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Enhancing land-based culture of coho salmon through genomic technologies: An economic analysis

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ABSTRACT

The selection of salmon broodstock can enhance certain economically important biological traits over generations, via the use of genomic technologies. Information related to flesh quality, disease resistance, growth rate, and feed conversion ratio, has been collected for coho salmon (*Onchorhynchus kisutch*) and may be applied to breeding programs in British Columbia. Marker-assisted selection (MAS) and genomic selection (GS) are two technologies used to identify breeders based on genes directly controlling performance traits. This study aims to quantify the net present value of these technologies, applied to coho salmon broodstock in recirculating land-based systems. We compute the value of these genomic technologies by taking the difference in profits for farmed coho salmon production, when the biological traits mentioned above are enhanced through selective breeding. Results indicate the value of the genomic technologies is around $700 to $6,280 per tonne of coho salmon produced, depending on the targeted trait. Flesh quality yields the greatest change in net present value, followed by growth rate. Our findings may offer a means to meet part of the growing demand for seafood through increased production of coho salmon and reinforce the importance of an ecologically sustainable and economically viable aquaculture industry in British Columbia.

KEYWORDS
Broodstock; coho salmon; genomic selection; land-based aquaculture; marker-assisted selection

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 (BC), 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

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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). Despite the lower profitability margin, land-based farming comes with several benefits not found within open-net pens, including an increase in control over the rearing environment, higher bio-security, and the ability to properly dispose of waste and bio-accumulation that builds up from feed and the growth of the fish (Bjørndal & Tusvik, 2019; Liu et al., 2016).

Recent regulatory changes regarding open-net pens in British Columbia provide an incentive for a larger production of salmon in land-based farms. Following the Canadian federal election in 2019, the re-elected liberal government stated it will formalize the plan to transition out of open-net pens in BC by 2025 (Trudeau, 2019). This comes after several years of pressure from First Nations throughout the province, many of whom have opposed the farms on their traditional territories due to the biological risks associated with sea farming, including the transmissions of pathogens onto wild salmon populations, a rise in diseases and a large abundance of sea lice that may be common in the pens (Gross, 2002; Liu et al., 2011; Naylor et al., 2005). The open-net pens have nonetheless provided a profitable industry in BC, in which the production of farmed salmon was valued at $770 million in 2018 and has contributed to Canada becoming the fourth largest producer of farmed salmon in the world (Statistics Canada, 2019). Farm managers are likely to take advantage of the high prices and rising demand for farmed salmon (FAO, 2018b, 2019), and explore alternative means of farming salmon, such as in a recirculating land-based system. In addition, the economic efficiency and growth of land-based farms can further be improved through the selection of favorable broodstock (Gjedrem, 2012; Yáñez et al., 2015).

Broodstock development programs for salmon aquaculture began in the 1980s with a focus on Atlantic salmon, and are now being applied more often in major salmon producing countries with a focus on a range of species (Rye et al., 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 color, growth rate and market size, as well as feed conversion ratio (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 may be 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 Chile (Neira et al., 2014; Withler & Beacham, 1994). Coho salmon production has not yet reached the level at which Atlantic salmon is produced, but their shorter life cycle (FAO, 2006), higher selling price (FAO, 2018a; Weston, 2013), and ability to be grown using freshwater (Ecoplan International Inc., 2008) make them well suited for rearing in land-based farms.

As important as the genomic technologies have been in enhancing broodstock, their potential to improve the profitability of the salmon farm itself should also be noted. Nevertheless the economic values of these technologies are not always measured in the studies that implement their use. Therefore, 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 via a system that is isolated from the natural environment (Weston, 2013), and may help meet the growing demands for farmed seafood (Gjedrem, 2012).

Previous studies have addressed the economic importance of traits improvement programs by applying profit equations or bioeconomic models (Krupová et al., 2008; Lhorente et al., 2019). While the former approach focuses mainly on changes in the culture productivity either measured by individuals or biomass (Steine et al., 2008), the latter allows a better description and understanding of the biological, technical and economic components that are inherent to aquaculture activity, making it possible to assess different scenarios using dynamic simulations, and estimating the profitability of the farming venture (Ivkovíc et al., 2009; Lhorente et al., 2019). The objective of this study is to measure the value of the genomic technologies that can improve coho salmon broodstock for use in land-based farms. In order to do so, we identify the economically important biological traits in coho salmon broodstock and how the genomic technologies are likely to affect these traits. Then, a bioeconomic model based on recirculating aquaculture systems is used to explore how improved coho salmon broodstock may make land-based aquaculture more profitable. The capital investment and production costs required differ in each type of land-based farm, all of which we examine in greater detail. In the discussion section, we note some of the market and technological risks that could be considered, and provide some analytical approaches to address the uncertainties behind the use of genomic technologies for selective breeding.

