014; Irvine, 2002). High exploitation rates in the mid-1990s exacerbated the low returns, and such grim outlook prompted the Committee on the Status of Endangered Wildlife (COSEWIC) in Canada to list the IFR coho as an endangered species in 2002 (COSEWIC, 2002). Escapements of IFR coho started to rebound progressively between 2005 and 2012, and its status has since been re-examined and designated as threatened (COSEWIC, 2016). Figure 1.2 below illustrates the decline in adult returns as well as the exploitation rate on returning IFR coho from 1985-2012. By focusing on the years 1994-1998, it is seen that exploitation rates were cut several years after the population began to decline. This can be attributed to the lack of an efficient stock identification system to provide estimates of survival and exploitation in times of dwindling returns (PSC, 2005b).

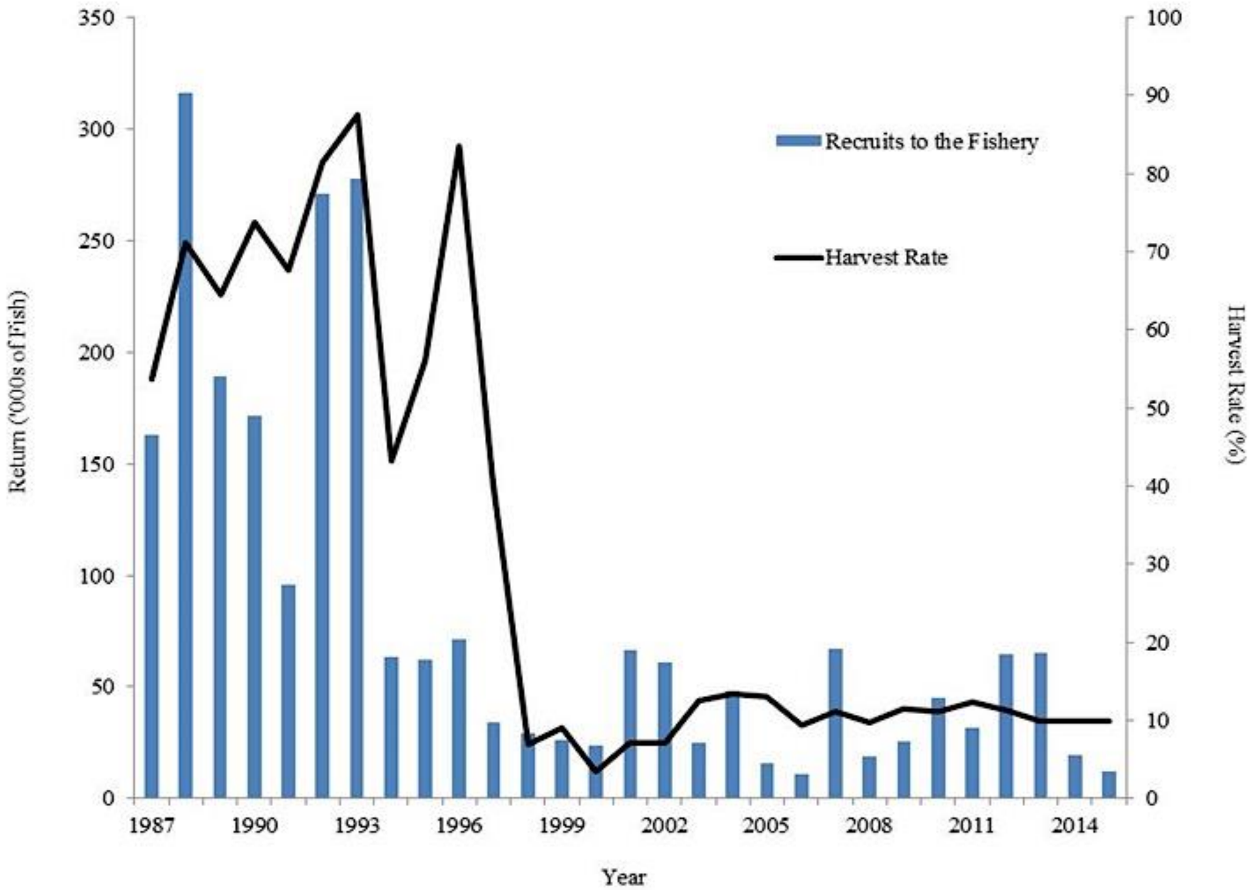

Figure 1.2: Returns of adult coho to the Interior Fraser watershed on the primary axis with the exploitation rate on those returns as the secondary axis. Data is from years 1985-2012.

Current low survival

Interior Fraser coho salmon are currently in a period of low productivity in which the number of returning adults per spawner three years prior is around 1 to 1 (Decker et al., 2014). Since the mid-1990s until today, marine survival has been extremely minimal for wild and hatchery coho. In some years, the survival rate of coho was low enough that the population decreased with little fishing pressure. High exploitation rates during the 1980s have contributed to the current threatened population but there are more factors that presumably have led to poor marine survival, including a shift in marine conditions within the Strait of Georgia (Chittenden et al., 2010b), and an increase in freshwater runoff from the Fraser's mainstem (Beamish et al., 2010).

These conditions led to unprecedented restrictions on wild coho salmon starting in 1998. Today, there are currently no directed fisheries on wild stocks of IFR coho and a mandatory non-retention and non-possession of incidentally caught coho. Southern BC is divided into red zones, in which no fishing is allowed to minimize accidental bycatch, and yellow zones, in which fishing is allowed but fishers must carry revival boxes and release any IFR coho (DFO, 2001). However, since the IFR coho stock also migrates into US waters, a considerable amount of harvest does occur by United States fishers in the Strait of Juan de Fuca. The Pacific Salmon Commission (PSC) allows the US to harvest around 10% of returning coho, and an estimated additional 3% harvest rate from incidental bycatch from Canadian fishers (PSC Coho Technical Committee, 2013). Retention of wild IFR coho does occur for food, social, and ceremonial fisheries in specific terminal areas (PSC Coho Technical Committee, 2013).

1.3.1 Hatchery Supplementation and Production

The following section describes the use of hatchery enhancement practices and some of the concerns related to salmon enhancement. These concerns are not synonymous with the Interior Fraser population only, but can affect all salmon populations that utilize hatchery enhancement. I believe it is worthwhile to mention these concerns as it has impacted the management and survival of wild and hatchery coho originating from the Fraser, and provide a basis for the demand for technologies.

Hatcheries have been a key feature meant to increase the abundance of numerous coho stocks in British Columbia. The higher survival rate of fry and smolts in hatcheries can address conservation concerns for declining stocks and provide for more fishing opportunities for commercial, recreational and FSC fisheries (MacKinlay et al., 2004). This is a distinction that illustrates the two types of hatchery enhancement goals: conservation and production. Conservation hatcheries are meant to improve the abundance of an endangered or threatened wild population by integrating hatchery-reared fish into that wild population (Naish et al., 2007). It is necessary that the adaptive genes found within the endangered population remains intact and that the hatchery-released fish return to the proper spawning ground. The objective of production hatcheries is to augment salmon populations for the purpose of increasing fishing opportunities, as well as to redirect fishing pressure away from vulnerable or endangered stocks (Naish et al., 2007). The hatcheries success is based on the contribution of the released fish to wild-capture fisheries. Furthermore, both types of enhancement are considered successful if the release of hatchery fish does not impact the survival of wild stocks they are meant to protect. In this study, the objective of hatchery enhancement is to conserve certain populations of IFR coho, and as such, the hatchery fish are meant to spawn with hatchery and wild fish from the same population.

Low survival of hatchery fish

Once released into the wild, hatchery fish face the same marine conditions and high marine mortality rates as their wild counterparts do. However, many sources have claimed that hatchery-reared fish tend to have a lower survival rate in the marine environment than those of natural origin (Chittenden et al., 2010a; Fleming & Petersson, 2001; Hedgecock & Coykendall, 2007). A study identifying phenotypic differences between hatchery and naturally-reared coho concluded that those reared in hatchery were less likely to identify and avoid predators, and had weaker swimming performance, which likely leads to higher rates of mortality (Chittenden et al., 2010a).

Straying of hatchery fish into streams other than those in which the hatchery is found can have a negative impact on the survival of future generations (Bakke, 1997; Hindar, Ryman, & Utter, 1991; Waples, 1991). A hatchery fish can spawn with either a hatchery or natural origin fish once it has returned to the spawning grounds. The hybridization of purely wild populations from hatchery fish straying into a non-natal stream can have negative consequences on the survival of future generations (Bakke, 1997). Fitness traits that may be specialized within a wild population may be reduced over time due to the straying of hatchery fish with fitness traits that are not matched with those of the wild-origin salmon.

1.3.2 Coho salmon management tools

To estimate the contribution of hatchery salmon from each enhancement facility, as well as to measure the post-season harvest rate of Canadian and United States fisheries, managers rely on a coded-wire tag[1] (CWT) program indicating the hatchery of origin (PSC Coho Technical Committee, 2013). The ability to estimate the proportion of the

[1] Coded-wire tags are 1mm long encoded wire inserted into the nasal cavity of a hatchery smolt before release.

catch that an individual hatchery provides, and to derive an accurate estimate of the harvest rate, is crucial to redirect fishing pressure from endangered or threatened stocks. Tagged salmon are recovered either within a fishery sample or on the spawning ground and pertinent information is deduced based on the percentage of tagged fish released and retrieved (PSC, 2015).

However, Beacham et al. (2018) claims that the coded-wire tagging system is no longer the best tagging option to estimate exploitation and survival rates. The CWT program has remained relatively unchanged since its inception in the 1970s. One major issue with the use of CWTs is that the number of tags recovered has decreased over time due to the decrease in marine survival (Beacham et al., 2018; PSC, 2005a; Steele et al., 2013). Less and less hatchery fish were inserted with a CWT beginning in the 1990s, when all hatchery-origin fish were adipose fin-clipped in order to quickly differentiate hatchery fish from natural-origin fish. Adipose fin clipping allows for mark-selective fisheries in the commercial and recreational sectors that would only retain fish without an adipose fin, indicating that it is a hatchery fish and required all salmon with the fin intact to be released, as it is of wild origin (Naish et al., 2007). Consequently, adipose fin clipping has made sampling for CWT much more tedious as numerous clipped fish must be scanned before a coded-wire tag is found (Anderson & Garza, 2005).

Since CWTs are inserted into a portion of hatchery smolts, the very low marine survival (around 1.6%) of hatchery fish resulted in a smaller amount of tags recovered in fisheries and on the spawning grounds. The estimates of exploitation rate and marine survival are likely to have a high degree of error and may not have been as accurate during these years (Beacham et al., 2017b; Steele et al., 2013). Therefore, the Pacific Salmon Commission may not always find CWT suitable as a fishery management tool as it does not provide accurate estimates of the marine survival or exploitation rate of wild stocks. It simply provides estimates for a handful of hatchery stocks that are then assumed to reflect that of wild stocks (PSC, 2005a). Salmon populations would benefit if management incorporated the identification of both wild and hatchery fish (Beacham et al., 2017b).

1.4 Salmon Aquaculture in British Columbia

Aquaculture is another key industry used to supplement wild marine populations and provide for a steady source of seafood. Within Canada, aquaculture has grown to represent approximately one third of Canada's fisheries value and twenty percent of seafood production (DFO, 2013a). Finfish production represents the largest component of Canada's farming sector, with Atlantic salmon generating the largest value by species (Pinfold, 2013).

Farmed salmon can be grown in one of three ways: (1) as juveniles in land-based hatcheries; (2) grown-out in ocean-based net pens; or (3) using a broodstock land-based enterprise (DFO, 2016a, 2016b). While hatchery operations will release the juveniles into the wild for the remainder of the growth cycle, the land-based enterprise and ocean-based net pens utilize full grow-out cycles from the smolt phase to adult phase, after which the salmon are harvested for market sale. Within British Columbia, the ocean-based pens rearing Atlantic salmon have a higher market presence over the land-based ventures (DFO, 2013a).

Amidst the development of open-net salmon pens, the BC government conducted a review of the current methods and processes used in farming operations, known as the Salmon Aquaculture Review (SAR). The review concluded that aquaculture, at its current production levels, presented a low overall risk to the environment (Government of Canada, 2011). Issues related to farm siting, salmon escapes, waste discharges, and wild-farmed salmon interactions have since become more publically known since the SAR was accepted in 1999. The Department of Fisheries and Oceans Canada (DFO) has responded to ensure that minimum harm on the natural environment occurs. Today, farm tenures of open-net pens are set at 121, with 36 land-based farms as well (DFO, 2016a, 2016b).

1.4.1 Concerns with Open Net Farms

The salmon farming industry in British Columbia has raised awareness and concerns regarding the ecological and health effects of farmed fish on the natural environment, as well as wild stocks. Interactions between the farmed Atlantic salmon and wild Pacific salmon occur when salmon escape from the open-net pens, which has been a major issue for numerous farms along the B.C. coast (Naylor et al., 2005). While escaped Atlantic salmon cannot successfully breed with wild Pacific salmon, they may migrate up-river and can become a source of competition for food and space, and can spread diseases and parasites to local stocks (Gross, 2002; Naylor et al., 2010). Escaped coho or Chinook salmon pose a greater concern as these may successfully breed with wild coho or Chinook. The interbreeding of a domesticated and wild population of the same species of salmon can be harmful to the future success of that wild population (Forseth et al., 2017; Gross, 1998).

Diseases and Pathogens

The spread of disease and parasites are a major strain on production of farmed salmon in BC, as is in other nations around the world (Naylor et al., 2010). There are a number of diseases and pathogens that have been identified in salmon farms, but the spread of sea lice, *Lepeophtheirus salmonis* is one of the largest threats (Naylor et al., 2010). Sea lice may kill an adult salmon by feeding on its skin and mucous, and while it is endemic to the natural ocean environment, it has the ability to grow in abundance when fish are found in high density, such as they are within open-net pens (Liu, Sumaila, & Volpe, 2011). Large numbers of sea-lice have been found on pink salmon smolts, which are more susceptible than adult salmon, in areas where numerous fish farms are located (Naylor et al., 2010).

Beyond the external sea lice parasite, farmed salmon are exposed to several infectious diseases. The most prevalent disease is known as Infectious Hematopoietic Necrosis (IHN). IHN affects several organs within salmon, such as the kidney, liver, and spleen, and causes organ malfunction with high rates of mortality. IHN is endemic to the Pacific Northwest and was discovered in sockeye salmon over 50 years ago, but recent findings have shown that Atlantic salmon are very susceptible to the disease, and may carry the virus at a higher density then found within sockeye salmon (Morton & Routledge, 2016).

Piscine reovirus causes heart and skeletal muscle inflammation (HSMI) in salmon in Norway and Chile. The Norwegian salmon farming industry has seen large economic losses due to HSMI, and the same type of symptoms was seen in coho salmon within Chile. Evidence of HSMI within Atlantic salmon farms is emerging, with traces of the disease becoming apparent in 2008 (Di Cicco et al., 2018; Morton & Routledge, 2016). The ecological concerns have sparked interest in land-based farms, which separate the fish from their wild counterparts.

1.4.2 Shift to Land-Based Aquaculture

Land-based aquaculture (LBA) or closed-containment aquaculture (CCA) refers to a number of technologies that seek to isolate the rearing environment from the natural environment to reduce or eliminate the interactions between the two (DFO, 2008). Today, there are a number of prevailing closed containment technologies; the ocean-based solid wall containment, the land-based flow-through system, and the land-based, recirculating aquaculture system (RAS), each allowing the waste to be filtered out of the system to be used as a fertilizer or compost rather than dissolving within the ocean (Weston, 2013). Only the RAS has no discharge of effluent water back into the natural environment. Numerous studies have evaluated the economic efficiency of this system, which is becoming popular within the land-based aquaculture industry (e.g. Bjørndal & Tusvik, 2017; Boulet et al., 2010; Murray et al., 2014; Wright & Arianpoo, 2010).

Recirculating System

In recirculating systems, water is pumped from a source and circulated throughout the system. However, instead of being returned to the source, up to 98% of the water is filtered and recalculated back through. CO_2 and pH levels are closely monitored and the solids are separated and removed (Stechey & Robertson, 2010). Since the water is treated before it enters the system and all waste is contained in holding tanks, there is no vector for disease, parasite, or pathogen transfer between the wild and farmed salmon (Weston, 2013).

Limitations

As there is no interaction between the farmed salmon and the natural environment, many of the environmental externalities found in open-net farms are not found within land-based systems. However, CCA does have some concerns that should also be noted.

The energy needed to run such a facility is much higher due to the need to pump water, filter waste, and regulate water temperature (DFO, 2008). This energy is in addition to the energy needed within the feeding system, transportation, and construction of the farm that is shared with the energy consumption of the marine open-net pens. The capital needed for land-based systems is greater than those required for open-net farms. This includes a pump, and several biological filters to maintain a high water quality for the salmon. Storage tanks are required for waste until the waste is properly disposed or converted into manure for a more sustainable recycling method (Pinfold, 2014; Wright & Arianpoo, 2010).

Land usage, and competition with other users, is an impeding factor for land-based systems and can become restrictive to the expansion of production sizes. A study conducted by Wright & Arianpoo (2010) estimates a land requirement of 1,600 m^2 if that farm was to produce 100 MT and 22,500 m^2 to produce 1,000 MT. Salmon farmers may be limited to smaller farms due to British Columbia's rugged coastline and expansive coastal mountain ranges.

All of these limitations result in a higher start-up and operating costs. As a result, broodstock development programs have produced salmon smolts well suited for rearing within land-based farms (Neira et al., 2014; Yáñez et al., 2015). By targeting certain traits, scientists can improve growth rate, feed-conversion ratio, and flesh quality of adult salmon for a higher market price (Dufflocq et al., 2017; Neira et al., 2004; Yáñez et al., 2013).

1.5 Genomic technologies in salmon fisheries and aquaculture

Recent development within the field of fisheries and aquaculture research has led to the use of genomic-based technologies as a way to improve production, assessment, and management of salmon (PSC, 2008b; Yáñez et al., 2015). Here, I outline the types of genomic tools that are utilized within the wild-capture fisheries and farmed production industries, as well as some of their successful application to wild and farmed salmon species.

1.5.1 Genomic technologies within wild-capture fisheries

Due to the many uncertainties and biases of using coded-wire tags, the PSC requested the advent of new innovations and techniques for managing coho salmon. One such technology relies on the use of genomic sequencing of wild and hatchery coho salmon as an identification tool. Parentage-Based Tagging (PBT) works by genotyping an entire hatchery broodstock annually and allows the subsequent progeny to be sampled (i.e. reading the genetic sequence) and assigned back to their parents, indicating the hatchery of origin and the age of the fish (Anderson & Garza, 2006; Steele et al., 2013). A pedigree can be constructed over several generation of a hatchery population and measure the changes in fecundity, reproductive success, egg size, and other factors related to the fitness and heritability of hatchery fish (Beacham et al., 2017). Genetic stock identification (GSI) is applied to wild and hatchery stocks to match individuals caught in a mixed-stock fishery to their river of origin and allows managers to measure the presence of endangered stocks at a given time and area. Managers may then open or close a fishery, as needed, to minimize harvest on stocks of low abundance. By combining both techniques, survival rate and exploitation rates can be measured based on stock composition within a fishery and hatchery composition on the spawning grounds (Beacham et al., 2018).

Application of GSI and PBT in fisheries

The use of GSI and PBT has proven to be successful in numerous salmon fisheries in Canada and the United States. Steele et al. (2013) demonstrated one of the first empirical validations of PBT within the Snake River in Idaho. 52 out of 59 genotyped hatchery steelhead trout (*Oncorhynchus mykiss*) were correctly assigned to their hatchery stock using PBT (Steele et al., 2013). In Beacham et al. (2004), genomic stock identification was used to reveal an early shift in the return of the endangered Late-run Cultus Lake sockeye. Early returns to the Fraser River are associated with high levels of pre-spawning mortality. In response, a conservative 15% harvest rate was applied on the Late-run to account for in-river pre-spawning mortality, and the restricted harvest allowed an escapement size that was twice the size of the preceding generation (Beacham et al., 2004) A study by Beacham et al. (2008) illustrated the use of GSI in the Northern BC troll fishery, which faces strict restrictions due to conservation concerns on the West Coast of Vancouver Island (WCVI) Chinook salmon. From 2002-2005, in-season stock identification via GSI allowed for Northern BC troll fishers to harvest around 92% of their total quota without overfishing the WCVI Chinook stocks. This is in contrast to catching 30% of the quota when the fishery was managed using a coded-wire tagging system. Stocks of coho salmon are currently being genotyped and entered into a database for the successful use of PBT and GSI (Beacham et al., 2017b).

The use of parentage-based tagging and genetic stock identification may be applied as a way to identify a hatchery or wild fish to its river, or population, of origin. The higher accuracy these tools provide over the coded-wire tags can lead to improved productivity through a more efficient assessment and management system of wild and hatchery stocks. Additionally, this assessment and management system would save on sampling costs and may provide higher economic benefits to commercial salmon fisheries. This serves as the underlying objective for Chapter 2, which is to measure the economic value of these genomic technologies using the Interior Fraser coho populations as a case study.

1.5.2 Genomic technologies within salmon aquaculture

Broodstock development programs are aimed at increasing the economic return of aquaculture systems by way of selective breeding (Gjedrem, 2012). Selective breeding utilizes the genotypic information from a potential breeder to pass on desirable traits to future generations (Yáñez et al., 2015).

Traditionally, the genetics of complex traits, such as disease resistance, in farmed species has been studied without identifying the genes involved (Goddard & Hayes, 2009). Selecting broodstock has been based on estimated breeding values calculated from phenotypic records and pedigrees, and on knowledge of the heritability of each trait. This has been successful, but the process is slow for certain traits. Therefore, to improve on the process of selection, it would be valuable to identify genes for them and select the individuals carrying the desirable alleles (Goddard & Hayes, 2009). Marker assisted selection (MAS) refers to a selection process in which molecular markers that are tightly-linked to a specific gene are identified (Liu & Cordes, 2004). Salmon that possess that particular gene can be selected based on their genetic makeup, rather than their physical appearance. Genomic Selection (GS) uses a large sample of breeders, which are measured for the desirable trait and genotyped for certain molecular markers (Sonesson & Meuwissen, 2009). The genotypes are assigned a value, and a statistical analysis of the reference population is used to estimate the effect of each marker (Liu & Cordes, 2004).