The model

Biological component

Economically important biological traits

We use several published sources to identify the important biological traits that managers look for when selecting coho salmon 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 1, we 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 salmon without the use of genomic technologies will hereafter be referred to as the base-case scenario.

Each of the traits listed above plays a role in the production of farmed coho salmon, and can impact the net value of the grow-out cycle. It is important 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 analysis 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 the data section.

Table 1. Economically important biological traits in coho salmon 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.	(Yáñez 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:* Increases 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.	(Gutierrez et al., 2015; Neira et al., 2014)
Flesh quality	Flesh quality pertains to traits such as color 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 color 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)

Production of coho salmon

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

$$B_t^i = F^i\left(R, W_t,\ \overline{M}\right),\ i = \ \{\text{without},\ \text{with}\}\ \text{genomics} \tag{1}$$

where B_t is the biomass in kilograms at time t, R is the initial recruitment size, 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. $t = 1,2\ldots,12$). 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):

$$B_t^i = Re^{-M_t}{W^i}_t,\ i = \left\{\text{without},\ \text{with}\right\}\ \text{genomics} \tag{2}$$

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 we rely on the thermal growth coefficient (TGC), which expresses the growth rate based on the temperature of the rearing environment and the size of the fish (Thorarensen & Farrell, 2010). The equation reads:

$$\text{TGC} = \left({W_{t+1}}^{1/3} - {W_t}^{1/3}\right)/(C*\Delta t*30) \tag{3}$$

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

$$W_{t+1}^i = [{W_t}^{1/3} + \text{TGC}*(C*\Delta t*30)]^3,\ i = \{\text{without},\ \text{with}\}\text{genomics} \tag{4}$$

Farmed coho salmon can be reared until they reach a weight of 2.5–3.5 kg (FAO, 2006). For the purpose of the analysis, we assume the weight at time of harvest will be equal to 2.5 kg which is standard with farmed coho salmon 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).

Economic component

Revenues

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):

$$V_t^i = B_t^i * p_t^i, \;\; i = \{\text{without}, \;\; \text{with}\} \;\; \text{genomics} \tag{5}$$

where p_t is the market price of farmed coho salmon 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 1). Price may generally be dependent on the weight (Bjørndal, 1990), but we 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 account for the effort and time used to prepare the salmon before they are sent to a processing facility or restaurant buyer. We 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 6 (Bjørndal, 1990):

$$H_t^i = C_k * B_t, \;\; i = \{\text{without}, \;\; \text{with}\} \;\; \text{genomics} \tag{6}$$

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):

$$f_t^i = \frac{Q_t}{w'_t}, \;\; i = \{\text{without}, \text{with}\} \;\; \text{genomics} \tag{7}$$

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):

$$Q_t = f_t^i * w'_t \tag{8}$$

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), multiplied by the unit cost of feed in kilograms (C_t). The total months of feeding will be equal to 12 in the base-case scenario. Total Feed cost F_t is calculated as follows (Bjørndal, 1990):

$$F_t = \sum_{t=0}^{12} C_f * Q_t * N_t \tag{9}$$

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

$$CR^i = B_{t=0} * c_R, \;\; i = \{\text{without}, \text{with}\} \text{ genomics} \tag{10}$$

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 could 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 cost in dollars per kilogram of smolts is therefore equal to $0.78 ($140/3,000 smolts per pair/0.06 kg per smolt), an 11% increase from the $0.67 per kg cost found in BCACFB (1989). 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

The next step is to incorporate capital investments and annual operating costs. We compute the value of the production of coho salmon using the land-based recirculating system. Table 2 below describes the recirculating system and some of the designs and operating criteria involved.

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

Table 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 & 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 & Slaski, 2010)
Solid Waste	Directed to on-site storage facility. Experiments focused on turning waste into manure.	(Stechey & Robertson, 2010)
Soluble Waste	Constructed wetlands could be used to manage soluble waste.	(Stechey & Robertson, 2010)
Effluent Discharge	Discharge is passed through a UV filter with 98% of effluent recirculated back to incoming make-up water supply.	(Stechey & Robertson, 2010)

that produce a smaller quantity to remain competitive with farms that may produce 1,000 tonnes a year. We 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 labor (L_y) and energy (E_y) costs per year, which are accounted for in the second year of the farm's cycle, at $y = 1$, and every year onwards. Production of coho salmon begins in the second year as well, to allow for one year of preparation and farm construction.

A depreciation rate is applied to assess the necessary maintenance costs and re-investment of capital over time. The depreciation rate reflects the normal wear and tear of the equipment which eventually will be replaced, whereas the maintenance costs are meant to cover the daily or weekly or monthly modifications of the equipment to keep it running constantly. The rate will depend on the individual equipment, but a straight-line depreciation method is used in which the same depreciation cost (D_y) is accounted for every year. It is assumed that the capital investment will require a loan from the bank. Therefore, we apply an annual interest rate (r) on the capital investment (CI) to the Net Present Value (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, we use three production sizes ranging from 100 to 1,000 tonnes 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. We include a production quantity of 500 tonnes as well because that is close to the current quantity of farmed coho salmon produced in BC (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. Because of the latter, production quantities will increase from the initial scenarios (100, 500 and 1,000 tonnes) to higher levels (115, 575 and 1,150 tonnes) in the genetically-enhanced scenarios. 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 labor, and a lowered capital investment cost per unit output.

Bio-economic model

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). We will be using the conventional NPV equation as it works well with short-term projects, in contrast to the intergenerational NPV equation, which would be more fitting if the project spanned several decades (Liu, 2008). The general equation is as follows (Sumaila, 2004):

$$\mathrm{NPV} = \sum_{y=0}^{Y} \frac{V_y - C_y}{(1+\delta)^y} \tag{11}$$

where V_y is the economic benefits of the farmed production, C_y denotes the costs associated with the production, δ is a discount rate, and $y = 0,1,2,\ldots Y$ is the time, in years, in which the farm is in production, with Y being the final year. In the analysis, we use a discount rate of 5.8%, the real rate[1] that is generally accepted in cost-benefit analysis by the government of British Columbia (Treasury Board of Canada Secretariat, 2007).

At each production level, we calculate the NPV of the land-based farm over a 10-year period. We chose a 10-year period because licenses for land-based aquaculture operations are issued for up to a maximum of 9 years by Fisheries and Oceans Canada (DFO, 2017). However, we also include one year for the construction and preparation of the farm, where no coho salmon production occurs. We 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, we first account for all sources of revenue, and all of the capital, operating, and production costs. The biomass value of the coho salmon produced is the only source of revenue. The present value of revenue (PV_R^i), over the 10-year period, is calculated using the following equation:

$$PV_R^i = \sum_{y=1}^{Y} \frac{V_y^i}{(1+\delta)^y}, \quad i = \{\text{without, with}\} \text{ genomics} \tag{12}$$

The revenue will accrue starting with $y=1$ as we 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 $y=0$. The present value of costs is calculated using the following equation:

$$PV_c^i = CI + \sum_{y=1}^{Y} \frac{(H_y^i + F_y^i + CR_y + (r*CI) + D_y + E_y + L_y)}{(1+\delta)^y}, \quad i = \{\text{without, with}\} \text{ genomics} \tag{13}$$

with a real discount rate of 5.8%.

The NPV is therefore given by:

$$NPV^i = PV_R^i - PV_C^i, \quad i = \{\text{without, with}\}\text{genomics} \tag{14}$$

Value of genomic technologies

To calculate the value of the analyzed genomic technologies, we compute the NPV of the recirculating land-based farm without the use of genomics and measure how much the NPV changes due to the use of genomic technologies, following Table 1. This difference in NPV will be equal to the value of the genomic technologies. This will show which of the traits generate a greater increase in NPV and which traits show a minimal change in NPV. Additionally, to address uncertainties around the estimated value of the genomic technologies, we conduct a sensitivity analysis on each of the economically important variable traits and assess the change in NPV.

Data

Production without genomic technologies

Table 3 below shows the parameters used to determine the biomass value (B_y) and the variables costs in the base-case scenario.