Application of genomic tools in broodstock development programs

Current breeding objectives for coho salmon aquaculture are based on estimated breeding values weighted by their marginal economic values including harvest weight, flesh colour and disease resistance (Neira et al., 2014).

Harvest weight is the single most studied trait in salmonid species, and has the highest economic value (Neira et al., 2014). A study by Neira et al. (2006) estimated an average increase in harvest weight by 10.2-13.9% per generation, or around 302-382 grams per generation (Neira et al., 2006).

The carcass and flesh quality is another important trait, with high consumer preference (Neira et al., 2014). A genetic analysis conducted by Neira et al. (2004) used 3,444 individual coho salmon from two populations and showed clear carcass differences between sexes. The dressing percentage and fillet percentage, both of which indicate the amount of edible meat in proportion to body weight, were found to have medium to low heritability (Neira et al., 2004). The study also found lower abdominal fat content (7% of visceral weight) in coho than in previous studies (4-5%). The amount of abdominal fat is considered undesirable as it results in a lower fillet weight (Neira et al., 2004).

In most markets, flesh colour can yield a higher price premium. A study conducted by Dufflocq et al. (2017) showed a low, but positive correlation between an increase in harvest weight and an increase in pigmentation of flesh colour. Both of these traits are favourable when the farmed coho salmon are processed and sold (Dufflocq et al., 2017).

Lastly, disease resistance, while not as economically valuable as harvest weight, is still an important trait identified in selective breeding programs. In Chilé, the success of many coho salmon farms is vulnerable to the *Piscirickettsia salmonis* bacterium, which causes an infection commonly known as Salmon Rickettsial Syndrome. Conventional control measures (i.e. vaccines and antibiotics) have not shown to be consistently effective in field conditions, and as a result, resistance to this particular pathogen is included in many breeding programs (Yáñez et al., 2016). A study by Yáñez et al. (2016) found a negative correlation between harvest weight and resistance to *P. salmonis*. Future breeding programs should take into account the impacts of breeding for growth on the susceptibility to certain diseases.

The use of genomic selection and marker assisted selection may be used in identifying the broodstock with the highest breeding values, to ensure consequent generations are well-suited for certain economic traits. This serves as the underlying objective for Chapter 3, which is to measure the profitability of different land-based aquaculture systems when these genomic technologies are used to improve coho broodstock.

1.6 Thesis Objectives and Structure

While the use of genomic technologies has proven to be useful in the production and management of both wild and farmed salmon, research is lacking in measuring the economic value of these technologies in comparison to the *status quo*, or a management and production system which does not utilize genomic tools. Furthermore, previous economic analyses on the use of genomic technologies have not focused on coho salmon (Boulet et al., 2010; Colt, 2010; Pinfold, 2014; Satterthwaite et al., 2015; Wright & Arianpoo, 2010), a species of large socio-economic importance with dwindling wild populations (Beamish et al., 2010) and minimal farmed production in BC (DFO, 2013b). The objective of my thesis is therefore to quantify the economic value of the genomic technologies described above. Specifically, the two primary research objectives that I answer with this thesis are:

1. What is the economic value of the genomic-based technologies that may contribute to taking coho salmon off the endangered species list?
2. What is the economic value of improved coho salmon broodstock that can increase the profitability of the land-based aquaculture industry in British Columbia?

In Chapter 2, I compute the net present value of commercial coho fisheries that would be managed using the genomic technologies and compare it to the net present value of the same fishery, managed using the coded-wire tagging system. The model employed to compute the net present value is comprised of a biological and economic component. Stock-recruitment models estimate future production of coho based on different determinants of survival. The economic model accounts for the landed value of coho salmon, in addition to the cost of fishing and the cost of technological implementation. The results signify the value of these genomic technologies in the Interior Fraser coho fisheries, as well as all coho fisheries in BC, up to the year 2050. The study shows that the net present value of these technologies could be around a total of $65,000 in the current low productivity period and up to $1,200,000 in a period of high productivity, from present day until 2050.

In Chapter 3, I identify the economically important biological traits in coho salmon broodstock and the ways in which these traits can be improved through selective breeding. The traits that I focus on in this study are growth rate, susceptibility to disease, and flesh quality. Then, I calculate the net present value to see how profits within two land-based farming systems change when the broodstock is enhanced via genetic selection and marker assisted selection. The change in net present value signifies the economic value of these genomic technologies. Results are based on a 10-year life span of the farming system. The study shows the economic value of these genomic technologies could be between $1,384,000 and $13,840,000, accrued over a period of 10 years, depending on the production capacity of the farm.

Chapter 4 summarizes the findings of this thesis and provides some potential policy recommendations to further improve the production of wild and hatchery coho, as well as the profitability of land-based farming systems in British Columbia. To conclude the chapter, I go over the strengths and weaknesses of my study and provide guidelines for future research.

Chapter 2: Bio-Economic Model of Genomic Technologies as a Fishery Management Tool

Interior Fraser coho case study

2.1 Introduction

Coho salmon (*Onchorhynchus kisutch*) were once a thriving species in British Columbia, a source of food, culture, recreation, and livelihood for those who call the province home. In the late 1990s, one of the most historically prominent stocks of coho in BC, the Interior Fraser River (IFR) stock, fell to notably low returns (Decker et al. 2014). Hypothesized causes of the decline include overfishing, climate change, and habitat alteration (Beamish et al., 2010; Bradford & Irvine, 2000; DFO, 2010).

Research on the survival and status of IFR coho, along with numerous other southern stocks, prompted an unprecedented moratorium for commercial fisheries beginning in 1998. Certain areas, mainly off the West Coast of Vancouver Island as well as the Strait of Juan de Fuca, were designated red zones, in which no fishing was allowed during certain months of the years. The remainder of southern BC was designated a yellow zone, with a non-retention policy on all incidentally caught coho issued for most commercial fisheries, excluding certain terminal, ceremonial, and test fisheries (DFO, 2001). In 2002, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) listed the Interior Fraser stock as an endangered species (COSEWIC, 2002). Escapements of wild fish started to rebound progressively, reaching 25,000 spawners, on average, during the late 2000s. This is around one-third of the escapement size during the 1980s, in which a 3-year average of 60,000-70,000 spawners was common (Decker et al., 2014). In recent years, the stock experienced moderately high returns, and was re-assessed and designated as threatened in 2016 (COSEWIC, 2016).

Efficient management has been a topic of concern when it comes to coho salmon, as it is for all species of Pacific salmon. Since the 1970s, coho have been managed using a coded-wire tagging system, in which 1mm long encrypted tags are inserted into hatchery origin fish, as well as a smaller number of natural origin fish, to guide research and regulations for these fish. Coded-wire tags allow managers to identify an individual with its hatchery of origin. In theory, with a known tagging rate, they are also able to estimate hatchery-specific exploitation and marine survival (PSC, 2008a). The hatcheries that utilize CWTs become indicator stocks, where the exploitation rate and survival of nearby stocks are assumed to match those of the tagged fish. Since only a portion of hatchery and wild fish are tagged, there is a large sampling bias and often times, inaccurate estimates of exploitation rates. It is likely that the high fishing pressure that was put on IFR coho in the 1990s was due to the inability to measure an accurate estimate of exploitation via the CWT system (see Figure 1.2 in Chapter 1).

Since coho salmon cross international boundaries into Washington State and Alaska, they are managed under the Pacific Salmon Treaty (PST). This agreement between the United States and Canada ensures that cooperative management is applied (PSC, 2016b). Under the treaty, fishery regimes for coho are designed to constrain exploitation on specified aggregates of stocks (PSC, 2008a). With the rise of emerging problems with CWTs, a higher funding requirement to retain accurate estimates of survival, and the increased concern for the health of the region's salmon, new genomic technologies were proposed and examined for possible application(PSC, 2008b, 2015).

Parentage-based tagging (PBT) provides the same type of information as CWTs. Hatchery broodstock are genotyped, and the subsequent offspring of the broodstock are automatically genetically tagged (Beacham et al. 2017b). Post-release, the progeny can be assigned back to its hatchery of origin, in addition to its age and sex. Relying on genomic identification results in all hatchery offspring being genetically tagged for a more accurate estimation of hatchery-specific exploitation and survival (Beacham et al. 2017b).

Genetic stock identification (GSI) uses genetic sequencing analysis to match individuals caught in a mixed stock fishery to their river of origin (PSC, 2008b). In contrast to the CWT system, GSI may estimate stock-specific exploitation rates of wild populations, whereas CWTs focus mainly on hatchery stocks. This is due to a stock identification baseline data comprising around 117 populations of coho (Beacham et al., 2017b). With the high success of GSI in practice, it has been used in-season to help managers detect the presence of endangered stocks and shut down a fishery as needed (Beacham et al., 2008; Beacham et al. 2004). Consequently, GSI also allows for more selective harvest of abundant stocks when permitted.

The economic feasibility of the proposed genomic technologies has been debated, as the Pacific Salmon Commission may adopt the technologies as primary management tools, assuming the application of CWTs do not improve (Hankin et al. 2015; Satterthwaite et al. 2015). This has prompted the first half of my M.Sc. research. The primary objective of this chapter is to determine the value of these genomic-based technologies that may contribute to taking coho off the endangered species list. To answer the primary objective, I measure the net present value of commercial coho fisheries that would be managed using the genomic technologies and compare it to the net present value of the same fishery, managed using the coded-wire tagging system. The net present value is comprised of a biological and economic component. Stock-recruitment models estimate future production of coho based on different determinants of survival. The economic model accounts for the landed value of coho salmon, in addition to the cost of fishing and the cost of technological implementation. The overall results illustrate how these technologies can be beneficial to future generations who will depend on healthy and well-managed salmon populations.

2.2 Methods

2.2.1 The biological component

Determinants of Wild and Hatchery Survival

The first step in classifying how genomic technologies may improve recruitment and provide a greater economic surplus than the current system in place is to identify the different factors that may impede or improve survival of both wild and hatchery fish. Since effective fisheries management can lead to a higher number of salmon surviving to spawn, I include management measures as well. I used a thorough literature review to identify what determinants may lead to a period of high and low survival. Table 2.1 provides each factor, how it may impact survival, and the citation source. Certain determinants can be ameliorated by the use of genetic stock identification and parentage based tagging. These are bolded and italicized.

Table 2.1: Determinants related to productivity and survival of both hatchery and natural origin coho salmon.

Factor	Description	Source
Habitat Degradation	Loss of stream habitat and riparian vegetation has reduced the capacity of the Fraser River and its tributaries to support rearing of coho salmon.	Interior Fraser Coho Recovery Team, 2006; Cohen, 2012; Meffe, 2012; English, Glova, & Blakely, 2008
Competition	Interactions between wild and hatchery salmon, including competition for space and resources, may impact survival of both of these groups; however, the impact of IFR hatchery releases on wild stocks is not well documented.	Orr, Gallaugher, & Penikett, 2002; Interior Fraser Coho Recovery Team, 2006;
Susceptibility to Disease	A number of diseases, such as Bacterial Kidney Disease (BKD), are found within hatchery and wild fish. Susceptibly and resistance to certain diseases can improve the survival of hatchery fish within the captive and wild environment, but a high level of uncertainty concerning the genetic basis of disease resistance remains. Genetic tools can assess the level of genetic diversity required to maintain healthy populations and the heritability of resistance to diseases within hatchery fish.	BC Centre for Aquatic Health, 2010; Rhodes & Yanagida, 2018; Naish et al., 2007
Ocean Conditions	Steady decline in marine survival for coho salmon coincides with an increase in sea-surface temperature by 1C since 1970; higher surface wind speed is positively related to lowered marine survival.	Beamish et al., 2010
Predation	Early marine survival is highly defined by predation preceding entry into ocean environment; Hatchery fish may exhibit behavior indicating a lack of predator awareness, making them more susceptible to mortality.	Noakes et al. 2000; Chittenden et al., 2010a.
Migratory Changes	A change in marine conditions resulted in migratory changes that show a majority of coho would leave the Strait of Georgia quicker then preceding years, likely exposing them to higher rates of predation.	Chittenden et al., 2010b; Beamish et al., 2010.
By-Catch	Following the moratorium on IFR coho in commercial fisheries, a certain amount of by-catch from fisheries targeting Chinook and sockeye still occurred; a maximum of 3% bycatch rate was implemented. High rates of bycatch will result in lower escapement numbers and can impede the rebuilding of the stock.	Pacific Salmon Commission, 2017; DFO, 2001.
U.S. Interception	Since IFR coho are managed under the Pacific Salmon Treaty as a trans-boundary stock and are found within US waters in the Strait of Juan de Fuca, U.S. fleets may harvest a maximum of 10% of total returns per year.	Pacific Salmon Commission, 2017.
Catch/Release	The release of accidentally landed coho salmon still results in	Cox-Rogers et al., 1999;

	significant mortality as some fish will not survive long enough to make it to the spawning ground.	Lawson & Sampson, 1996.
Anthropogenic Pollution	Anthropogenic pollution and toxic stormwater runoff in urban developments has been linked with pre-spawning mortality in coho salmon, in which large numbers of fish die after entering the freshwater environment but before reaching the spawning grounds.	McIntyre et al., 2018; Scholz et al., 2011.
Straying	High rates of straying in hatchery fish results in genetic outbreeding, and the offspring are often unsuited for survival in freshwater system they are reared in; hatchery fish that have strayed spawn with wild and hatchery fish of another population, therefore minimizing the offspring's genetic profile and fitness.	Meffe, 1992; Bakke, 1997 Waples 1991; Hindar, Ryman, and Utter 1991; Gharrett and Smoker 1991.
Fecundity	Lowered fecundity is indicated by a smaller number of eggs per female and smaller egg size can result in a reduction in productivity, namely in hatchery fish.	Hedgecock & Coykendal, 2007; Bradford & Irvine, 2000; Orr et al., 2002; DFO, 2001.

Parentage-based tagging is an identification tool that generates more practical information from samples than the coded-wire tagging system. It allows hatchery and fishery managers to identify a hatchery fish with its river of origin, due to a population baseline database of hatchery stocks (Satterthwaite et al., 2015). In developing baseline knowledge that will be used to match a hatchery fish to its parents, fisheries scientists can examine if there are any genetic components that will increase or decrease survival of hatchery fish (Davidson, pers. comm.), through the successful identification of genetic markers for genes related to survival and reproductive fitness. More specifically, these genes may be related to higher fecundity, a lower susceptibility to disease, such as bacterial kidney disease, and a greater ability to hone back to the released stream to minimize straying of hatchery stocks. PBT is likely not to be used as a tool for selective breeding of hatchery fish for better survival (Beacham, pers. comm.). Instead, it may be used to maintain a wide variety of fitness-related genes in the population, and ensure those genes are present over several generations. Additionally, it is used to measure the contribution of certain hatchery stocks to wild-capture fisheries, and by doing so, can indicate how successful a hatchery program is in 1) providing for more fishing opportunities, and 2) assisting in the rebuilding of endangered stocks by increasing the number of spawners from that stock (Section 1.3.1). Estimates of fishery exploitation and marine survival rates of hatchery fish will be more accurate due to all hatchery progeny being genetically tagged (Beacham et al., 2017b). Subsequent management responses from exploitation and survival estimates on hatchery stocks can help the productivity of hatchery and wild stocks over time.

While it is not the current objective of a parentage-based tagging management system, the information that is currently being collected for PBT to be successfully implemented can also be used to guide hatchery managers in standardizing their husbandry practices to enhance the survival of families with lower fitness, without the use of selective breeding programs. Since changes in the fitness-related genes can be associated with the rearing environment and to genetics by environment interactions, identifying which rearing practices have consequences on the survival of hatchery salmon will be a beneficial end result. This can be a large contribution to refining the use of hatcheries in British Columbia to meet their objective and to produce fish that will survive well in both the captive-rearing and wild environment.

GSI provides real-time estimates of stock composition within a given fishing ground. Managers may therefore open and close a fishery with more certainty that it would prevent the accidental bycatch of an endangered stock while maximizing the harvest of an abundant stock (Beacham et al., 2004; Shaklee et al. 1999). It is different than the coded-wire tagging system in that it does not rely on hatchery indicator stocks as a metric for exploitation of wild stocks, but samples the wild fish directly. Sampling requires a tissue extract, which is non-lethal, whereas the CWT system requires the head of the fish for the tag to be extracted. Additionally, GSI differs from PBT in that the individual salmon is identified with its stock, not the individual parents. Therefore, not every wild spawner must be genotyped for the baseline population information (Satterthwaite et al., 2015). It is also used on hatchery fish when a positive identification is not possible using PBT. In the Interior Fraser coho case study presented here, the goal of GSI is to promote the conservation of this endangered stock by identifying the time and location of wild IFR coho during commercial fishing seasons. Doing so can minimize accidental harvest of this population, allowing more adult fish to reach the spawning grounds. It could eventually be used in US fisheries to get accurate estimates of exploitation on IFR coho within the Strait of Juan de Fuca.

Stock recruitment

I use two different stock recruitment models to forecast future returns of Interior Fraser coho from the years 2013 to 2050, the Ricker and Beverton-Holt recruitment models. The reason for including two recruitment models is that there are numerous uncertainties in measuring future recruitment. By providing two estimates, I am able to establish a range, in both the abundance of the population and the net present value of the coho fishery (described further below). I rely on the Ricker and Beverton-Holt model specifically because these two models capture most of the behavior for the relationship between stock size and recruitment (Hilborn & Walters, 1992). As such, these two models are widely used in the scientific literature and stock assessment (i.e. Decker et al., 2014; Korman & Tompkins, 2014a, 2014b; Liu, Sumaila, & Volpe, 2011). Published data from DFO (Appendix A) provides estimations of spawners and recruits up until 2012 (Decker et al. 2014), which is used to estimate the recruitment parameters α and β in equation 2.1. The first model to be applied is the Ricker (1954) model:

$$R_{t+3} = S_t exp^{\alpha(1-\frac{S_t}{\beta})};\ t = 0,1,2, \ldots .T \tag{2.1}$$

in which R_{t+3} are future recruits, S_t is the current years' spawning size, α is the alpha parameter and β is the beta parameter, t indicates the year, with T being the final year in the analysis. It is best to transform the model into linear form:

$$LN\ (R/S) = a + bS \tag{2.2}$$

Using this linear function, LN(R/S), which denotes the measurement of productivity, becomes the dependent variable Y. *Alpha* becomes a, the intercept, and b becomes the slope meaning that *beta* is equal to (-*alpha*/slope). The spawning size becomes the independent variable, X. Plotting LN(R/S) vs. S and finding a line of best fit through a linear regression allows us to calculate both parameters. In this case, alpha becomes productivity at very low spawning biomass, in which S is at or close to 0. Beta becomes an important biological indicator, the value at which recruits is equal to spawners. Any spawning size above *beta* will result in a recruit/spawner ratio that is less than 1:1 and the population will deplete itself, even in perfect conditions with no fishing mortality.

The second stock recruitment model is the Beverton and Holt (1957), which reads:

$$R_{t+3} = \frac{\alpha S_t}{\beta + S_t}; t = 0,1,2, \dots T \tag{2.3}$$

where R_{t+3} are future recruits, S_t is the current years' spawning size, α is the maximum number of recruits produced, and β is the spawning stock needed to produce recruitment equal to *a*/2. To estimate the *alpha* and *beta* in this model, I relied on a published study by Decker et al. (2014), which contains estimates of the parameters using escapement data from 1975 to 2012. However, this study will only rely on data from 1987 to 2012, as there are missing data points for the years preceding, and so the estimates of *a* and *b* will be slightly different. I use the parameter estimates from the study and input them using the estimates of spawners and returns (Appendix C). Then I minimize the sum of squares of the residuals from the observed spawner-recruit relationship to the calculated spawner-recruit relationship using the estimates provided. The minimize function was implemented using the Solver software from Microsoft Excel.

The stock-recruitment of Interior Fraser coho indicates two different periods of productivity and survival. The first is considered to be a period of high productivity, in which the number of recruit-per-spawner was around 3 or 4. This period occurred from 1985-1994. Following a period of high productivity, survival of IFR coho decrease significantly and the number of recruits-per-spawners averaged at or around 1 at low spawning biomass. I model these two periods, as well as a third one (Mid Productivity) by estimating the alpha and beta parameters for both the Ricker and Beverton-Holt recruitment models. Using data from the years (a) 1985-1994 indicating a period of high productivity; (b) 1995-2012 indicating a period of low productivity, and the average of the two, indicating a period of mid productivity, I am then left with three distinct productivity regimes that I incorporate into the analysis. Forecasting future recruitment is always hard as ocean conditions vary greatly from one year to the other (Beamish et al., 2010). I felt that with three scenarios of productivity, I am able to get a better overview of possible future recruitments. The coefficient of Determination (R^2) may indicate which model most likely explains the trends in productivity from the years of data, (i.e. 1985-2012).

The analysis therefore comprises of a total of 6 scenarios, dependent on the management tool in place and the productivity and survival regime. A description of each scenario is provided below:

Table 2.2: Description of the six scenarios used in the analysis.

Scenario	Description
1	Low productivity using a coded-wire tagging system
2	Low productivity using a genomic-based tagging system
3	Mid productivity using a coded-wire tagging system
4	Mid productivity using a genomic-based tagging system
5	High productivity using a coded wire tagging system
6	High productivity using a genomic-based tagging system

Hatchery releases

I want to account for the release and presence of hatchery fish in the wild environment, which spawn with other hatchery fish as well as wild fish, to improve future recruitment. Under the scenarios utilizing genomic technologies, the number of hatchery-released fish would be the same as with the CWT scenarios, but with higher survival rates. This is due to the notion that PBT may improve the survival of hatchery-reared fish in ways that CWT cannot: by identifying fitness-related genes and how captive rearing impacts those genes. If genetic sampling provides enough information for managers to refine husbandry practices, then the higher rates of survival will lead to more adults reaching the spawning grounds and contribute to the recruitment of the next year class, without having to increase the number of smolts released.

I collected hatchery release data for the same time period as that of low productivity, (i.e., 1995-2012) which were released into the Interior Fraser River watershed. Release estimates were found within the Regional Mark Processing Center (RMPC) database, which provides releases of hatchery origin fish either as an egg, fry, or smolt (RMPC, 2018). I standardized the release number by assuming a 20% survival rate for the egg-to-fry stage (Bradford, 1995), and a 10% fry-to-smolt survival rate post release (Beacham, pers. comm.). I then used a random number generator based on the 95% confidence interval of the estimated smolt release (20% of eggs + 10% of fry + smolts) as an indicator of future releases of hatchery coho to use in forecasting recruitment (summarized Appendix B). A majority of releases stem from a combination of six Salmonid Enhancement Program (SEP) and Community Economic Development Program (CEDP) hatcheries, including those from Spius, Deadman, and Dunn creek. Marine survival rates of hatchery indicator stocks from Korman & Tompkins (2014b) were used to estimate the number of returning hatchery fish that would then be considered as part of the spawning size for that year.

Recovery objective and exploitation

Future recruitment is subject to the same fishing pressure on coho salmon that is in place today. Average exploitation rate was determined using published data from Decker et al. 2014. Both wild and hatchery fish were subject to the same exploitation rate. I assumed the current catch restrictions (i.e. no retention, 3% bycatch by Canadian fishers, and maximum 10% exploitation rate by US fishers) remains in place until enough wild spawners return that meet the long-term recovery objective stipulated in IFRCT (2006). The long-term recovery objective is set at a 3-year aggregate mean of 40,000 wild spawners returning to the Interior Fraser watershed. Once that objective is met, I assume coho would be directly harvested in commercial fisheries, and I set the exploitation rate based on a fixed escapement policy. This is set at a level that allows 40,000 wild spawners to escape to the watershed each year (Interior Fraser Coho Recovery Team, 2006):

$$ER_{f,t} = 1 - \left(\frac{40,000}{R_t}\right) \tag{2.4}$$

where $ER_{f,t}$ is a fishery specific (f) exploitation rate. Following equation 2.4, the exploitation rate is 0 when returns are at or below 40,000. As the number of returns increase, so does the exploitation rate.

If the recovery objective is not met, then a maximum allowable harvest is established based on current bycatch rates, as well as the survival of coho salmon post-release in a commercial fishery. The average rate (1995-2012) of harvest in a closed fishery is assumed to be 13%. Several studies have been conducted that measure the post-release mortality of coho salmon caught in troll fisheries (e.g. Lawson & Sampson, 1996). A study in 1998 determined a mortality rate of 9-56%, depending on the location of the hook, for coho incidentally caught in the marine environment (Cox-Rogers, Gjernes, & Fast, 1999). The study shows hooking mortality to be very variable, so I use the average between the low and high end estimates presented, or around 32%. For the years in which the fishery remains closed, I am using the average harvest rate of coho salmon during the period of low productivity (1995-2012). Under the current coded-wire tagging system, I keep the harvest rate as is (13%). However, to model the use of genomic-based technologies, I will estimate the harvest rate assuming the accidental by-catch of endangered coho is minimized. Genomic stock identification may allow for more accurate estimates of stock composition and fisheries may consequently be closed with more certainty that an endangered stock is present within the fishing grounds. Therefore, the rate of harvest used for the genomic technology scenarios will be the average from the years 1995-2012 (13%) minus the 32% post-release mortality rate that occurs from incidental harvest. This comes out to 9% (Table 2.7), which is synonymous with the current harvest from US fishers.

Catch functions

With a new directed coho fishery, I must then model the catch, taking into account gear and location of the potential fishing fleet. During the 1980s and 1990s until the strict commercial harvest limits were put in place, the West Coast of Vancouver Island troll fishery would land around 85-90% of the total Interior Fraser coho landings (DFO, 2001). Therefore, I am assuming that, once a directed fishery were allowed, a similar allocation of harvest would be put in place, allowing the WCVI troll fishery around 90% of the total allowable harvest. To model that, I first estimate the total harvest based on the size of the return for that year, and ensuring that 40,000 wild spawners escape to the spawning grounds. Harvest is measured by:

$$H_{f,t} = ER_{f,t}R_tA_{f,t} \tag{2.5}$$

where $A_{f,t}$ is that year's allocation for a given fishery. With a set total allowable catch allocated to the WCVI troll fishery, I calculate the effort, measured in boat-weeks[2], which it would take for a vessel, or a fishery, to catch their quota. I then apply the Schaefer production model (Clark, 1990):

$$H_{f,t} = E_{f,t}q_{f,t}R_t \tag{2.6}$$

where $q_{f,t}$ is a gear-specific catchability coefficient, translating one unit of effort into one unit of harvest. $E_{f,t}$ is the effort, measured in boat-weeks, and R_t signifies the total return of coho into the fishing grounds. To solve for $E_{f,t,I}$ I use:

$$E_{f,t} = \frac{H_{f,t}}{q_{f,t}R_t} \tag{2.7}$$

Catchability is assumed to increase over time as technological progress allows fishers to harvest more fish for the same amount of effort and the same fish stock size. The catchability coefficient is measured using the following equation.

$$q_{f,t} = y_f \exp(\phi_f t) \tag{2.8}$$

where y_f is the catchability in the first year of the analysis, and Φ signifies the percentage increase in catchability each year. Catchability in the first year will be:

$$y_f = \frac{H_{f,t}}{R_{f,t}E_{f,t}} \tag{2.9}$$

[2] Boat-Weeks refers to a unit of effort that measures the total number of weeks fished by the combined number of fishing vessels.

in which $H_{f,t}$ is the harvest from one troll fishery targeting a specific stock, $R_{f,t}$ is the total size of the return for that stock, and $E_{f,t}$ is the number of boat-weeks it took to land the total harvest. Since harvest on IFR coho is minimal, I am relying on data from the Northern BC troll fishery to estimate the catchability coefficient, y. I have accurate data from the 2009 fishing season and the catchability will then be measured for 2018 using equation 2.8 above. 2018 serves as the first year in the economic analysis.

2.2.2 The economic component

Costs of fishing

A certain fleet will spend a certain number of weeks harvesting the allowable size. The cost of fishing is captured by the following equation:

$$C_t = c_{f,t}E_{f,t} \tag{2.10}$$

where $c_{f,t}$ is the variable cost of fishing per week, and $E_{f,t}$ is the number of weeks fished. There are certain costs to account for when estimating the variable cost of fishing. These include gas, wages, food, and repairs. I decided not to include any capital costs related to the purchasing of the boat itself into the analysis. The reason for this is that, following the commercial closure in 1998, many fleets remained licensed and made their living harvesting other species. The purchase of the boat is considered a sunk cost and would not influence fishers to enter or leave a fishery (Marsden et al., 2009). In British Columbia, it is legal for a licensed vessel to stack licenses and can therefore target multiple species of fish, salmon or otherwise, throughout the year (Ecotrust Canada, 2004). Re-opening a directed coho fishery would simply allocate a fishing quota onto a vessel that is likely targeting other species. It would not require the capital investment of a vessel and a crew. I do, however, include the cost of buying and owning a Salmon Troll (AT) licence as this is a yearly required investment, and a major variable cost that fishers account for when deciding on entering or leaving a fishery.

Costs of technological implementation

A secondary cost that I take into account is the implementation costs of the proposed technologies; genetic stock identification and parentage based tagging. These costs will be compared to those of the current coded-wire tagging system in place; for this reason, I calculate costs related to the genomic technologies that would generate the same amount of pertinent information for managers as would be given from coded-wire tag recoveries. It is a way to measure the costs of the activities that are currently conducted using the CWT system and would no longer be required if these genomic technologies are adopted instead.

It is important to note the differences in estimating exploitation rates using the CWT system versus that using the PBT/GSI system. The number of recovered CWTs is used to estimate the exploitation rate based on the number of tagged fish at the hatchery and the number of tagged fish on the spawning grounds. It is essential to sample on the spawning grounds under the CWT system in order to measure exploitation rate in the fishery, equated as: Catch/(Catch + Escapement). Since not all released smolts have a coded-wire tag, the rate of tagged fish/(tagged + untagged fish) is essential to measure the exploitation rate for that year (PSC, 2005a).

However, in a scenario where coded-wire tags are no longer used, managers may rely simply on the number of adipose fin clipped individuals to estimate the portion of hatchery fish on the spawning grounds. Managers rely on the fish from the spawning ground to serve as broodstock for the next year class. Since the broodstock is genotyped, and if the analysis shows very minimal straying, then it can be assumed that all clipped fish originated from that hatchery. Exploitation rate would then be calculated as the number of clipped fish sampled in a fishery over the number of clipped fish in a fishery + clipped fish on the spawning grounds. Genotyping would still be required in the fishery, as numerous hatchery and wild stocks can be found within a sample, and managers must identify the hatchery or river of origin for the individuals within that sample. However, no genotyping would be required on the spawning ground, beyond those of the broodstock. Current sampling data of coho salmon within the spawning grounds of Inch Creek and Chilliwack hatchery, both located within the Fraser watershed, indicate very minimal straying (Beacham et al., 2018). Any hatchery fish that has strayed from another stream in BC, into a stream in which wild and hatchery IFR coho are found, it can be removed to mitigate any sources of outbreeding depression (Beacham et al., 2018). The use of parentage based tagging and improved hatchery rearing practices can lead to negligible straying of hatchery stocks and would no longer require a genotyping cost on the spawning grounds (Table 2.11).

Benefits

Landed value is generated by:

$$V_t = P_t H_{f,t} g_t \tag{2.11}$$

in which P_t is the price per kilogram, $H_{f,t}$ is the size of the catch, in individual salmon, and g_t is the average weight of a 3 year old adult coho. Data regarding the price and average weight of coho salmon came from DFO Commercial Catch Statistics (DFO, 2010, 2016c).

I also provide the same analysis on a provincial wide scale as this is the level at which GSI and PBT would be used. I use the results on recruitment and catch from the Interior Fraser analysis as metric for BC wide coho recruitment and catch. The harvest, at the provincial scale, is calculated by the ratio of landed Interior Fraser coho to all coho landed in BC during the years of high (1985-1994) and low productivity (1995-2012), respectively. The ratio of coho landed under a scenario of mid productivity will be the average of the two described above. Once harvest is measured, the landed value and effort needed relies on the same equations as those on the local, Interior Fraser scale.

2.2.3. Bio-economic component: net present value

By combining the biological and economic model, I answer the primary objective for this chapter, the net present value of the genomic technologies. Here, I illustrate two methods of estimating net present value: conventional and intergenerational. I compare the results of both methods to show how each generates a different net present value, over a time span of 32 years.

Conventional net present value

The conventional NPV sums up the net benefits of a project or tool over a given period of time, and discounts the benefits to their present value (Sumaila, 2004; Sumaila & Walters, 2005). The equation reads (Sumaila, 2004):

$$NPV = \sum_{t=0}^{T} \frac{V_t - C_t}{(1-\delta)^t} \tag{2.12}$$

in which δ is a discount rate, t=0,1,2,…T is the year of the analysis with T being the final year. The conventional discount equation is useful for projects that are carried out over a short period of time (Liu, 2008). The net benefit is discounted only on the time perspective of the current generation. Future generations, therefore, are not considered with the same weight as the current generation. This can undervalue the importance of natural resources to future generations, especially those resources that face uncertainty in a changing climate (Newell & Pizer, 2003).

Intergenerational net present value

To properly account for the time perspective of future generations, I use the intergenerational NPV equation, which discounts net benefits as each generation, current and future, comes into existence (Ainsworth & Sumaila, 2005). The equation reads (Sumaila, 2004):

$$NPV = \sum_{t=1}^{t_1} \frac{V_t - C_t}{(1+\delta)^t} + \sum_{t=t_1+1}^{t_2} \frac{V_t - C_t}{(1+\delta)^{t-t_1}} + \cdots + \sum_{t=t_{L-1}+1}^{t_L - T} \frac{V_t - C_t}{(1+\delta)^{t-t_{L-1}}}$$

(2.13)

in which t_1, $t_{2,}$, …. $T_{l\text{-}T}$ is a generation, with t_L being the last generation in the analysis. The equation shown above resets the time perspective to t=0 as a new generation comes to existence. In this case, and for the conventional equation, the discount rate is set at 8%, which seems to be the norm when conducting a cost-benefit in British Columbia (Treasury Board of Canada Secretariat, 2007). I set the time in which a new generation comes into existence at t=18. Eighteen is around the age at which someone enters the job force and would benefit from increased participation within the commercial fishery (Ainsworth & Sumaila, 2003).

Once the net present value is calculated for each scenario, I estimate the value of genomic technologies by taking the difference in NPVs of each scenario using coded-wire tagging to its genomic-based tagging counterpart (i.e. $NPV_{S2} - NPV_{S1}$; $NPV_{S4} - NPV_{S3}$; $NPV_{S6} - NPV_{S5}$; s_1 = scenario 1, etc). By showing both conventional and intergenerational NPVs, I hope to illustrate why accounting for future generations in a cost-benefit analysis is necessary.

2.3 Data

2.3.1 Biological component

Stock recruitment

Table 2.3 and 2.4 show the estimates for the recruitment parameters as well as the coefficient of determination for the Ricker and Beverton-Holt models, respectively.

Table 2.3: Interior Fraser coho recruitment parameters using the Ricker model.

	Alpha	Beta	R^2
Low (1995-2012)	0.978	40,554	0.373
Mid	1.474	90,793	NA
High (1985-1994)	1.971	141,043	0.309

Table 2.4: Interior Fraser coho recruitment parameters using the Beverton-Holt model.

	Alpha	Beta	R^2
Low (1995-2012)	53,095	10,392	0.122
Mid	145,615	11,608	NA
High (1985-1994)	238,134	12,824	0.043

Hatchery releases

Release information from the RMPC database for the years 1995-2012 is summarized in Table 2.5 below:

Table 2.5: Hatchery release information from the Regional Mark Processing Center database for the years 1995-2012.

Variable	Size
Eggs Released	236,010
Fry Released	4,323,934
Smolt Released	4,584,819
Total Smolt Released	5,064,414
Average Smolt Released	281,356
95% Confidence Interval	+/- 38,640

With this information, I conducted a random number generation to be used in the model using the average smolt release +/- the 95% confidence interval. Marine survival (MS) was calculated as the average hatchery survival for the years indicated by the productivity regime. Lastly, by switching to a genomic-based identification system, I assume marine survival of hatchery fish would improve by a factor of 1.5 due to changes in rearing practices. This is an assumption based on various rationales. First, the marine survival of hatchery could be improved through the use of PBT, so the factor of improvement has to be greater than 1x. Furthermore, published data on MS of hatchery indicates survival rates of close to 2-3% for several years associated with the low productivity (1995-2012) (Korman & Tompkins, 2014b). Therefore, it would be realistic to see sustained marine survival rates of 2.25% under a period of low productivity. During the years of high productivity (1985-1994), hatchery marine survival ranged from 5-20% for Interior Fraser coho (Korman & Tompkins, 2014b), supporting the notion that a 1.5x survival increase is possible. These changes in rearing practices may result in a lowered rate of straying, higher fecundity, and an overall greater fitness of hatchery fish. The marine survival (MS) estimates using both management systems are provided in Table 2.6.

Sensitivity analysis of the improvement of hatchery survival under a genomic-based management is carried out with an initial assumption of a factor of 1.5 but the analysis includes a wider variation, from 1 to 4. The variation is based on historical hatchery survival estimates that range up to 20%, even reaching higher than 30% in the 1970s (Korman & Tompkins, 2014b).

Table 2.6: Average hatchery marine survival (MS) using both coded-wire tag (CWT) and parentage based tagging/genetic stock identification (PBT/GSI).

Productivity Regime	Average MS (%) using CWT	Average MS (%) using PBT/GSI
High (1985-1994)	4.5	6.75
Mid	3.0	4.5
Low (1995-2012)	1.5	2.25

Catch functions

Based on historical catch data, I assume that the commercial fishery that would benefit the greatest from a new, directed coho fishery, would be the Area G Troll fishery, as defined under the management of DFO (Appendix D). Today, the Area G Troll fishery operates during January until May and closes for the summer months due to the presence of IFR coho off the west coast of Vancouver Island (GSGislason & Associates Ltd., 2011).

The average harvest rate of IFR coho during the years 1995-2012 is 13%. By adopting genetic stock identification as a primary management tool in salmon fisheries, I estimate that the harvest rate could be closer to 9%, as this would account for U.S. interceptions and post-release mortality from recreational anglers. Incidental bycatch from Canadian fishers would be minimized. For the scenarios in which a directed fishery is opened, the harvest rate will be based on a fixed escapement policy of 40,000 wild spawners (Interior Fraser Coho Recovery Team, 2006). Table 2.7 below shows the average exploitation rate for each scenario. The range in exploitation rate is due to the different stock-recruitment models used.

Table 2.7: Average exploitation rate (ER) using both the coded-wire tagging (CWT) system and parentage based tagging/genetic stock identification (PBT/GSI).

Productivity Regime	Average ER (%) using CWT	Average ER (%) using PBT/GSI
High (1985-1994)	76-78	77-78
Mid	57-65	58-65
Low (1995-2012)	13	9

The catchability of the troll fleet, as described by equation 2.9, is assumed to be 0.00389 boat-weeks per fish. Accounting for advancements in technology and gear, I assume the catchability coefficient (Φ) will improve exponentially at a rate of 3% per year (Eigaard et al. 2014).

2.3.2 Economic component

Costs of fishing

The variable costs that are included in the analysis are shown in Table 2.8. Capital costs are limited to licenses, as described in Section 2.6 (Table 2.9).

Table 2.8: The variable costs, per week, that are using in the analysis, including the sources.

Costs	Amount ($)	Source
Wages for Skipper	1,201	Statistics Canada, 2018
Wages for Crew	764	Statistics Canada, 2018
Gear/Fleet Repairs	430	GSGislason & Associates Ltd., 2011
Gas	700	GSGislason & Associates Ltd., 2011
Food	75	GSGislason & Associates Ltd., 2011
Skipper Bonus	371	GSGislason & Associates Ltd., 2011

Table 2.9: Capital costs included in the analysis.

Costs	Amount ($)	Source
Salmon Troll (AT) Licence	120,000	Nelson, 2016

The parameters used to estimate effort, catchability, and the landed value are listed in Table 2.10.

Table 2.10: Catch function parameters used in the analysis.

Parameter	Amount	Source
Area F Troll Harvest in 2009 (H)	220,436	DFO, 2009b
Total coho run in 2009 (R)	327,636	DFO, 2009a, 2009b
Active boat-weeks in Area F troll fishery in 2009	750	GSGislason & Associates Ltd., 2011
Weeks of Fishing for coho in 2009	12	DFO, 2009b; GSGislason & Associates Ltd., 2011

Costs of technological implementation

Table 2.11 provides the estimated total costs related to sampling for both the coded-wire tagging system and the proposed genomic-based technologies.

Table 2.11: Implementation costs of both coded wire tag and genomic-based technologies, for the Interior Fraser stock.

	Coded Wire Tagging			Genomic Based Technologies		
	Number of Fish	Unit Cost ($)	Total Cost ($)	Number of Fish	Unit Cost ($)	Total Cost ($)
Juvenile Marking	28,000	0.21	5,880	210	20	4,200
Fishery Sampling	250	5	1,250	250	20	5,000
Escapement Sampling	1,000	5	5,000	Included In Broodstock		0
Total			12,130			9,200

I assume that an average of 280,000 smolts are released from hatcheries within the Interior Fraser watershed (RMPC, 2018). Around 10% of all released hatchery coho smolts are inserted with a coded-wire tag (Beacham et al. 2017b). Each CWT costs around $0.12, with an additional cost of tag insertion of $0.05 (Anderson & Garza, 2005; Beacham et al., 2017a). I include maintenance cost as a part of the cost of the coded-wire tag, estimated at $0.04. Given the low survival rate of hatchery fish, I estimated a maximum of 1,000 tags recovered on the spawning ground (3.5% of released) and due to the heavy restrictions on coho fisheries, I account for 250 tags recovered within test fisheries. The difference in sampling cost on the spawning ground is explained in Section 2.2.2.

This research focuses solely on the Interior Fraser River coho as a case study, to exemplify the costs and benefits of genomic technologies in salmon fisheries. However, as with the CWT system, PBT and GSI would be adopted on a BC-wide scale, encompassing much more than the IFR stock. For this reason, I present the cost differentials for the two systems on larger scale, using the same format as with the local scale (Table 2.11). I also calculate the NPV on the same provincial wide scale to show the increased value of genomic technologies as it is applied to a greater number of fisheries (Table 2.16).

Table 2.12: Costs of technological implementation on a British Columbia-wide scale.

	Coded Wire Tagging			Genomic Based Technologies		
	Number of Fish	**Unit Cost ($)**	**Total Cost ($)**	**Number of Fish**	**Unit Cost ($)**	**Total Cost ($)**
Juvenile Marking	800,000	0.21	168,000	6,000	20	120,000
Fishery Sampling	1,000	5	5,000	1,000	20	20,000
Escapement Sampling	4,000	5	20,000	Included In Broodstock		0
Total			193,000			140,000

The unit costs remain the same, with a larger number of coded-wire tagged fish released and recovered. The genomic-based technologies still offer a lower implementation cost, around 3/4th of the costs of the CWT system. This allows for a high net present value for the genomic-based technologies under all productivity regimes (Table 2.17).

Benefits

The parameters used to measure the landed value are listed below in Table 2.13.

Table 2.13: Price and average weight of coho used in the analysis.

Parameter	Amount	Source
Price/kg ($)	3.02	DFO, 2010, 2016a
Average weight (kg)	3.46	DFO, 2010, 2016a

2.4 Results

2.4.1 Biological and economic components

Table 2.14 and 2.15 below shows the average recruitment and average catch for the period 2020 to 2050 under each stock recruitment model.

Table 2.14: Average recruitment and average catch for each scenario, using a Ricker model.

Productivity	Coded Wire Tagging		Genomic Technologies	
	Average Recruits ('000s of Fish)	**Average Catch ('000s of Fish)**	**Average Recruits ('000s of Fish)**	**Average Catch ('000s of Fish)**
Low	44.7	No Fishery	46.7	No Fishery
Mid	102.0	52.5	107.2	55.6
High	181.3	124.4	189.6	130.6

Table 2.15: Average recruitment and average catch for each scenario, using a Beverton-Holt model.

Productivity	Coded Wire Tagging		Genomic Technologies	
	Average Recruits ('000s of Fish)	**Average Catch ('000s of Fish)**	**Average Recruits ('000s of Fish)**	**Average Catch ('000s of Fish)**
Low	46.7	No Fishery	49.6	No Fishery
Mid	123.0	72.1	128.0	75.2
High	195.8	137.7	203.4	143.3

Under a period of low productivity, both stock-recruitment models show an average recruit size that is over 40,000. However, this is not enough to sustain a fishery with an exploitation rate higher than the current rate of 13%. Therefore, the fishery would remain closed, with strict non-retention of wild Interior Fraser coho. In a period of mid and high productivity, the Beverton-Holt model shows a higher number of recruits than those measured using the Ricker model. This is examined in greater detail in the discussion section. Catch increases as productivity improves, with a maximum of 143,300 coho per year under a high productivity scenario.

2.4.2 Bio-economic component: net present value

Table 2.16 shows the NPVs using a conventional discounting equation, as well as an intergenerational discounting equation. The values provided indicate the net present value range between the Ricker and Beverton-Holt Model. The value of genomic technology is given by taking the differences in NPVs for each parallel scenario, using the intergenerational equation. Table 2.17 shows the NPV using a Ricker model with an 8% discount rate, on a scale that encompasses the all coho fisheries in British Columbia.

Table 2.16: Net present value of each scenario, using an 8% discount rate.

	Coded Wire Tagging		Genomic Technologies		
Productivity	**Conventional (‘000s $)**	**Intergenerational (‘000s $)**	**Conventional (‘000s $)**	**Intergenerational (‘000s)**	**Value of Genome Tech-Intergenerational (‘000s $)**
Low	-152	-265	-114	-199	65
Mid	1,456 – 4,077	3,615-8,712	1,684 – 4,815	4,092 – 10,011	477 – 1,288
High	8,503 – 10,900	17,157 – 21,799	8,960 – 11,623	18,111 – 23,000	953- 1,226

The net present value would be negative under a period of low productivity. The absence of a targeted coho fishery means that only the technology implementation costs are accounted for. The genomic technologies may therefore save $65,000 in implementation costs, even with no fishing allowed, over 32 years (2018-2050). Net present value increases with improved productivity, and so does the value of the genomic technologies.

Table 2.17: Net present value using Ricker recruitment model, with an 8% discount rate, British Columbia-wide scale.

	Coded Wire Tagging		Genomic Technologies		
Productivity	**Conventional (‘000s $)**	**Intergenerational (‘000s $)**	**Conventional (‘000s $)**	**Intergenerational (‘000s)**	**Value of Genome Tech-Intergenerational (‘000s $)**
Low	9,878	17,447	10,505	18,545	1,097
Mid	116,137	219,186	123,464	233,251	14,066
High	304,587	575,246	320,459	605,722	30,527

The successful adoption of GSI and PBT as a management tool would occur on a provincial scale, with greater success if the United States adopts the technology as well.

The improved productivity of both wild and hatchery coho means a longer fishing season off the west coast of Vancouver Island, where the Area G troll fishery is located. Even today, at a time in which catches of coho are severely restricted in Southern B.C. and productivity is low, the value of the genomic technologies would be around $1,097,000 more than the value of the coded-wire tags.

2.4.3 Sensitivity analysis

The discount rate that is chosen in cost-benefit analyses is a fundamental parameter as it denotes how much one values future generations. I conduct a sensitivity analysis of the net present value of adopting genomic-based tagging technologies instead of the coded-wire tagging system, with discount rates ranging from 0-12% (Figure 2.1). Note that I only provide the scenarios using the Ricker model. The scenarios using the Beverton-Holt model would exhibit the same behavior.

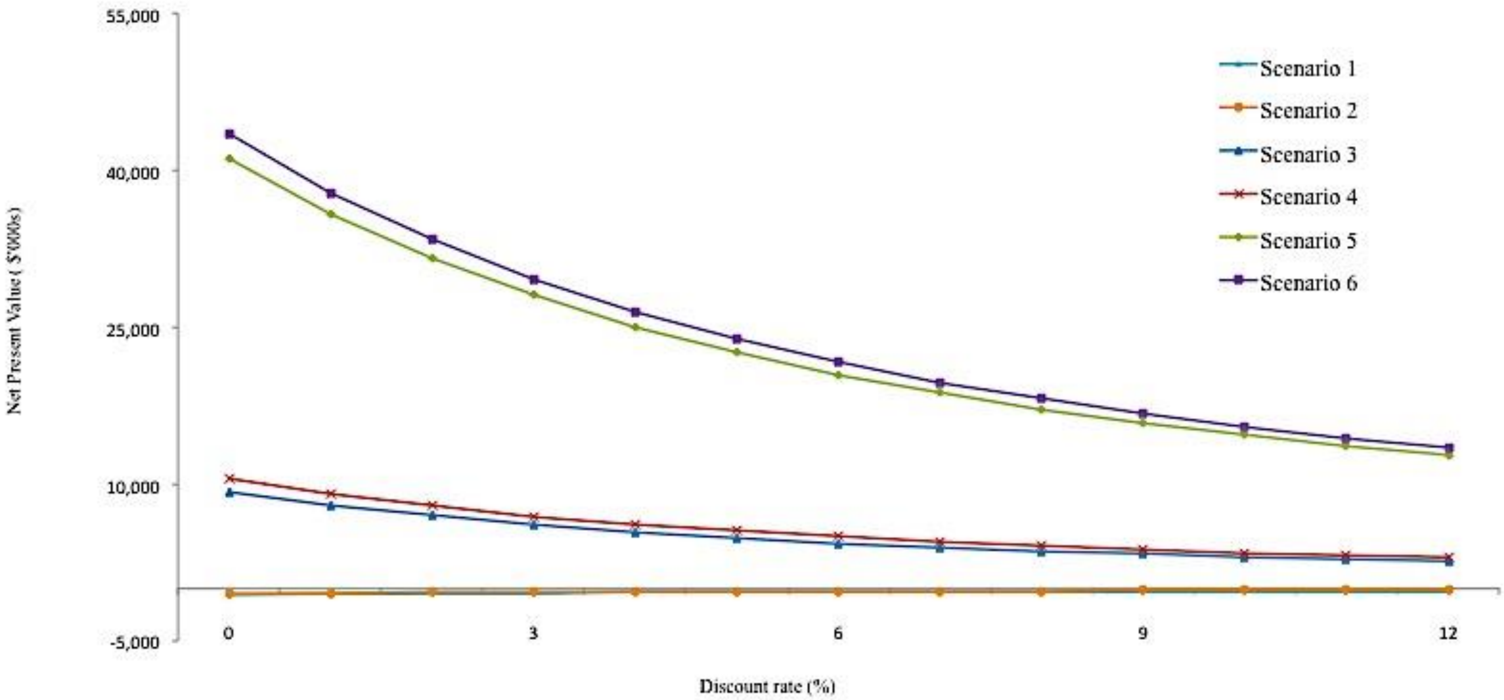

Figure 2.1: Sensitivity analysis of the net present value of each scenario measured using the Ricker model, with different discount rates.

The figure shows the net present value decreasing for every scenario in which the fishery opened (Scenario 3-6). For scenario 1 and 2, the net present value becomes close to 0 but remains negative at each discount rate. None of the scenarios intersect, indicating a robust model.

When implementing a genomic-based management system, the model assumes hatchery survival improves by a rate of 1.5x the survival used in the CWT scenario. Since it is unsure as to how much effect parentage-based tagging can have on improving survival of hatchery fish, I conduct an additional sensitivity analysis using the improvement of hatchery survival rate as an independent variable to see how it may impact net present value. Parentage-based tagging may identify traits related to survival and fitness, and see if those traits are genetic and can be passed down to future generations, or if they are the result of the fishing environment. I use different impacts of survival by switching from CWT to PBT (i.e. 1x, 1.5x. 2x, 2.5x, 3x…), shown in Figure 2.2 below. The values indicated are those attributed to the genomic technologies. It reveals the rise in the value of the genomic technologies as hatchery survival improves.

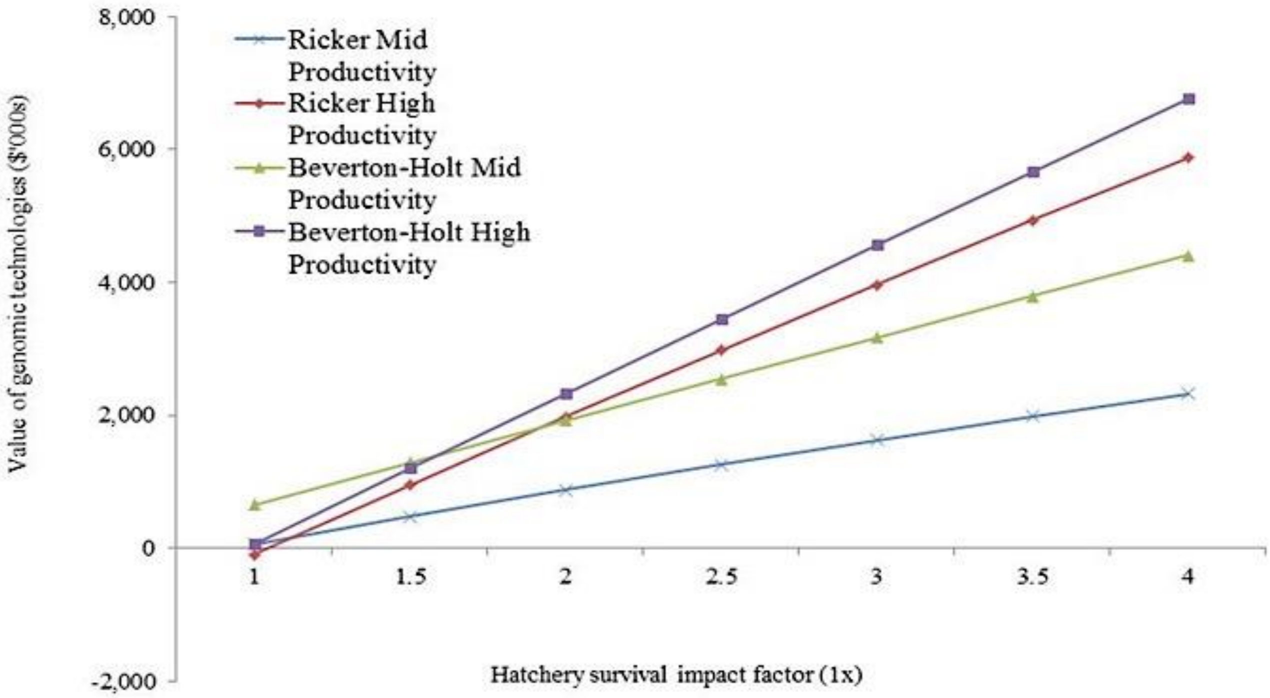

Figure 2.2: Sensitivity analysis of the genomic-based technologies' value under different impact factors of hatchery survival.

The figure shows that if hatchery survival did not improve (impact factor of 1x), the genomic technologies would have a negative value under a period of high productivity, when using the Ricker model to measure recruitment. As hatchery survival improves to 2x that of the coded-wire tagging scenarios, a trend forms in which a period of high productivity, using the Beverton-Holt model, generates the greatest value for the genomic technologies. This is followed by the same productivity, using the Ricker model. In fact, the Beverton-Holt model generates more revenue than the Ricker model in any productivity with an impact factor of 2x or higher. This is due to the differences in the recruitment models and how a higher density of hatchery fish will affect overall productivity. The Beverton-Holt model exhibits the greatest number of recruits at the larger spawning sizes, whereas the Ricker model exhibits decreasing recruits-per-spawners as spawning size increases.

Average prices of coho salmon may increase or decrease over time as well. Prices will depend on several factors, including the abundance of yearly returns, as well as competition on the market from farmed salmon. The development of salmon farms, both open net pens and land-based ventures, may provide a lowered price per kg due over time as input costs become more affordable (Liu, 2008). However, on the other hand, consumers may be inclined to pay a price premium for wild caught salmon, a product that is more environmentally-conscious (Liu & Sumaila, 2007), and supports local communities (Ecotrust Canada, 2004). For this reason, I provide a sensitivity analysis using a price range from $1 to $5 per kilogram (Figure 2.3). As in Figure 2.1, the sensitivity analysis comprises of the values for the Ricker model only, and the scenarios in which a fishery opened, allowing a price to be set (scenario 3-6).

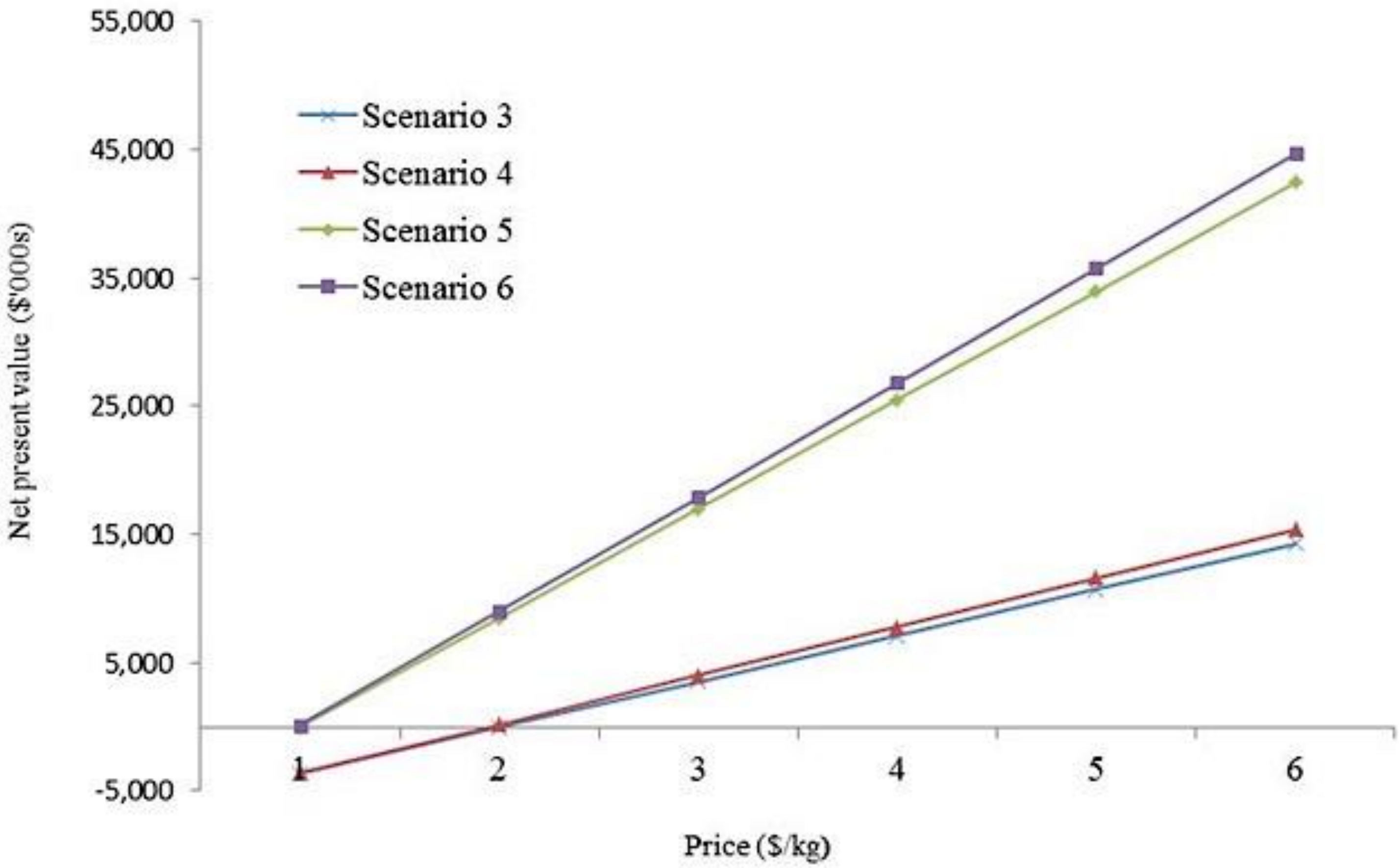

Figure 2.3: A price sensitivity analysis showing net present value of scenarios 3-6 using the Ricker recruitment model.

If the price of coho salmon were to drop to $1/kg, the model shows negative net present value for scenarios 3-5. The price per kilogram at which scenario 3 exhibits a NPV of 0 is $2.01. For scenario 4 and 5, it is $1.94 and $1.01, respectively.

2.5 Discussion

2.5.1 The proposed technology

As a novel technology, whether or not the genomic-based systems should replace or complement the existing CWT system depends on the relative operating costs and on the quality and quantity of information generated (Hankin et al., 2015; Satterthwaite et al., 2015). The results presented above indicate both of these factors to favor the genomic-based technologies. This holds true even in the absence of fishing during a period of low productivity, such as the period exhibited today. The lowered cost comes from the lack of sampling on the spawning grounds with the adoption of parentage-based tagging in hatchery rearing, as explained in Section 2.3.2. In addition, whereas the coded-wire tags are inserted in 10% of released hatchery smolts, parentage-based tagging only requires the sampling of broodstock and all subsequent progeny are genetically tagged. The number of offspring from a pair of female and male coho can generate around 3000 fertilized eggs in captivity (MacKinlay et al. 2004). There are significantly less fish sampled in the juvenile marking stage using genomic technologies, as only the broodstock must be sampled.

The data shown in Table 2.11 indicates that PBT and GSI are less costly on their own, regardless of how effective the tools are in practice. It would seem rational to adopt them as management tools over the coded-wire tags regardless of the outcomes of this study. However, doing so would require several years of transition in which the genomic technologies are used alongside the CWTs (PSC, 2015). Coordination with the United States is needed as well to measure the harvest on transboundary stocks, such as the Interior Fraser coho. These are limitations that are not included in the analysis but should be addressed in the synthesis of the Pacific Salmon Treaty negotiations in 2018 and 2019.

Issues related to funding for the CWT recovery program resulted in smaller release sizes, exacerbating the complexities and uncertainties in sampling and the consequent statistical information (PSC, 2008a). Funding has surely been a factor in the lack of representation of important production regions. Addressing these concerns would include more funding allocated to the number of tags used in hatcheries, as well as a funding to increase temporal coverage of fishery sampling and increase sampling rates in terminal fisheries. These hold especially true when it comes to managing coho, as often times, funding is allocated to improve the CWT system for Chinook (PSC, 2015). Several wild indicator programs for coho were cancelled following lack of funding, and those remaining became increasingly dependent on volunteers (PSC, 2008a). To get as accurate a representation of all production regions as can be done with genomic technologies would require an estimated $1,735,000 in funding. Direct sampling in recreational fisheries has been suggested as well, including extra creel surveys, which is estimated at an additional $1,500,000 in funding (PSC, 2008a). These are all important distinctions to account for when comparing the economic feasibility of both systems. Funding may be prioritized for the CWT program in the following years, which may be a driving factor in foregoing the adoption of the genomic technologies.

Whether or not the Pacific Salmon Commission opts for the adoption of the genomic tools or decides to further spending on the coded-wire tagging program, the CWT system is facing high rates of sampling bias. Little sampling is conducted on terminal fishery grounds and on spawning grounds (PSC, 2008a). As a consequence, imprecise estimates of fishery impacts may add to the uncertainty in preseason abundance forecasts that are used to set exploitation rates for that year. Low sampling on the spawning grounds underestimates the cohort size causing survival to be biased low and exploitation rates to be biased high. Sampling issues arise in the three main types of fisheries in British Columbia (commercial, recreational, First Nation Food Social and Ceremonial). In commercial fisheries, sampling for CWTs usually involves scanning the heads with an electronic detection system (EDS) for both clipped and unclipped salmon. In troll fisheries with on-board freezers, such as that in Northern BC, fishers often freeze the catch with head-off, discarding the head at sea. When freezer space is limited, requiring the coho heads to be retained for increased sampling can become problematic and cost-inefficient for commercial fishers (PSC, 2016a). Sampling for tags in food and ceremonial fisheries generally relies on voluntary head submission from First Nation fishers. Head samples are not mandatory in these fisheries, as often times it can interfere with ceremonial and traditional use of heads for food (PSC, 2016a).

In recent years, there has been an increase in the proportion of the total catch in recreational fisheries in relation to commercial fisheries (DFO, 2016d). Recreational fisheries frequently have lowered sampling rates as this is also based on voluntary submission of salmon heads to the CWT recovery program. As the proportion of total catch taken in recreational fisheries likely increases, the uncertainty in CWT-based estimates will increase as well (PSC, 2008a). The use of an electronic detection system, as is used in commercial fisheries to detect the presence of a coded-wire tag on an unmarked (wild) fish, is not available to recreational anglers. Only adipose-clipped (hatchery) fish heads may be voluntarily submitted to DFO and only a portion of those heads are actually submitted to DFO.

For the analysis in comparing the costs of the two systems, I did not account for the infrastructure costs and the costs of maintaining a database. I also did not account for the capital investments used to sample a baseline of stocks to make PBT and GSI applicable coast-wide. However, no such data was included in regards to the capital investments related to the CWT system as well. These are all factors that should ultimately be considered for the future management of coho salmon.

Seeing as the CWT system has been plagued with concerns and sampling bias, all of which should be addressed for future years, it is fitting that I also address the potential of GSI and PBT in future years. Satterthwaite et al. (2015) conducted an economic assessment comparing the CWT system with the parentage based tagging system and a number of hybrid systems relying on both technologies. He concluded that the genomic technologies are not cost-effective at this time (Satterthwaite et al., 2015) In response, a Committee on Scientific Cooperation from the Pacific Salmon Commission advised that, due to the development of new technologies and downward evolution of costs in the PBT-field, its cost-effectiveness should be re-assessed in five years or sooner (Hankin et al., 2015). Operating and sampling costs are likely to decrease over time, making the PBT/GSI system even more economically viable (Anderson & Garza, 2005).

2.5.2 The biological component

The greatest differences in the final results stems from the measurement of wild productivity, characterized by the number of recruits-per-spawner (R_{t+3}/S_t). Survival, and therefore productivity, of coho salmon is highly dependent on marine conditions (Beamish et al., 2010). Regulating the allowable catch or releasing hatchery smolts that are well suited for survival can help production in the wild, but poor marine conditions can still lead to considerably low returns.

It is also important to note that hatchery marine survival is a larger contributor to the high net present value of the genomic technologies, in comparison to the effects of bycatch reduction. Hatchery supplementation can improve harvest opportunities for commercial fishers and contribute to the escapement size, but the importance of bycatch reduction should not be understated. In periods of low productivity in which an endangered coho population may barely sustain itself, a small difference in harvest can have a great impact. For those fisheries that have an opening (i.e. WCVI troll fishery targeting Chinook), regulating bycatch via GSI may allow fishers to catch their maximum quota with minimal harm on the endangered population. This study shows the high economic value of the genomic technologies with IFR coho as a case study, but more revenue may accrue due to GSI to the commercial fisheries facing strict periodic closures.

It may get to the point in which PBT can be used to standardize hatchery-rearing practices for optimal survival of released smolts. This may include practices related to high predator awareness, swimming endurance, and the ability to migrate back to the hatchery of origin (Chittenden et al., 2010a) The increase in revenue comes from a combination of additional harvest within commercial fisheries and additional spawners in the wild environment.. Efficient hatchery rearing practices may become crucial as several commercial fisheries are rarely profitable (GSGislason & Associates Ltd., 2011). The interaction between wild and hatchery fish would need to be heavily observed, to ensure that this does not come at a detrimental cost to wild stocks. PBT offers the ability to measure the introgression of hatchery stocks onto wild stocks over time, which the CWT system cannot (Beacham et al. 2017a). Stock enhancement via hatchery releases has been a contested issue as several believe that the large release of hatchery origin fish have led to decline in wild populations. Measuring the impacts of hatchery fish on the health of wild stocks must be the focal point of future research, and the genomic technologies presented here allow such research to be done. The introgression of hatchery fish into wild populations may decrease the fitness of those wild populations (Gharrett & Smoker, 1991; Hindar et al., 1991; Waples, 1991), but proper hatchery enhancement is capable of conserving endangered populations. Presumably, PBT may disclose on how to ensure conservation hatcheries meet their objectives with as little effect on healthy wild populations as possible. The lack of the CWT system's ability to do so may result in the decline of wild populations due to hatchery influence.

There are several determinants of survival that cannot be addressed by neither coded-wire tags nor genomic-based technologies. I have discussed the effects of a higher density of predators and shifting climate conditions on marine survival, but a very crucial factor impeding survival is the quality of rearing habitat and freshwater systems in which coho spend their first and last months in. A study of 40 Thompson River watersheds concluded that human disturbances, such as agriculture, forestry, and urban development degrade the same streams that coho found favorable for spawning (Bradford & Irvine, 2000). As returning adults, coho are subject to pre-spawning mortality, which has been linked to urban stormwater runoff with high levels of pollutants (McIntyre et al., 2018; Scholz et al., 2011). With no restored habitats and spawning channels, even a large release of hatchery fish well suited for survival, or a total absence of harvest, may not be enough to rebuild depleted stocks. Conservation will only be successful if the all causes of decline of natural and hatchery origin are remedied (Fleming & Petersson, 2001; Meffe, 1992).

2.5.3 The economic component

Commercial salmon fisheries, regardless of the management system in place, are becoming increasingly unprofitable. An analysis of the 2009 BC salmon commercial fishery found that only those located within northern BC (Area A seine and Area F troll) generated positive net returns for that year (GSGislason & Associates Ltd., 2011). It is becoming clear that the relationship between costs of fishing and the revenue is an ever-widening gap. The costs that create such an economically unsustainable fishery are those allotted to the vessel and the license. Vessels may be used in different fisheries (i.e. rockfish, halibut, herring) and participating in more than one fishery could make up the costs of buying a vessel. However, the licenses and quotas in salmon fisheries are becoming more and more expensive (Grafton & Nelson, 2007). From the early 1970s to the late 1980s, when harvest rates on Pacific salmon were higher than current rates, the capital value of the salmon fleet tripled and more than half of that value was attributed to licenses. The analysis shows the same to be true today, with licenses estimated to be the highest cost incurred to fishers. This is a result of a shift towards privatizing the salmon fleet, by introducing transferable quotas that could be bought, sold, or leased and stacked onto additional licenses (Ecotrust Canada, 2004). With the decline in abundance of several salmon stocks, many fishers were forced to sell their license during the 1990s. Those that could stack different area licenses gained more profit and the value of those licenses rose. The ability to lease licenses also attributed to the rise in value, as some fishers charged more for a portion of their quota. The rising prices in licenses and quotas may put more pressure on future managers to allow a higher quota on salmon stocks (Ecotrust Canada, 2004). This can prove problematic for the threatened Interior Fraser stocks, as well as other endangered BC stocks.

While the analysis only focuses on the value of these genomic technologies to the commercial sector, I can predict additional benefits to accrue to the recreational fishery as well. With low returns and strict fishing limits, the recreational sector has become the primary source of salmon landings in British Columbia. In some years, more than 80% of total salmon landed in BC were within the recreational industry (DFO, 2016d). The industry has seen an increase in participation and has more of an economic impact to the communities along the BC coast. Domestic and international anglers invest in fishing lodges, charter boats, and hired guides to spend their leisure time fishing (Bailey & Sumaila, 2013). Improving hatchery survival means more opportunities for anglers, as current regulations only allow for the retention of hatchery coho in southern BC (Interior Fraser Coho Recovery Team, 2006). A portion of additional allowable catch from more productive wild coho stocks will be allotted to the recreational sector, likely before the commercial fisheries are given higher quotas. DFO prioritizes food and ceremonial fisheries and recreational fisheries before commercial fisheries when it comes to conservation concerns (DFO, 1998).

2.6 Conclusion

The purpose of this chapter is to compare how to different management tools may impact the productivity of wild and coho salmon, and how that productivity may then provide for more fishing opportunities and more revenue to the commercial fishing sector. I focus the research on the Interior Fraser River coho stock, used as a case study, and offer results on a local and provincial scale. Coded-wire tags, while relatively inexpensive, has misled management efforts and is has brought about large sources of sampling biases which can lead to unconstructive fishing regulations put in place. In contrast, genomic technologies provide a higher sampling rate and minimize the sampling bias for more accurate data.

I estimate future production of coho using two recruitment models (Ricker and Beverton-Holt), accounting for the presence of hatchery-released fish in the wild environment. There are a total of six scenarios for each recruitment model that are meant to demonstrate the varying degree in marine survival and harvest rates of IFR coho. Production from each scenario is inputted into an economic model. The sources of cost stem from fishing and implementing the management tool, while the sole source of revenue stems from the landed value in the troll fishery. I measure the net present value of increased production, looking at induced value to future generations as well (Sumaila, 2004), from present day until 2050. Results show that genomic technologies may provide an additional $65,000 in revenues in a period of low productivity, between $477,000 and $1,288 in a period of mid productivity, and $953,000 to $1,226,000 in a period of high salmon productivity to southern BC commercial fisheries. On a larger, BC wide scale, the additional revenues may range from $1,097,000 to $30,527,000 in a low and high productive period, respectively. The overall results indicates that GSI and PBT have strong potential to be more cost-effective management tools, regardless of current ocean conditions and marine survival, and may be adopted into the Pacific Salmon Treaty on a local and provincial scale.

Chapter 3: Economic Analysis of Genomic Technologies used to Enhance Coho Broodstock

3.1 Introduction

Closed-containment aquaculture (CCA) or land-based aquaculture (LBA) involves the rearing of salmon in an environment that has little or no physical connection to the marine environment (Liu, 2008; Weston, 2013). In British Columbia, salmon are reared in open-net pens at a much higher quantity than in land-based systems (Weston, 2013). This is due to the current high capital and operating costs associated with land-based aquaculture (Boulet et al., 2010; Wright & Arianpoo, 2010), which results in a lower profitability margin and lower rates of return than the open-net pens (Liu & Sumaila, 2007; Weston, 2013). One way to improve the economic efficiency and growth of land-based farms is through the selection of favorable broodstock (Gjedrem, 2012; Yáñez et al., 2015).

Broodstock development programs for salmon aquaculture, while uncommon during the 1980s and 1990s, are now being applied more often in major salmon producing countries (Rye, Gjerde, & Gjedrem, 2009). Their purpose is to enhance the production of farmed salmon, by targeting certain biological traits and ensuring that these are passed on to future generations. As a result, a farming venture can yield higher profits by lowering production costs and increasing the economic value of their product. To do so requires the use of genomic technologies that measure the breeding value of an individual salmon, and whether or not that salmon carries the favorable trait (Liu & Cordes, 2004; Sonesson & Meuwissen, 2009).

There are two primary genomic technologies utilized in broodstock development programs, marker assisted selection (MAS) and genomic selection (GS) (Liu & Cordes, 2004; Sonesson & Meuwissen, 2009). Marker assisted selection is a methodology that allows scientists to identify a specific region of the genome, known as a quantitative trait locus (QTL). By doing so, scientists know whether the breeder carries the favorable gene, or trait, at the QTL, and can increase the accuracy of selection in breeding programs (Liu & Cordes, 2004). Genomic selection is used when hundreds or thousands of genes regulate the sought-after trait. The genetic strengths of an individual salmon are calculated with more accuracy than using pedigree records, as was done in previous broodstock selection programs (Goddard & Hayes, 2009; Sonesson & Meuwissen, 2009).

The economically-important biological traits that comprise the main focus of these programs include susceptibility to disease, flesh quality and colour, growth rate and market size, as well as feed conversion ratio (i.e. Dufflocq et al., 2017; Gutierrez et al,, 2015; Neira et al., 2014; Yáñez et al., 2016). Over numerous generations, these traits can lead to a production method that is more cost-efficient and generates higher profits. Today, many of the broodstock development programs that use MAS and GS are focused on Atlantic salmon, rainbow trout, and coho salmon, the latter of which is applied in British Columbia, the United States, and Chilé (Neira et al., 2014; Withler & Beacham, 1994). Coho salmon production has not yet reached the level at which Atlantic salmon is produced (Appendix E), but their shorter life cycle (FAO, 2006), higher selling price (FAO, 2018b; Weston, 2013), and ability to be grown using freshwater (Coastal Alliance for Aquaculture Reform, 2008) make them well suited for rearing in land-based farms.

As important as genomic technologies have been in enhancing broodstock, which in turn can improve the profitability of the salmon farm itself, the economic values of these technologies is not measured in the studies that implement their use. There is a shortage of studies whose primary aim is to calculate the value of these technologies, as well as the economically-important biological traits (Neira et al., 2014). Measuring the economic value of the technologies is necessary as they can compensate the high capital and operating costs associated with land-based aquaculture. This may lead to a larger production of salmon in an ecologically sustainable way (Weston, 2013), and may help meet the growing demands for farmed seafood (Gjedrem, 2012).

The objective of this chapter is to measure the value of the genomic technologies that can improve coho broodstock for use in land-based farms. In order to do so, I identify the economically important biological traits in coho salmon broodstock and how the genomic technologies are likely to affect these traits. Finally, I use a recirculating aquaculture system (Appendix F) to explore how improved coho broodstock may make land-based aquaculture more profitable and ecologically sustainable than current studies indicate. The capital investment, production costs, and the externalities created differ in each type of land-based farm, all of which I examine in greater detail.

3.2 The Model

3.2.1 Biological component

Economically important biological traits

I use several published sources to identify the important biological traits that managers look for when selecting coho broodstock. Not all of these traits may be used in a specific breeding program, but all are being tested for high genetic variation, which implies that the trait may be improved through broodstock selection (Yáñez et al., 2014). In Table 3.1, I provide each of these sought-after traits, and a description of how improvement of the trait through genomic technologies may impact production and profitability. The production of coho without the use of genomic technologies will hereafter be referred to as the base-case scenario.

Table 3.1: Economically important biological traits in coho broodstock selection and how the genomic technologies will impact the trait.

Trait	**Without genomic technologies**	**With genomic technologies**	**Source**
Mortality	Mortality may stem from the susceptibility of salmon to diseases such as bacterial kidney disease and Salmon Rickettsial Syndrome. Mortality is assumed to be higher without the use of genomic technologies.	*Effect on trait:* Lower mortality through disease resistance. *Effect on revenue*: Increases revenue due to a higher percentage of fish reaching market size. *Effect on costs:* Total feed consumption per cycle would increase as more salmon reach market size which increases total feed costs. However, there is also less feed wasted on salmon who do not reach market size and face mortality during the grow-out cycle.	Yanez et al. 2016
Growth rate	The growth rate signifies the amount of time it takes for salmon to reach maturity and harvest size. If the length of the growth cycle remains constant, then an increase in growth rate would result in a larger weight at harvest. The growth rate would result in a lower harvest weight without the use of genomic technologies.	*Effect on trait:* Increase the market weight without increasing the length of growth cycle. Doing so inadvertently decreases the feed conversion ratio. *Effect on revenue:* Increases revenue by increasing the biomass at the time of harvest, *ceteris paribus.* *Effect on costs:* Increases operating costs related to biomass, such as energy. Feed consumption will remain the same, as growth rate improves due to selective breeding, not because the salmon are fed larger diets.	Neira et al. 2014; Gutierrez et al. 2015
Flesh quality	Flesh quality pertains to traits such as colour and fat content. The coloration of the flesh is pinker and contains higher fat in salmon farms that do not rely on genomic technologies for broodstock selection. This will yield a lower market price.	*Effect on trait:* Lower fat content and a red-orange flesh colour that is desired in markets, and will yield a higher market price. *Effect on revenue:* Revenue will increase due to a higher unit price. *Effect on cost:* No effect on cost.	Dufflocq et al. 2017; Neira et al. 2004

Each of the traits listed above plays a role in the production of farmed coho, and can impact the net value of the grow-out cycle, as shown by the upcoming equations. I would like to note that, by targeting growth rate, managers are inadvertently improving the feed conversion ratio (FCR). The FCR is the amount of feed needed to produce 1 kg of farmed salmon. By lowering the FCR through a quicker growth rate, there is less feed per kg of growth required. Currently, broodstock development programs that focus on coho salmon are not targeting FCR directly (Yañez, pers. comm.). While this may change in the future, an economic analyses such as this should differentiate how much of the decrease in FCR is attributed to enhancing growth rate, and how much is attributed to enhancing FCR specifically. This is discussed in greater detail in Section 3.3.2.

Production of coho

The production of coho is a function of the initial recruit size, growth rate, and mortality (Bjørndal, 1990), which can be expressed as:

$$B_t^i = F^i(R, W_t, \bar{M}), i = \{without, with\}\ genomics \tag{3.1}$$

where B_t is the biomass in kilograms at time t, R is the initial recruitment size, and W_t is the weight of the recruits at time t, and M_t is the rate of mortality exhibited within the farm, which is assumed to be constant. Time is measured in months, with the base-case growth cycle assumed to last 12 months (i.e. t=1,2…,12).. The number of recruits at the start will depend on the mortality rate and the maximum stocking density of the farming system. Weight at a given time will be dependent on the growth rate, which will be explained in further detail below.

The specific equation that measures the biomass is expressed as (Bjørndal, 1990):

$$B_t^i = Re^{-M_t}{W^i}_t,\ i = \{without, with\}\ genomics \tag{3.2}$$

Growth rate

The growth of the coho salmon is measured by the change in weight from W_t to W_{t+1}. The growth rate, therefore, is a function of weight and the time it takes for the salmon to reach maturity. There are several methods to predict the change in weight in salmon over time, and I rely on the thermal growth coefficient (TGC), which expresses growth independently of temperature and size of the fish (Thorarensen & Farrell, 2010). The equation reads:

$$TGC = {W_2}^{1/3} - {W_1}^{1/3}/(C * t * 30) \tag{3.3}$$

where C is temperature (^oC), and t is time between W_t and W_{t+1}. The growth of the fish at t+1 is therefore expressed as:

$$W_{t+1}^i = [{W_t}^{1/3} + TGC * (C * t * 30)]^3, i = \{without, with\} genomics \tag{3.4}$$

Farmed coho can be reared until they reach a weight of 2.5-3.5 kg (FAO, 2006). For the purpose of the analysis, I assume the weight at time of harvest will be equal to 2.5 kg which is standard with farmed coho production in Chile (FAO, 2006). This weight will be attained over a period of a 12 month growth cycle, from smolt to adult (FAO, 2006).

3.2.2 Economic component

Benefits

The fish biomass value (V_t) is the value of all fish at a given time, which is captured by the following equation (Bjørndal, 1990):

$$V_t^i = B_t^i * p_t^i,\ \ i = \{without, with\}\ genomics \qquad (3.5)$$

where p_t is the market price of farmed coho at time t, in dollars per kilogram. In this analysis, price will be affected by the flesh quality, which can be improved through the use of genomic technologies (Table 3.1). Price may generally be dependent on the weight (Bjørndal, 1990), but I assume a weight-independent price for every harvest size. This is to ensure that any change in price will reflect a change in flesh quality, not simply harvest size.

Production costs

Harvesting costs are included to indicate the effort and time needed to transport the fish into a new tank and before being harvested and put on ice to be sent to a processing facility or to a restaurant buyer. I assume that the harvesting cost within land-based facilities are lower than those within open-net pens as the fish are easily accessible in a tank with a maximum depth of 5.6 meters (Stechey & Robertson, 2010). These costs are fixed per kg of fish (C_k), at the time of harvest (T) as expressed in equation 3.6 (Bjørndal, 1990):

$$H_t^i = C_k * B_T,\ \ i = \{without, with\}\ genomics \qquad (3.6)$$

In many salmon farms, the feed is the highest incurred operating cost (Boulet et al., 2010). This is especially true in open-net farms, as they do not require as much capital investment or maintenance. Land-based farms still find feed cost to be substantial and having a low feed conversion ratio can greatly influence economic viability. The feed conversion ratio is defined as (Bjørndal, 1990):

$$f_t^i = \frac{F_t}{w'_t},\ i = \{without, with\}\ genomics \tag{3.7}$$

Feed conversion ratio is a relationship between the quantity of feed consumed, Q_t, and the change in growth of the salmon, w'_t. Feed quantity is therefore given by (Bjørndal, 1990):

$$Q_t = f_t^i * w'_t \tag{3.8}$$

Feed costs must be accounted for every month of the growth cycle, and is a factor of the feed quantity and number of fish at time t, (N_t). The total months of feeding will be equal to 12 in the base-case scenario. Feed cost is determined using the following equation (Bjørndal, 1990):

$$F_t = \sum_{t=0}^{12} C_f * Q_t * N_t \tag{3.9}$$

The costs consist of the amount spent on smolts (CR) used as the broodstock in the production phase, which is assumed to be constant at the time of purchase. It is determined by the following equation (Bjørndal, 1990):

$$CR^i = B_{t=0} * c_R,\ i = \{without, with\}\ genomics \tag{3.10}$$

Here, c_R is the unit cost of smolts in dollars per kilogram, and $B_{t=0}$ is the biomass of the initial recruits in kilograms.

Cost of genotyping

The use of MAS and GS requires genotyping individual salmon to identify the genetic value of each potential breeder. This is an additional cost that is incurred to the breeding program, but not to the farm itself since the analysis assumes that the broodstock is purchased at the start of the grow-out cycle. The breeding program would instead raise the price of the smolts to incorporate the cost of genotyping. The genotyping cost is around \$70 per fish, or \$140 per breeding pair (Yañez, pers. comm.). Each breeding pair can yield 3,000 smolts and weighs up to 2.5 kg each (MacKinlay et al., 2004). The estimated additional cost in dollars per kilogram is therefore equal to \$0.0093 (\$140/5 kilograms per pair/3,000 smolts per pair). While it is necessary to include the genotyping cost into the analysis, the difference in unit cost for smolts from breeding programs that do not use genomic technologies and breeding programs that do use genomic technologies is negligible.

Capital investment and operating costs

Following the biological and economic components, the next step is to incorporate capital investments and annual operating costs. I compute the value of the production of coho using the land-based recirculating system. Table 3.2 below describes the recirculating system and some of the designs and operating criteria involved.

Table 3.2: Design and operating criteria for the recirculating aquaculture system.

Criteria	Description	Source
Stocking density	The stocking density is the maximum amount of biomass per cubic meter of water that ensures that the health of the salmon is not compromised. For the analysis, it is set at 50 kg/m^3. However, it is possible for stocking density to reach 70 kg/m^3 in recirculating systems, and increasing growth rate will result in a stocking density higher than 50 kg/m^3.	Colt, 2010; Stechey and Robertson, 2010; Wright &Arianpoo, 2010
Water source	Pumped from freshwater source, with 98% of the water recirculated through the system. Water is filtered using ultraviolet irradiation.	Forster and Slaski, 2010
Solid Waste	Directed to on-site storage facility. Experiments focused on turning waste into manure.	Stechey and Robertson, 2010
Soluble Waste	Constructed wetlands could be used to manage soluble waste.	Stechey and Robertson, 2010
Effluent Discharge	Discharge is passed through a UV filter with 98% of effluent recirculated back to incoming make-up water supply.	Stechey and Robertson, 2010

Many recirculating aquaculture facilities use a multi-group production cycle, in which a new year-class is added to the facility every couple of weeks (Bjørndal & Tusvik, 2017; Stechey & Robertson, 2010). This is in contrast to the single stock production system, in which all the salmon must be harvested before a new brood class is added, allowing for all equipment to be checked and cleaned in between stocking. However, the multi-group production cycle ensures a constant harvest, allowing farms that produce a smaller quantity to remain competitive with farms that may produce 1,000 metric tonnes (MT) a year. I apply this type of production cycle to the analysis, as this is becoming the standard in recirculating systems, and likely where future research and development will be focused on (Stechey & Robertson, 2010).

Operating costs include labour (L_t) and energy (E_t) costs per year, which are accounted for in the second year of the farm's cycle, at t=1, and every year onwards. Production of coho begins in the second year as well, to allow for one year of preparation and farm construction (e.g. Appendix I).

A depreciation rate is applied to assess the necessary maintenance costs and re-investment of capital over time. The rate will depend on the individual equipment, but a straight-line depreciation method is used, in which the same depreciation cost (D_t) is accounted for every year. It is assumed that the capital investment will require a loan from the bank. Therefore, I apply an annual interest rate (r) on the capital investment (CI) to the NPV equation, to account for the cost of borrowing money.

Economies of scale

Over time, land-based facilities can develop and refine their rearing practices to incorporate a larger production size. To meet the growing demand for seafood, land-based farms will also need to aim for greater output, if they are to compete with the numerous open-net farms. For this reason, I use three production sizes ranging from 100 to 1,000 MT per year. The low and high-end production quantities are based on previous economic analysis (i.e., Wright &Arianpoo, 2010; Liu, 2008; Boulet et al., 2010), in which the maximum stocking density is 50 kg/m^3. I include a production quantity of 500

MT as well because that is close to the current quantity of farmed coho salmon produced in British Columbia (*Sea Around Us*, 2016). It is a way to measure profitability if the current production was matched, within a land-based system. As mentioned above, when growth rates improve due to selective breeding, the production quantity of the farm will as well, as the salmon will attain a larger harvest weight. Production quantities in this scenario will range from 115 to 1,150 MT, with a quantity of 575 MT as well. Regardless of the stocking density, the profitability of the farm should increase as production size increases (Wright & Arianpoo, 2010). This is due to the economies of scale, a concept that shows a lowered cost per unit output as a farm expands its production size, up to some limit. Economies of scale also result in a lowered average variable cost, such as labour, and a lowered capital investment cost per unit output.

3.2.3 Bio-economic model: computing net present value

Net present value

The net present value (NPV) is the sum of the net benefits of a given project, discounted to its present value. If the NPV is positive, it indicates that a project will be rewarding, and would attract investors (Liu, 2008). I will be using the conventional NPV equation as it works well with short-term projects (Liu, 2008). The general equation is as follows (Sumaila, 2004):

$$NPV = \sum_{t=0}^{T} \frac{V_t - C_t}{(1+\delta)^t} \tag{3.11}$$

where V_t is the economic benefits of the farmed production, C_t denotes the costs associated with the production, δ is a discount rate, and t=0,1,2,…T is the time, in years, in which the farm is in production, with T being the final year in the analysis. In the analysis, I use a discount rate of 8%, the rate that is generally accepted in cost-benefit analysis by the government of British Columbia (Treasury Board of Canada Secretariat, 2007). When discounting natural resources, such as salmon, the discount rate used reflects how future generations are valued. A higher discount rate puts less weight on future benefits than a lower discount rate (Newell & Pizer, 2003; Sumaila & Walters, 2005). For this reason, I conduct a sensitivity analysis, in section 3.4 that shows the NPV for each production size at different discount rates.

At each production level, I calculate the NPV of the land-based farm over a 10-year period. I chose a 10-year period because licenses for land-based aquaculture operations are issued for up to a maximum of 9 years by the Department of Fisheries and Oceans Canada (DFO, 2017). However, I also include one year for the construction and preparation of the farm, where no coho production occurs. I assume that after 10 years, the manager of the farm would then decide to renew the license or stop operations, based on the net present value.

Present value of revenue

To calculate the NPV, I first account for all sources of revenue, and all of the capital, operating, and production costs. The biomass value of the coho produced is the only source of revenue. The present value of revenue (PV_R^i), over the ten-year period, is calculated using the following equation:

$$PV_R^i = \sum_{t=1}^{T} \frac{V_t^i}{(1+\delta)^t}, \qquad i = \{without, with\}\ genomics$$

(3.12)

The revenue will accrue starting with t=1 as I assume the first year will be used for construction and preparation of the farm.

Present value of costs

The present value of costs includes the capital investment, and the operating and production costs. Capital investment is considered to be a one-time cost and will not be discounted. This will be the sole cost for the initial year, where t=0. The present value of costs is calculated using the following equation:

$$PV_c^i = CI + \sum_{t=1}^{T} \frac{(H_t^i + F_t^i + CR_t + (r * CI) + D_t + E_t + L_t)}{(1+\delta)^t},$$

$$i = \{without, with\}\ genomics$$

(3.13)

The interest rate is set at 3.70%, which is the annual interest rate used by the major banks in Canada for loans, as of August 2018 (Bank of Canada, 2018).

The NPV is therefore given by:

$$NPV^i = PV_R^i - PV_C^i\ ,\ i = \{without, with\} genomics \qquad (3.14)$$

Value of genomic technologies

The use of marker-assisted selection and genomic selection serve useful purposes in selecting the broodstock that will fare best in rearing conditions, and that will most likely pass on the economically important biological traits to the next generation. Over time, the coho broodstock may improve their growth rate, susceptibility to disease, and flesh quality. To calculate the value of these genomic technologies, I compute the NPV of the recirculating land-based farm without the use of genomics and measure how much the NPV changes when the biological traits change, following Table 3.1. Additionally, this will show which of the traits generate a greater increase in NPV and which traits show a minimal change in NPV.

3.3 Data

3.3.1 Production without genomic technologies

Benefits

Table 3.3 below shows the values used in the assessment of the base-case scenario. These are used to measure the biomass value (B_t).

Table 3.3: Values of each variable trait used in the base-case scenario, without the use of genomic technologies.

Factor	Value	Description	Source
Thermal Growth Coefficient	2.34	The thermal growth coefficient will produce a 2.5 kg coho over 12 months, which is the standard rearing time from smolt to adult.	FAO, 2006; Thoraenson & Farrell, 2010
Mortality per year (%)	15	Loss of broodstock due to disease or culling for optimum stocking density.	FAO, 2006
Market price ($/kg)	7.15	This is the unit price of the global farmgate value of farmed coho.	FAO, 2018
Harvest weight (kg)	2.50	Weight ranges from 2.5-3.5 kg, but for the analysis, I	FAO, 2006

assume the coho will be raised to 2.5 kg.

Costs

Table 3.4 below shows the factors and variable costs used as the base-case scenario. The factors listed here are used to measure the cost of production.

Table 3.4: Value of the variable traits used to measure the costs of production, base-case scenario without genomic technologies.

Factor	Value	Description	Source
Harvesting cost ($/kg)	0.50	This is the estimated harvest cost for a recirculating system raising Atlantic salmon. I assume the price to be the same for coho.	Wright & Arianpoo, 2010
Feed price ($/kg)	1.50	Different studies estimate a wide range of feed price. This value was estimated from a feasibility study for Atlantic salmons in a recirculating system.	Boulet et al. 2010
Feed conversion ratio	1.3	Feed conversion ratio varies with the weight of the salmon. This is an average value used to incorporate the entire cycle from smolt to adult, from a recirculating farm producing coho in Agassiz, BC, as well as a test facility in Cedar, BC.	Walker, 2017; Coastal Alliance for Aquaculture Reform, 2008
Smolt price ($/kg)	0.67	This is the value used in a financial analysis in 1989 using Chinook and coho smolts, estimated in 2018 dollars.	BCACFB, 1989
Smolt weight at purchase (kg)	0.06	Smolt size ranges from 60-80 grams. I use the low range estimate.	FAO, 2006

3.3.2 Production with the genomic technologies

Following Table 3.1, I assess the effect of the genomic technologies on the production of farmed coho. The economically-important biological traits will be modified, based on previous studies encompassing each trait.

Benefits

Table 3.5 below shows the values used in the assessment of production using the genomic technologies. These are used to measure the biomass value (B_t). Reasoning for the change in value of each factor is given below.

Table 3.5: Values of each variable trait used in to measure benefits of production, with the use of genomic technologies.

Factor	Value
Thermal Growth Coefficient	2.48
Mortality per year (%)	10
Market price ($/kg)	8.20
Harvest weight (kg)	2.85

The change in thermal growth coefficient is to reflect the change in harvest weight after a 12-month growth rate. A study by Neira et al. (2006) indicates a change in harvest weight of 302-383 grams per generation, with an average close to 350 grams. Therefore, I assume a new harvest weight of 2.85 kg (2.50 kg + 0.350 kg = 2.85 kg). Mortality decreases due to increased resistance to certain diseases, including Salmon Rickettsial Syndrome (Yáñez et al., 2016). However, disease resistance is very hard to measure and incorporate into studies, as it requires information on the likelihood of a disease outbreak, what percentage of total abundance will be exposed to the disease, and what percentage of those exposed will exhibit mortality from the disease. There are also additional sources of mortality, such as mechanical failure and selective culling. To encompass a more resistant brood of coho salmon, I use a low-end estimate of mortality that has been achieved in land-based farms, at 10% per year (Bjørndal & Tusvik, 2017; Davidson et al., 2016). This is to account for the additional sources of mortality while still diminishing mortality due to disease.

There are very few studies that indicate the extent that market price may change due to more desirable flesh quality, and none focused on coho salmon. In 2006, Alfnes et al. published a study on consumer's willingness to pay for Atlantic salmon with darker flesh, within Norway. The authors concluded that consumer's would pay an additional 12.57 to 15.67% for salmon with colours that were darker than the faint pinkish tint often found in farmed salmon (Alfnes et al., 2006). For the analysis, I am incorporating a 15% price premium for higher quality flesh, bringing the unit price for coho salmon to $8.20/kg.

Costs

Table 3.6 below shows the factors and variable costs used in the assessment of production with genomic technologies. The factors listed here are used to measure the cost of production. Reasoning in the change of each value is given below.

Table 3.6: Value of the variable traits used to measure the costs of production, with the use of genomic technologies.

Factor	Value
Harvesting cost ($/kg)	0.50
Feed price ($/kg)	1.50
Feed conversion ratio (FCR)	1.14
Smolt price ($/kg)	0.67
Smolt weight at purchase (kg)	0.06

Harvesting cost, feed price, and smolt weight at purchase are not dependent on selective breeding and do not change in the analysis. Smolt cost remains constant, as described in Section 3.2.2 (*Costs of genotyping).* The only factor that changed due to the genomic technologies is feed conversion ratio. While there are no current published studies indicating the impacts of selective breeding on feed conversion ratio in coho salmon, it could be a breeding goal for broodstock development programs (Yañez, pers. comm.). It also decreases when growth rate is enhanced. If the coho salmon reach a larger weight over the same length life-cycle, and the feed consumption remains constant, FCR decreases from 1.3:1 to 1.14:1. Following equation 3.8, feed consumption is equal to the change in weight multiplied by the FCR. Under the base-case scenario, it is equal to ((2.50kg- 0.06kg) x 1.3)=3.172. Assuming feed consumption remains the same, as the increase in harvest weight is attributed to selective breeding, and not a higher amount of feed, the FCR when the salmon reach a weight of 2.85 kg is equal to (3.172/(2.85kg- 0.06kg)) = 1.14 .

3.3.3 Capital and operating costs

Capital Investment

In Table 3.7, I outline the capital that is needed for the recirculating system, as well as the estimated cost for each production size. Data regarding the capital costs and equipment needed are taken from Wright & Arianpoo (2010).

Table 3.7: Capital and cost for recirculating system.

Equipment	Unit cost ($'000s)	Depreciation (years)	Cost by production size ($'000s) 100 MT	500 MT	1,000 MT
Culture tanks (200m3)	20.00	20	200.00	1,000.00	2,000.00
Swirl separators	1.00	10	10.00	50.00	100.00
02 injection cones	4.40	10	44.00	220.00	440.00
Oxygen generators	50.00	10	150.00	325.00	500.00
C02 degassing tower ($18m^3$)	3.59	10	3.59	17.97	35.93
Degassing media ($18m^3$)	7.19	10	7.19	35.94	71.87
Blowers	11.00	10	22.00	110.00	220.00
Bio-Filter tank ($25m^3$)	5.14	20	5.14	25.69	51.37
Bio-Filter media (25 m^3)	1.80	20	1.80	8.99	17.98
Low head oxygenator	2.00	10	2.00	10.00	20.00
Foam fractionators	1.50	10	15.00	75.00	150.00
Drum filters	17.00	10	34.00	170.00	340.00
Settling tanks	10.00	20	10.00	50.00	100.00
Pumps	5.86	10	58.64	293.21	586.41
Plumbing costs	7.50	None	75.00	340.00	750.00
CPU monitoring and control	40.00	5	40.00	200.00	400.00
UV-C sterilization	20.00	15	20.00	100.00	200.00
Ozone sterilization	40.00	10	40.00	200.00	400.00
Robotic feeding system	8.00	10	80.00	400.00	800.00
Back-up generators	25.00	20	50.00	200.00	300.00
Land preparation	10.00	None	10.00	37.50	50.00
Land purchase	57.00	None	22.80	158.46	316.92.00
Building construction	400.00	20	400.00	2,000.00	4,000.00
Total cost ($'000s)			**1,301.16**	**6,062.74**	**11,850.48**
Depreciation cost per year ($'000s)			89.32	401.61	783.22

An overview of the layout and arrangement of a 100 and 1,000 MT recirculating farm can be seen in Appendix G and H, respectively. Data for energy usage is from Liu et al.

(2016). I use a unit price of $0.07 per kilowatt hour, as is common in Canada (Wright & Arianpoo, 2010). Total energy costs for each production level can be found in Table 3.8 below.

Table 3.8: Energy costs and usage per year for each farming system.

Production size (MT)	Unit cost ($/kwh)	Energy usage (kwh/kg/year)	Total cost ($'000s)
100	0.07	5.4	37.80
500	0.07	5.4	189.00
1,000	0.07	5.4	378.00

Operating Cost

Table 3.9 shows the labour costs and quantities associated with each production quantity. Data on wages came from Wright & Arianpoo (2010) as well as Liu (2008).

Table 3.9: Labour costs calculated by the type of employee, quantity needed, and annual wage.

Production size (MT)	Employee	Quantity (#)	Annual wage ($'000s)
100	Worker	1	34.74
	Manager	1	100.00
	Vet technician	1	200.00
	Total		**334.74**
500	Worker	5	34.74
	Manager	1	100.00
	Vet technician	1	200.00
	Total		**473.68**
1,000	Worker	10	34.74
	Manager	1	100.00
	Vet technician	1	200.00
	Total		**647.36**

3.4 Results

3.4.1 Net present value: without genomic technologies

Table 3.10 below shows the NPV for each of the production quantities in the recirculating system. These are obtained using the base-case scenario, with the values of the variables described in Table 3.3.

Table 3.10: Net present value under the base-case scenario for each production quantity.

Production Size (MT)	Net present value ($'000s)
100	-1,895
500	-1,133
1,000	82

The results for the base-case scenario show that the recirculating system generates negative profits at production capacities ranging from 100 to 500 metric tonnes. The tonnage of coho produced does not offset the high capital costs needed. As the production capacity increases to 1,000 MT, there is a small positive profit of $82,000, which is unlikely to attract investors due to the high risks involved in land-based aquaculture (Liu, 2008). Positive profits are realized within a larger farm because of the diminishing capital and operational cost per tonne produced, as output increases. If the farm had the ability to renew its aquaculture license for an additional 9 years with no required additional capital expenses, positive profits could start to accrue within that time period.

3.4.2 Net present value: with genomic technologies

To estimate the value of the genomic technologies, I calculate the NPV of the production of coho, incorporating the changes on each of the economically important biological traits, as described in Table 3.5 and 3.6. The change in NPV as flesh quality, mortality, growth rate and feed conversion ratio increase or decrease from the base-case scenario (without genomic technologies) will signify the economic value of marker assisted selection and genomic selection.

Table 3.11: Net present value for each production quantity and the value of the genomic technologies.

Production Size (MT)	Net present value ($'000s)	Value of genomic technologies ($'000s)
115	-511	1,384
575	5,787	6,920
1,150	13,922	13,840

Results indicate that the use of genomic selection and marker assisted selection can make the production of coho in a recirculating system profitable at a production level of 575 metric tonnes, similar to current production of coho in BC. This may be vital for some farming ventures in British Columbia, as the availability of adequate land and water sources is limited due to the large coastal mountain ranges. The value of the genomic technologies, in a recirculating system producing 115 metric tonnes of coho, could be around $1,384,000, accrued over a period of 10 years. Net present value increases by 173% at this production quantity. In a larger land-based recirculating system, the genomic technologies can be valued at around $13,840,000, over a period of 10 years. Standardizing the results indicate the value of the genomic technologies may be around $12,035 per metric tonne of coho produced.

3.4.3 Value of genomic technologies from each biological trait

To assess which of the three biological traits used in the analysis yield the highest economic value, I calculate the net present value of the production of coho, modifying one trait while keeping the remainder constant.

Table 3.12: Net present value and the value of the genomic technologies for each of the four biological traits, at different production quantities.

Production quantity	Net present value ($'000s)			Value of genomic technologies ($'000s)		
	Flesh quality	**Mortality**	**Growth rate**	**Flesh quality**	**Mortality**	**Growth rate**
100-115 MT	-1,235	-1,820	-1,365	660	73	530
500-575 MT	2,165	-770	1,525	3,300	365	2,655
1,000-1,150 MT	6,675	810	5,395	6,595	730	5,310

The results indicate that, using the values from Table 3.5 and 3.6, flesh quality is the biological trait that has the largest impact on net present value of coho production. If a 15% price premium is attained due to consumer preference of flesh quality, then the genomic technologies may have an estimated value of around $6,600 per metric ton of coho produced. This accounts for around 52% of the total value of the genomic technologies. Growth rate is the biological trait that would generate the second largest change in net present value, and could add $530,000 at a production of 115 metric tonnes, which accounts for 42% of the total value. Disease resistance, if targeted alone, will only improve production to the point where a positive net present value is attained at higher production quantities.

3.4.4 Sensitivity Analysis

There is some uncertainty in the appropriate value of the parameters chosen in Table 3.5 and 3.6. To address these uncertainties, I conduct a sensitivity analysis on each of the economically-important variable traits and assess the change in NPV.

Flesh quality

Flesh quality is reflective of the colour of the flesh, fat content, and texture (Dufflocq et al., 2017; Neira et al., 2004). Higher quality flesh can attract a higher market price due to a greater preference from consumers, and can be improved through selective breeding by the use of genomic technologies. I show the value of the genomic technologies, which is equal to the change in NPV when market price includes a 5% and 10% price premium. These price premium estimates are lower than the initial analysis conducted above in order to show the variability in consumer preference from the Atlantic salmon used in the study by Alfnes et al. (2006), and coho salmon used in this study.

Table 3.13: The net present value (NPV) of each system and capacity with a 15% and 20% change in price.

Production capacity (MT)	NPV with 5% increase in price ($'000s)	Value of genomic technologies ($'000s)	NPV with 10% increase in price ($'000s)	Value of genomic technologies ($'000s)
100	-1,675	220	-1,455	440
500	-35	1,100	1,065	2,200
1,000	2,280	2,200	4,480	4,400

The results indicate that a 5% increase in price could generate a net present value of close to $-1,675,000 at the lowest production quantity, when targeting flesh quality alone. At the same production quantity, a 10% price premium still yields a negative net present value. Managers would need to ensure a price premium of 15% or higher at low production quantities, or increase their production output to 500 metric tonnes, with a price premium of 10%. At a production quantity of 1,000 MT, no price premium is needed (Table 3.10), but a 5% price premium may provide more certainty in achieving a positive NPV over 10 years.

Mortality

High rates of mortality may lead to a smaller harvest size and loss in the investment of smolts, as well as a loss of feed. Mortality may be influenced by the presence of viruses and bacteria (Neira et al., 2014; Yáñez et al., 2016) amongst other factors, such as mechanical failure within the farm itself (Forster & Slaski, 2010). Since it is hard to measure the extent to which disease resistance will improve mortality, I conduct a sensitivity analysis with mortality estimates based on adding and subtracting the average of the differences between the base-case production scenario (15%) and the scenario utilizing genomic technologies (10%). The average of the differences is 2.5% so the sensitivity analysis includes mortality estimates of 12.5% and 7.5%.

Table 3.14: The net present value (NPV) when mortality changes to 12.50% and 7.50%.

Production capacity (MT)	**NPV with mortality at 12.50% ($'000s)**	**Value of genomic technologies ($'000s)**	**NPV with mortality of 7.5% ($'000s)**	**Value of genomic technologies ($'000s)**
100	-1,860	36	-1,785	110
500	-950	180	-585	550
1,000	445	360	1,180	1,100

Mortality has very little impact on profitability and net present value. The value of the genomic technologies, if mortality was to decrease to only 12.5% as a result of more disease resistant coho, may be between $36,000 and $360,0000 for a recirculating farm producing 100 and 1,000 metric tonnes, respectively. Those values could increase to

$110,000 and $1,100,000 when mortality decreases to 7.5%. Even with a mortality rate of 7.5%, the farm would not yield a positive NPV at production of 500 MT, if no other economically important biological traits are targeted.

Growth rate

Increasing growth rate has a high positive impact on the profitability of the farm, as the biomass at time of harvest increases. While the assumption that coho salmon may reach an increase in weight of 350 grams over the same period is based off of a published study by Neira et al. (2006), this change in weight could vary from one farm to the other. Here, I measure the NPV if the growth rate resulted in a market size of 3.025 kg and 2.675 kg over a period of 12 months.

Table 3.15: The net present value (NPV) as the growth rate of coho salmon increases to allow a market size of 2.675 kg and 3.025 kg over 12 months.

Production capacity (MT)	NPV with market weight of 2.675 ($'000s)	Value of genomic technologies ($'000s)	NPV with market weight of 3.025 kg ($'000s)	Value of genomic technologies ($'000s)
115	-1,635	260	-1,100	793
575	167	1,300	2,833	3,965
1,150	2,680	2,600	8,015	7,930

The results show that, if a harvest weight of 3.025 kg can be attained over the 12 month growth cycle, then the net present value becomes positive at production capacity of 575 MT. The same holds true if the harvest weight only increases to 2.675 kg.

Discount Rate

There is some uncertainty in the appropriate value of the chosen discount rate to estimate the net present value, and therefore, the value of the genomic technologies. A lower discount rate will result in a higher NPV, as described in Section 3.2.3. I perform a sensitivity analysis on the discount rate, to calculate the value of the genomic technologies based on the parameters in Table 3.5 and 3.6. The discount rate will range from 6% to 10%.

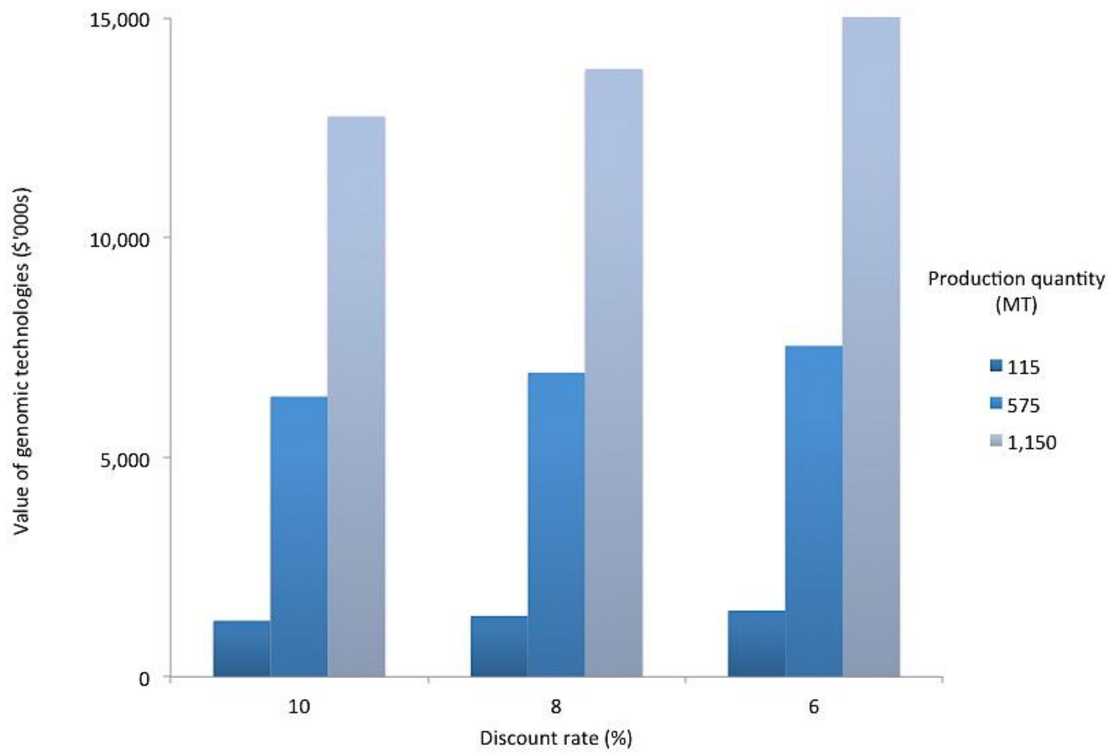

Figure 3.1: Sensitivity analysis of the net present value with different discount rates using the recirculating system.

A higher discount rate will value the future with less weight as does a lower discount rate (Sumaila & Walters, 2005). The value of the genomic technologies, and the NPV of the farmed coho production, will decrease as discount rates increase from 6% to 10%. It can be assumed that salmon farming has a lot of risk, as it requires a large capital investment and a strong knowledge of both the technology involved as well as the biological components that allow for salmon to grow in a healthy manner. While salmon farming in open-net farms has occurred in B.C. since the 1970s, the transition into land-based farms is much more recent. Therefore, producers of coho salmon in land-based farms would likely use a higher discount rate, to capture the risk involved in such an investment (Liu, 2008). At a discount rate of 10%, which is significantly higher than the standard 8%, the value of the technologies for the production of coho may still be around $1,506,000 at the lowest production capacity.

3.5 Discussion

3.5.1 Genomic Technologies

Intensifying production of farmed species through effective selective breeding results in a major change in productivity and resource efficiency (Gjedrem, 2012) which in turn leads to high profits accrued to the farm itself. Marker assisted selection and genomic selection provide the means to identify potential breeders based on their genetic strengths. These technologies may have great economic value and may offset the high capital and operational costs of a recirculating system at a production capacity of 500 to 575 MT, to generate positive profits. Without the use of genomic technologies in breeding programs, farms would only generate positive net present values at a production of 1,000 MT or higher. While it is possible to operate land-based salmon farms at higher capacities, expansion could be limited within British Columbia due to the rugged coastlines and expansive mountain ranges. However, as recirculating aquaculture systems become more prominent and operating costs decrease over time, due to advances in technology, more research and development, or new energy sources, it may be possible to attain a positive NPV at low production quantities. Production would have to be extended beyond the 10 year period shown in the analysis for profits to be positive at lower production quantities. It is worth mentioning that the economic analyses that are referenced in this chapter (i.e. Liu, 2008; Wright & Arianpoo, 2010; Boulet et al., 2010) calculate the NPV over the span of 20 years instead of ten. This insinuates that a licence renewal would be easier to obtain and that the recirculating aquaculture farm would be running for longer then ten years, given the large investment that is required. I decided to conduct the NPV over ten years to omit the likelihood of renewing an aquaculture licence and show the costs and benefits over a time frame that is guaranteed. Over 20 years however, it is likely to see a positive NPV at 100 MT with genomic technologies.

The genomic technologies can also provide a means to meet the growing demand for farmed seafood (Gjedrem, 2012). Salmon farming only comprises a portion of global farmed production (FAO, 2018b) but salmon are much more efficient utilizers of feed resources than terrestrial animals (Gjedrem, 2012). Feed conversion improved by 20% in Atlantic salmon over five generations of selective breeding (Thodesen et al., 1999). Today, the FCR for coho salmon ranges from 1.5 to 1.2 (Coastal Alliance for Aquaculture Reform, 2008; Walker, 2017) and for Atlantic salmon, it can be around 1.2:1 to 1:05 (FAO, 2006, 2018a; Thorarensen & Farrell, 2010). When compared to pork (FCR of 2.8), chicken (FCR of 1.9) and beef (FCR of 6-9), salmon can provide a source of protein with fewer inputs needed (BC Salmon Farmer's Association, 2017), and a more efficient use of land and water resources (Froehlich et al., 2018), making them an ideal species for aquaculture production. Furthermore, the success of breeding programs in coho salmon, enhanced by the use of MAS and GS, may help the adoption of genomic tools in additional farmed species (Gjedrem, 2012).

3.5.2 Coho broodstock biological traits

While the use of MAS and GS can enhance broodstock through selective breeding, there are other factors than can improve these traits outlined in the thesis, and apparent in broodstock programs for other species of salmon. I discuss and analyze how these factors and how they may further enhance broodstock without the use of genomic technologies.

Market Price

Beyond flesh quality, price is set by several market factors including the demand for and supply of farmed coho salmon. On the global scale, the current average price for farmed coho is $7.15 per kilogram. Over time, that price may increase or decrease. As Atlantic salmon is currently the highest produced farmed salmonid (Bjørndal & Tusvik, 2017), its prices often have an affect on similar goods, such as coho. A study conducted by Asche et al. (1999) concluded that Atlantic salmon has a weak price exogeneity compared to the Pacific salmon species, implying that a decrease in the price of Atlantic salmon will have a similar impact on Pacific salmon species. As the open-net farming of Atlantic salmon in the top farmed salmon producing countries, Norway, Chilé, Scotland, and Canada, continues, prices may fall over time as the market is saturated with supply (Asche et al., 2013; FAO, 2018). On the global market, prices of farmed coho may follow a drop in the price of farmed Atlantic salmon (Asche, Bremnes, & Wessells, 1999).

If producers of farmed coho market their product to a more local consumer-based, they may be able to fetch a higher market price. A price premium can be probable for salmon raised in a sustainable manner (Liu & Sumaila, 2007). Since open-net farms have become a largely controversial issue in British Columbia, most of the farmed Atlantic salmon is exported to the United States, Japan, and China (Government of Canada, 2018). British Columbians, for the most part, seek out wild caught Pacific salmon species over farmed Atlantic salmon, as most farmed Atlantic salmon exported to other nations (Government of Canada, 2018). If the farmed coho is marketed as sustainable and local, it may be sold at a price similar to its market supplement, wild caught Pacific salmon.

Growth Rate

Growth rate is influenced by the availability of oxygen and the water temperature in which the salmon are raised in (Emerman, 2016; Sirakov & Ivancheva, 2008; Thorarensen & Farrell, 2010). Seasonal reduction in oxygen levels during the fall may limit the growth of salmon in open-net pens (Thorarensen & Farrell, 2010). Regulating the oxygen concentration in land-based systems may give the industry an advantage. Several studies have also found that stocking above 50 kg/m^3 may reduce growth rate in salmonid species as it limits the available oxygen (Emerman, 2016; Sirakov & Ivancheva, 2008). Densities above 100 kg/m^3 can even lead to a 42% decrease in growth rate (Calabrese, 2017). The farm manager would be faced with a trade-off, to reduce the density of the rearing tanks or limit the weight that the fish can reach over the span of 12 months. Increasing the number of rearing tanks may provide a solution that would require a higher upfront capital investment but could pay off after several grow-out cycles.

Feed Conversion Ratio

Even if it is not an economically important biological trait that was used in the analysis, lowering FCR would still have a large impact on profitability, if it were to be incorporated into coho salmon breeding programs. Several studies show that the FCR is slightly lower in tanks than in open-net pens (Thorarensen & Farrell, 2010). Furthermore, it is generally accepted that an FCR of 0.9-l.0 is attainable in culture tanks under the right conditions (Thorarensen & Farrell, 2010). This is due to the stricter control of water circulation and the rearing environment, for more favorable metabolic rates in salmon raised in land-based systems, rather than open-net pens (Coastal Alliance for Aquaculture Reform, 2008).

Feed conversion ratio may be minimized in two ways. The first is by maximizing the consumption of feed and the second is by increasing the conversion rate of the fish itself (Coastal Alliance for Aquaculture Reform, 2008). Open-net farms may lose a lot of feed to the outside environment, while land-based tanks can regulate the intake and recycling of feed with more precision (Coastal Alliance for Aquaculture Reform, 2008). Feed pellets with lower protein and higher lipid contents have been shown to lower FCR from 2, as was exhibited in the 1980s to 1.05-1, as is exhibited today (Tacon, 2005). Lower protein diet also translates to a lower dependence on wild-capture fisheries to produce fishmeal and fish oil to be used as feed for farmed species. This is a major concern that the aquaculture industry faces, and efforts to use plant and animal-based alternatives must continue so as not to utilize higher quantities of food-grade fish to produce a lower quantity of salmon (Cashion et al., 2017; Naylor et al., 2009). Nonetheless, farmed salmon has one of the lowest feed conversion ratio, compared to other protein sources such as pork and chicken (BC Salmon Farmer's Association, 2017).

3.5.3 Externalities

Externalities are the costs or benefits of a project that are endured by a third-party who is not involved in the initial project (Clark, 1990). Farming salmon, both in land-based systems and open-net farms, creates numerous environmental externalities that must be addressed and minimized as much as possible. Externalities in the open-net farming industry includes the spread of disease and parasites to wild fish, as well as the degradation and pollution of the coastal seas in which these farms are located (Naylor et al., 2010). The recirculating system does have some externalities as well, which are different than those exhibited by open-net farms, but should still be taken into account.

One leading argument against the implementation of land-based technologies is that the high-energy costs do not outweigh the benefits of separating the farm from that marine environment. The energy required in the recirculating system can be more than twice as much as is needed in open-net pens. The main energy use in land-based farms is associated with pumping water from the source and throughout the system, but advances in technology have reduced energy usage over time (Murray et al., 2014). A First

Nations' owned recirculating Atlantic salmon farm located in northern Vancouver Island was able to reduce energy expenditure by using gravity-assisted flow, as well as geothermal heating and cooling (Kramer, 2015). Similar advancement in technology and renewable energy may further reduce energy expenditure.

Greenhouse gas emissions also vary within each farming system, and can be cause for concern when rearing salmon in a monitored environment. The study by Colt (2010) estimates twice as many kilograms of greenhouse gases are emitted into the atmosphere from recirculating systems then the open-net farms. Relying more on renewable energy sources may improve the number of pollutants entering the atmosphere from these farming ventures, but the study assumed the energy source was 90% hydropower and 10% natural gas, which produces significantly less carbon output than coal and other non-renewable fossil fuels (Sims, Rogner, & Gregory, 2003). However, the open-net farming industry incurs a high level of greenhouse gas emission from the transportation of farmed Atlantic salmon to the United States, Japan, and China, where the fish is consumed (Government of Canada, 2018). The demand for farmed Atlantic salmon from BC is not incorporated in the energy efficiency of the farm system itself. If there was a market for farmed coho produced and consumed in British Columbia, the energy costs may be reduced and comparable to that of the open-net farm.

Additionally, many of farms located within the coast face a rising number of plankton blooms which can cause high rates of mortalities (Weston, 2013), and has become a greater concern to managers then escapes and predation (Trainer & Yoshida, 2014). On the other hand, land-based freshwater systems would not be affected by the uncertainty of a changing climate on the acidity and temperature of the water source.

3.6 Conclusion

The use of MAS and GS may help salmon farmers improve coho salmon broodstock to be reared in land-based farms. By targeting certain traits, the broodstock may be less susceptible to disease, grow at a faster rate, or have a more desirable flesh quality. I use these traits to measure how the profitability of certain land-based farming systems changes as the traits improve over time. The results show that the genomic technologies could be valued at $1,384,000 at a low production quantity of 115 MT, accrued over 10 years. The value may increase to $13.8 million when the production is increased to 1,150 MT. The results also show that flesh quality and growth rate are the two factors that have the greatest impact on profits. Flesh quality traits, such as colour, texture, and fat content, may yield a higher market price and improve profits by $5,740 per metric tonne of coho produced, accrued over 10 years.

The value of the genomic technologies can reflect the increased profits they may generate for certain land-based farming systems. Since land-based salmon aquaculture requires high capital and operation costs, further growth may be impeded. Additionally, the large, and rising, production of farmed salmon in open-net pens in Canada, Chile, Norway, and Scotland has resulted in low market prices of farmed salmon (Asche et al., 1999; Liu, 2008), creating an disadvantage to managers wishing to produce salmon in land-based systems. Enhanced salmon broodstock, such as coho as this study shows, may incentive a shift to land-based recirculating systems.

Chapter 4: Conclusion

4.1 Summary

The results of this study show the economic value of genomic technologies in their multiple applications to coho fishery assessment and management, as well as coho broodstock selection in aquaculture. Chapter 2 focuses on the use of parentage based tagging and genetic stock identification as an alternative to the increasingly outdated coded-wire tagging system. Chapter 3 illustrates the potential of marker assisted selection and genomic selection as tools for effective selective breeding programs, meant to improve the economic viability of the land-based aquaculture systems using coho as the farmed species.

In Chapter 2, I use the Interior Fraser river coho populations as a case study to compute the net present value of the commercial fishery under the current restrictions, and possible future openings. By calculating the difference in the NPV of these fisheries managed using coded-wire tags and managed using the genomic technologies, I may show the economic value of these technologies to the commercial sector. The economic value stems from the variety of information that the two genomic tools present, which a coded-wire tag cannot.

Genetic stock identification provides fishery managers more accurate estimation of catch-composition, which in turn allows them to close a commercial fishery if needed to protect endangered populations, such as those found in the Interior Fraser. The reduction in accidental harvest may improve the recruitment of IFR coho over time, allowing it to rebuild. Parentage based tagging is useful in matching an individual to its river or hatchery of origin. Doing so provides accurate estimations of fishery exploitation and the marine survival of hatchery fish. In three different scenarios of productivity (low, medium, and high), the genomic technologies prove to be a more cost-efficient management and assessment tool than the one currently in place. This holds true even in the absence of a directed commercial fishery.

In Chapter 3, I compute the net present value of farming coho using the land-based recirculating system. I focus on three economically-important biological traits that may become more prominent in coho broodstock via the use of genomic technologies. By calculating the NPV of farmed coho production that has been enhanced through the use of genomic technologies, and comparing it to the NPV of farmed coho production without the use of genomic technologies, I am able to show the value that genomic selection and marker assisted selection could provide to broodstock development programs.

Results indicate that the flesh quality and growth rate are the two most economically valuable traits within broodstock selection. Flesh quality, which includes fat content and flesh colour, can increase the market price of coho and increase the profitability of a recirculating land-based system. Growth rate can increase over time, allowing for a larger biomass value without requiring additional capital investment. While lowering mortality is important to the success of a coho farming production operation, broodstock development programs may be more inclined to focus their efforts on enhancing the flesh quality and growth rate.

4.2 Improvements for future work

There are a number of uncertainties within each chapter that could be improved and resolved in future work. I address some of these uncertainties with the sensitivity analysis and show how results change when inputs to the model change. One major assumption in Chapter 2 is how the use of parentage based tagging may provide the means to improve hatchery-rearing practices over time. While this is not the current goal of parentage-based tagging, it surely can be an outcome from the information that is generated through this technology. Ongoing research from the Enhancing Production in Coho: Community, Culture, Catch (EPIC[4]) project is showing results on the applicability and successes of PBT each summer and fall as hatchery coho return back to their watershed. Allowing more data to accrue would improve the model presented in this thesis as there would be more indication as to the extent in which PBT can be used to standardize hatchery-rearing to ensure the released fish are well-suited to the current environment, therefore improving the recruitment of the population the given hatchery is meant to enhance.

In Chapter 2, I measure the economic value of the genomic technologies as they are applied to a commercial fishery. However, due to the commercial regulations, recreational anglers currently target the majority of coho salmon in British Columbia. The recreational fishing industry is larger than the commercial fishery in terms of participation, catch, and economic contribution (DFO, 2016d). It can be more complicated to estimate the non-use value of coho in an industry that is built upon leisure and relaxation (Bailey & Sumaila, 2013), but the adoption of the genomic technologies as a fishery management tool would also increase the value of BC's recreational fisheries. Therefore, further studies should be conducted that measure the value of these technologies and their ability to provide for increased angling opportunities and conserve any stock that may be accidentally targeted by recreational fishers.

The economic analysis is conducted on a time frame of 32 years (2018-2050). It is uncertain as to how well coho salmon will survive in future ocean conditions, which has a significant impact on the survival and productivity of coho salmon (Beamish et al., 2010). To account for this uncertainty, I use three metrics of productivity (low, medium, and high). Predicting the impacts of climate fluctuations is not simple but several studies are focused on getting a better understanding of changing ocean conditions and the impacts on coastal fisheries (e.g. Sumaila & Lam, 2015; Weatherdon et al., 2016). The results from Chapter 2 are wide ranging because of the differences in catch and survival under different productivity regimes. However, incorporating a model that shows indication of future ocean conditions would provide a more accurate estimation of the economic value of the genomic technologies.

In Chapter 3, one source of uncertainty stems from the data collection on the capital investment needed to construct a land-based recirculating system. The study presented here is novel in that it is an economic analysis of close-containment aquaculture using coho salmon as the farmed species, rather than the more commonly raised Atlantic salmon (*Salmo salar*). The studies by Wright & Arianpoo (2010), Boulet et al. (2010), and Bjorndal and Tusvik (2017), which were helpful in my data collection, are conducted using Atlantic salmon. While the equipment needed is the same, the depreciation of that equipment, as well as the number of units per tonne produced may differ with coho salmon for two reasons. The first is that the salmon in the studies cited above are reared in saltwater (30-35 ppt salt) or brackish (10 ppt salt) water (e.g. Wright & Arianpoo, 2010). This can cause more damage to the tanks and piping systems over time than would freshwater. Second, the Atlantic salmon is harvested at a size of 3.5 kg to 5.5 kg (FAO, 2018a; Wright & Arianpoo, 2010). This can limit the stocking density in comparison to the smaller coho salmon, and may also result in more removal of insoluble waste and the treatment of soluble waste. Further economic studies using coho salmon as the reared species would provide more accurate estimations of the capital and operational costs for the grow-out cycles, to offer more certainty in the valuation of the genomic technologies presented in this thesis.

The analysis in Chapter 3 would be corroborated by a marketing study that focuses on the likelihood of farmed coho salmon being a sought-after commercial product. Since the open-net salmon farming industry has been polarized in BC, it is unsure as to how British Columbians would respond to farmed coho salmon within the grocery stores. It is likely that this product would be popular in Japan and the United States, where a high portion of farmed Atlantic salmon from BC is exported. Labeling the farmed coho salmon as sustainable by the Ocean Wise program, as Atlantic and coho salmon reared in recirculating systems are (Ocean Wise, 2017), would likely help the demand for such a product, and ensure that the genomic technologies are utilized on a species that can have a large economic impact for salmon farms, processing plants, marketing firms, and grocery stores.

4.3 Policy Implications

The results in Chapter 2 indicate that parentage based tagging and genetic stock identification provides more accurate estimations of exploitation and survival in a more cost-efficient manner, but the analysis is conducted in depth only on a local scale. However, the effective management of coho salmon would require cooperation from both Canada and the United States as the coho stocks in Southern BC often migrate into US waters on their return to the Strait of Georgia. This implies that PBT and GSI be adopted within the Pacific Salmon Treaty as suitable management tools. Certain provisions of the PST will be renewed in 2018 and 2019, with the possibility of GSI and PBT adopted as primary management tools or to be used alongside the coded-wire tags for a transition period. These technologies are effective due to a growing database of genetic information from hatchery and wild stocks of coho, as well as Chinook and sockeye salmon. The addition of the genomic technologies into the PST would ensure that both the Department of Fisheries and Oceans Canada and the National Oceanic and Atmospheric Administration (NOAA) provide access to a genetic database to procure the accurate estimations of fishery exploitation and marine survival.

The results in Chapter 3 show that, with the use of genomic technologies for broodstock selection, rearing coho salmon in land-based recirculating systems can be profitable at production quantities as low as 500 metric tonnes. This is an important finding as it can support the rise of a land-based aquaculture industry within Canada. Currently, farmed salmon production within British Columbia is dominantly Atlantic salmon in open net farms (Asche et al., 2013; DFO, 2013). Concerns regarding the effects of open-net farming on wild salmon stocks (Gerwing & McDaniels, 2006; Liu et al., 2011; Morton & Routledge, 2016; Naylor et al., 2005) has made the salmon farming industry highly contested. Following the decline of Fraser River sockeye, the Cohen Commission investigated the link between salmon farms and the health of wild salmon stocks. While the report cited studies that identify open net farms both as posing a threat, and not posing a threat to wild salmon (Cohen, 2012a), one of the outcomes of the report was a recommendation regarding the relationship between DFO and the aquaculture industry. DFO is mandated to not only conserve the wild salmon species found within Canada, but also to support aquaculture development (Cohen, 2012b). DFO's role in promoting aquaculture can be problematic, as it may create a conflict of interest in its obligation to conserve wild salmon. A shift towards land-based recirculating systems will allow DFO to uphold it's obligations to both the aquaculture industry, as well as to the wild-capture commercial and recreational fisheries that rely on healthy salmon stocks.

The research exemplified here can contribute to the future management and conservation of endangered coho populations. Furthermore, it reinforces the importance of an ecologically sustainable and economically viable aquaculture industry in British Columbia and offers a means to meet the growing demand for seafood through increased production of coho salmon.

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Appendix A: Escapement and catch data for the Interior Fraser River coho populations, from 1987-2012.

	Escapement								
Return Year	**Fraser Canyon**	**Upper Fraser**	**North Thompson**	**Lower Thompson**	**South Thompson**	**Total**	**Catch**	**Exploitation Rate (%)**	**Returns**
1987	13,187	8,318	27,818	6,008	25,229	80,559	95,727	54	174,073
1988	16,060	10,130	34,329	5,907	30,275	96,702	244,405	71	335,731
1989	11,206	7,068	24,058	6,362	21,020	69,714	130,592	65	196,474
1990	7,110	4,485	16,965	8,290	11,635	48,485	140,904	74	184,037
1991	4,674	2,948	13,413	7,119	5,390	33,545	72,907	68	104,001
1992	7,506	4,735	15,320	8,091	14,875	50,528	227,782	81	272,605
1993	2,406	1,517	6,644	15,781	3,034	29,381	214,365	88	236,016
1994	4,348	2,742	11,074	10,937	6,416	35,517	27,983	43	62,677
1995	3,519	2,219	9,400	3,103	4,755	22,996	31,094	56	52,454
1996	1,473	929	4,068	966	1,858	9,294	50,791	83	56,316
1997	1,964	1,239	5,931	7,571	1,970	18,675	13,250	40	31,379
1998	5,460	4,002	9,256	2,190	5,848	26,757	2,086	7	28,867
1999	4,096	1,397	8,988	4,784	3,332	22,597	2,342	10	24,969
2000	2,719	2,004	7,424	4,318	3,787	20,252	774	4	21,035
2001	5,971	6,346	25,935	9,828	13,569	61,649	4,794	7	66,290
2002	3,817	4,194	20,805	16,217	11,081	56,114	4,863	8	60,874
2003	4,552	3,105	6,778	2,960	3,339	20,734	3,195	13	23,808
2004	5,872	4,761	10,501	4,359	15,385	40,878	6,287	13	47,062
2005	2,513	2,230	4,262	2,719	2,258	13,982	2,171	13	16,069
2006	84	1,286	3,279	1,082	1,976	7,707	1,083	12	8,766
2007	4,514	9,864	23,142	7,833	12,744	58,097	7,343	11	65,424
2008	1,138	1,471	3,695	3,011	6,694	16,009	1,782	10	17,748
2009	2,308	2,188	9,074	3,838	3,746	21,154	2,797	12	23,903
2010	1,365	4,462	11,617	9,285	8,858	35,587	5,391	13	40,905
2011	3,189	3,720	8,340	5,537	4,701	25,487	3,854	13	29,296
2012	5,134	7,334	20,209	8,828	13,327	54,832	8,249	13	63,025

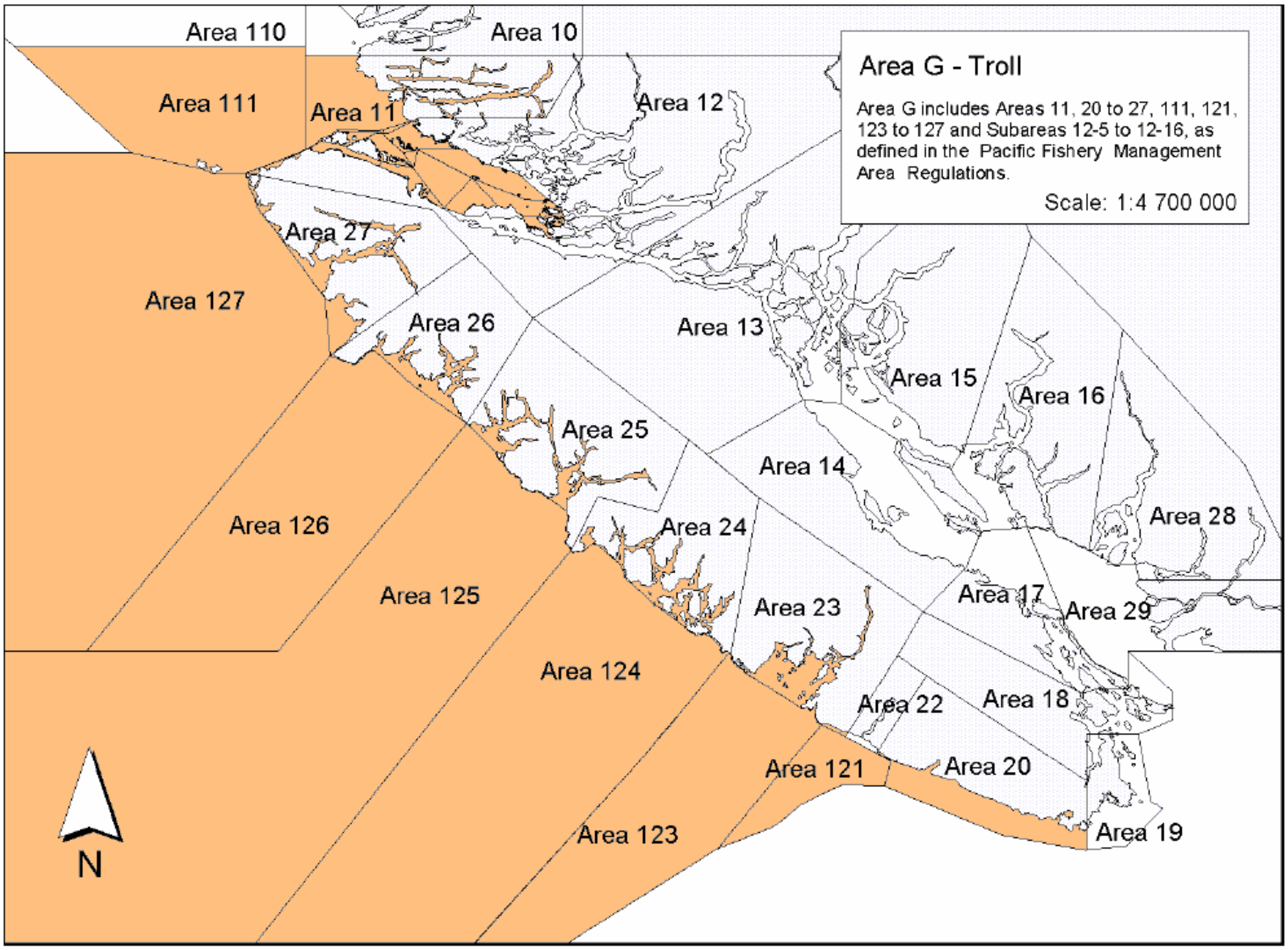
Appendix B: Hatchery fry and smolt release information from RMPC 1987-2012. Fry to smolt mortality is assumed to be 10%.

Return Year (RY)	Fry Released (RY-2)	Smolt Released (RY-1)	Total Smolt Released	Smolt to Adult Survival (%)	Hatchery Returns
1987	1,545,613	27,114	181,675	11.69	21,237
1988	1,347,645	117,275	252,040	16.10	40,573
1989	2,194,556	142,362	361,818	8.06	29,160
1990	1,511,194	193,871	344,990	8.27	28,544
1991	1,384,653	243,726	382,191	23.14	88,421
1992	1,530,232	288,857	441,880	11.91	52,608
1993	1,507,937	266,433	417,227	11.22	46,817
1994	894,265	232,799	322,226	4.46	14,365
1995	729,977	146,311	219,309	2.73	5,987
1996	379,954	214,083	252,078	1.76	4,431
1997	197,197	276,820	296,540	2.27	6,739
1998	357,805	195,760	231,541	0.91	2,104
1999	74,372	180,965	188,402	1.51	2,836
2000	80,685	208,038	216,107	2.82	6,100
2001	121,935	214,976	227,170	3.57	8,113
2002	340,738	367,129	401,203	3.58	14,375
2003	297,016	321,793	351,495	0.82	2,886
2004	419,755	320,822	362,798	0.87	3,154
2005	385,329	389,670	428,203	0.38	1,640
2006	121,127	214,699	226,812	0.31	706
2007	227,299	253,991	276,721	1.16	3,204
2008	127,061	413,478	426,184	0.42	1,795
2009	46,029	205,125	209,728	0.81	1,703
2010	117,480	241,800	253,548	1.00	2,548
2011	144,916	205,127	219,619	0.99	2,167
2012	155,259	214,232	229,758	0.66	1,523

Appendix C: Recruit per spawner estimates for Interior Fraser coho stock 1987-2012

Return Year (RY)	**Total Escapement (Hatchery + Wild)**	**Total return (Hatchery + Wild)**	**Recruit (RY+3) per Spawner (RY)**
1987	81,581	174,073	2.10
1988	105,442	335,731	0.91
1989	74,945	196,474	3.62
1990	54,276	184,037	5.12
1991	47,305	104,001	1.35
1992	56,696	272,605	1.10
1993	61,004	236,016	1.17
1994	42,409	62,677	0.80
1995	28,337	52,454	1.04
1996	14,373	56,316	1.80
1997	26,557	31,379	0.89
1998	29,332	28,867	2.27
1999	26313	24,969	2.32
2000	28,406	21,035	0.88
2001	69,493	66,290	0.69
2002	69,231	60,874	0.23
2003	24,423	23,808	0.44
2004	44,191	47,062	1.52
2005	15,378	16,069	1.22
2006	10,288	8,766	2.51
2007	62,601	65,424	0.72
2008	18,528	17,748	1.72
2009	24,346	23,903	2.65
2010	42,470	40,905	1.53
2011	29,894	29,296	0.65
2012	58,552	63,025	0.21

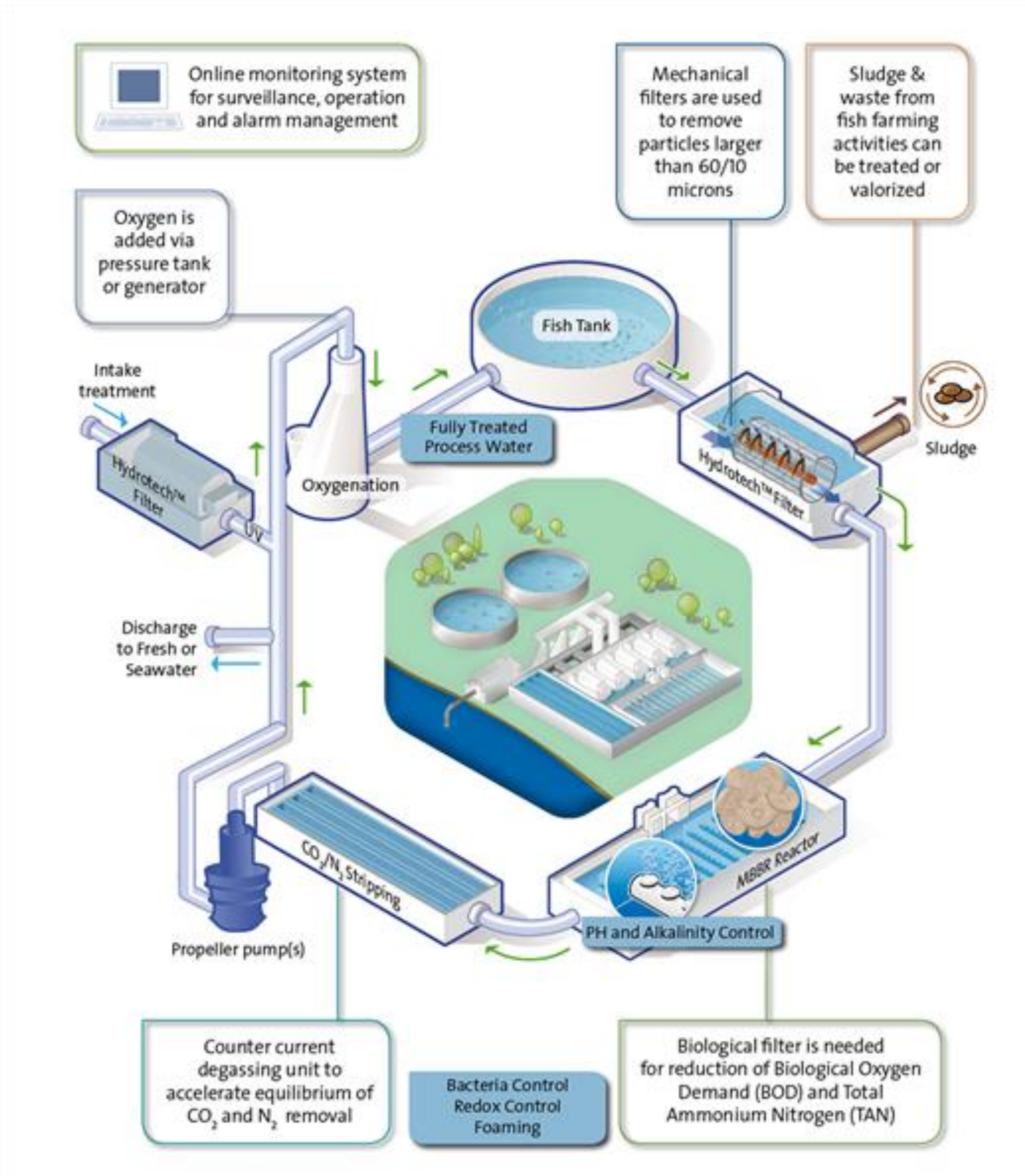
Appendix D: Area G Troll Fishery Map.



Appendix E: Production of Atlantic, Chinook, and coho salmon in tonnes, in British Columbia from 1985 to 2015.

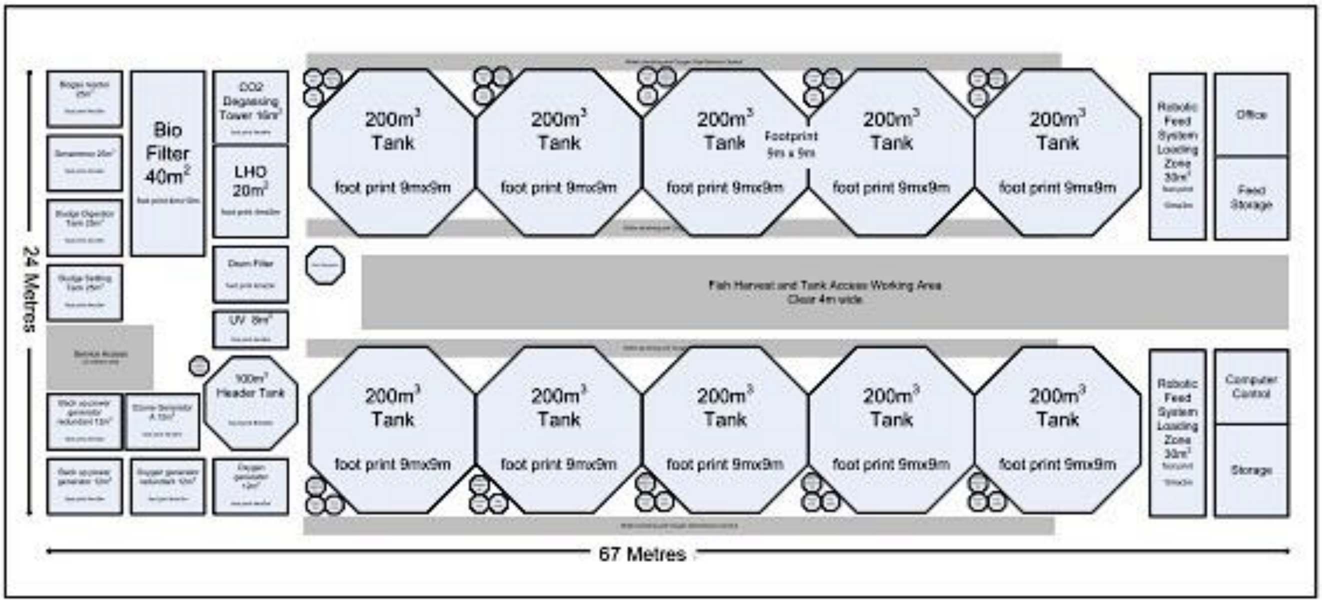
Year	Atlantic	Chinook	Coho
1985	0	0	0
1986	0	87	304
1987	3	949	791
1988	80	3,545	2,743
1989	1,280	8,514	1,815
1990	1,640	10,396	1,296
1991	2,996	19,002	2,863
1992	2,437	15,455	1,922
1993	3,143	19,933	3,143
1994	2,910	12,145	2,295
1995	21,275	4,357	389
1996	21,650	4,434	396
1997	28,443	5,825	520
1998	33,100	6,600	754
1999	38,800	8,800	886
2000	39,300	8,000	820
2001	58,000	7,500	820
2002	71,600	10,400	1,000
2003	55,600	15,700	1,400
2004	46,100	14,400	1,300
2005	53,800	15,200	1,400
2006	71,000	6,400	600
2007	73,300	5,100	500
2008	77,200	3,900	300
2009	72,700	3,343	257
2010	74,500	3,900	300
2011	83,144	0	44
2012	79,981	0	44
2013	74,673	0	44
2014	54,971	0	790
2015	92,926	0	718

Appendix F: Overview of recirculating aquaculture system.



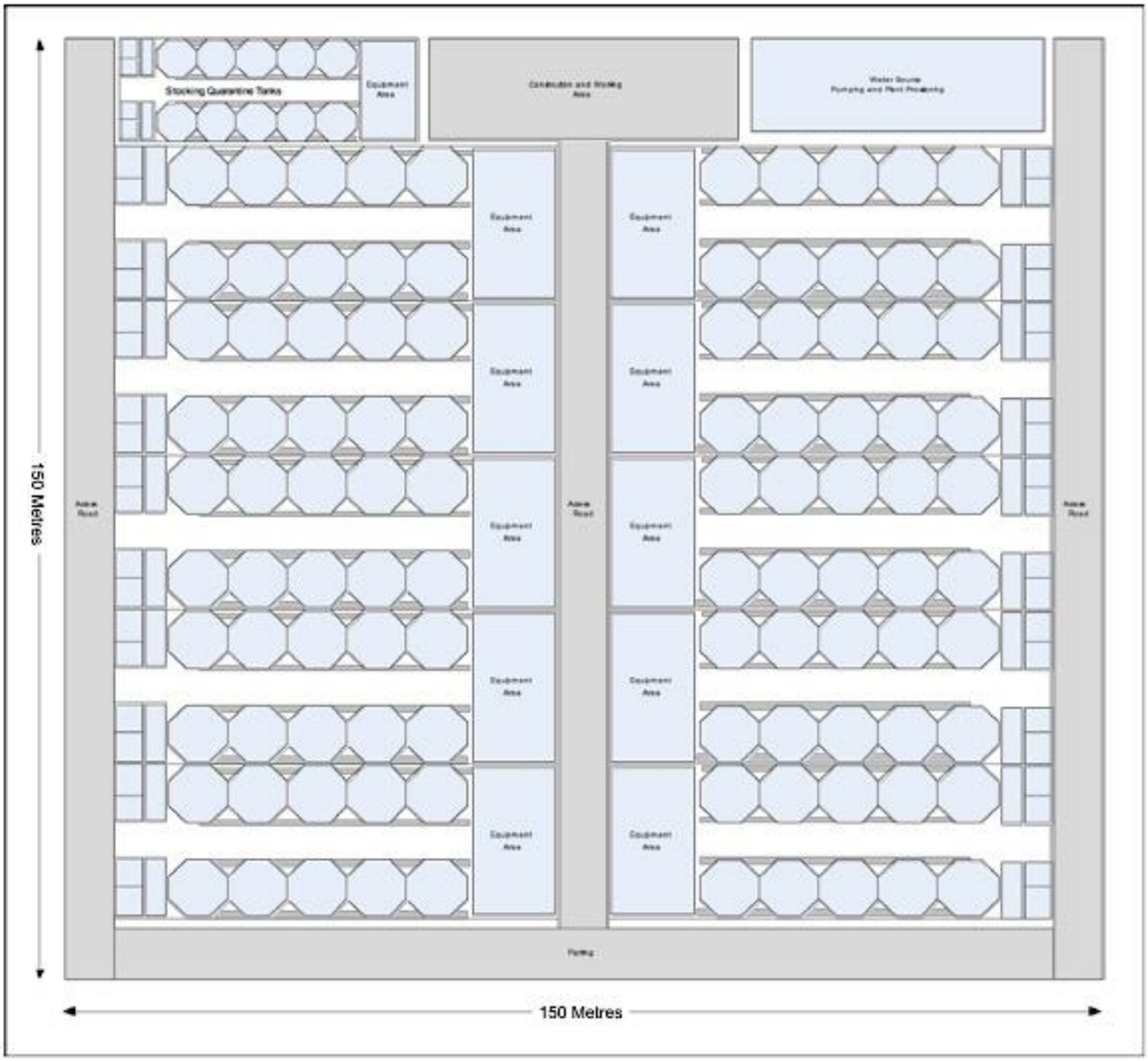
Source: http://aquabounty.com/sustainable/

Appendix G: Layout of 100 MT recirculating system farm with perimeter and area estimations.



Source: Wright & Arianpoo, 2010

Appendix H: Layout of 1,000 MT recirculating system farm with perimeter and area estimates.



Source: Wright & Arianpoo, 2010

Appendix I: Costs and revenues for a production of 575 MT of coho salmon over 10 years.

Year	Revenues ($)	Costs ($)
1	0	6,287,061
2	4,140,649	2,982,434
3	4,140,649	2,697,917
4	4,140,649	2,697,917
5	4,140,649	2,697,917
6	4,140,649	2,697,917
7	4,140,649	2,697,917
8	4,140,649	2,697,917
9	4,140,649	2,697,917
10	4,140,649	2,413,401