Production with the genomic technologies

Following Table 1, we assess the effect of the genomic technologies on the production of farmed coho salmon. The economically important biological traits will be modified, based on previous studies encompassing each trait.

Revenues

Table 4 below shows the parameters used to determine the biomass value and costs of production using the genomic technologies. Reasoning for the change in value of each factor is given below.

The change in the thermal growth coefficient from 2.34 to 2.48 is meant to reflect the change in harvest weight over a 12 month growth cycle. 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, we 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, we 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.

Table 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 salmon over 12 months, which is the standard rearing time from smolt to adult.	(FAO, 2006; Thorarensen & Farrell, 2010)
Mortality per year (%)	15	Loss of broodstock due to disease or culling for optimum stocking density.	(FAO, 2006)
Market price ($/kg)	7.15	This is the unit price of the global farmgate value of farmed coho salmon.	(FAO, 2018a)
Harvest weight (kg)	2.50	Weight ranges from 2.5–3.5 kg, but for the analysis, we assume the coho salmon will be raised to 2.5 kg.	(FAO, 2006)
Harvesting cost ($/kg)	0.50	This is the estimated harvest cost for a recirculating system raising Atlantic salmon. We assume the price to be the same for coho salmon.	(Wright & Arianpoo, 2010)
Unit feed cost ($/kg)	1.50	Different studies estimate a wide range of feed price. This value was estimated from a feasibility study for Atlantic salmons in a recirculating system.	(Boulet et al., 2010)
Feed conversion ratio	1.3	Feed conversion ratio varies with the weight of the salmon. This is an average value used to incorporate the entire cycle from smolt to adult, from a recirculating farm producing coho salmon in Agassiz, BC, as well as a test facility in Cedar, BC.	(Ecoplan International Inc., 2008; Walker, 2017)
Unit smolt cost ($/kg)	0.67	This is the value used in a financial analysis in 1989 using Chinook and coho salmon smolts, estimated in 2018 dollars.	(BCACFB, 1989)
Smolt weight at purchase (kg)	0.06	Smolt size ranges from 60–80 grams. We use the low range estimate.	(FAO, 2006)

Table 4. Values of each variable trait used to measure benefits and costs of production in the scenarios with genomic technologies.

Factor	Value
Thermal Growth Coefficient	2.48
Mortality per year (%)	10
Market price ($/kg)	8.20
Harvest weight (kg)	2.85
Harvesting cost ($/kg)	0.50
Unit feed cost ($/kg)	1.50
Feed conversion ratio (FCR)	1.14
Unit smolt cost ($/kg)	0.78
Smolt weight at purchase (kg)	0.06

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 consumers would pay 12.57% to 15.67% more for salmon with colors that were darker than the faint pinkish tint often found in farmed salmon (Alfnes et al., 2006). For the analysis, we are incorporating a 15% price premium for higher quality flesh, bringing the unit price for coho salmon to $8.20/kg.

Costs

Harvesting cost, feed price, and smolt weight at purchase are not dependent on selective breeding and do not change in the analysis. Smolt cost changes with the genomic technologies, as previously described. Another factor that changed due to the genomic technologies is the 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 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 (8), feed consumption is equal to the change in weight multiplied by the FCR. Under the base-case scenario, it is equal to $((2.50\,\text{kg}–0.06\,\text{kg}) \times 1.3) = 3.172$. 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 $(3.172/(2.85\,\text{kg}–0.06\,\text{kg})) = 1.14$.

Capital and operating costs

In Table 5, we outline the capital, energy, and labor needed for the recirculating system, as well as the estimated cost for each production size.

Results

Net present value: without genomic technologies

Table 6 below shows the NPV for each of the production sizes in the recirculating system. These are obtained using the base-case scenario, with the values of the variables described in Table 3.

The results for the base-case scenario show that the recirculating system generates negative net present values at production capacities of 100, 500,

Table 5. Capital, energy, and labor costs for recirculating system.

Capital[a]	Unit cost ($'000s)	Depreciation (years)	Cost by production size ($'000s) 100 tonnes	500 tonnes	1,000 tonnes
Culture tanks (200m^3)	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	N/A	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	N/A	10.00	37.50	50.00
Land purchase	57.00	N/A	22.80	158.46	316.92
Building construction	400.00	20	400.00	2,000.00	4,000.00
Total capital cost ($'000s)			**1,301.16**	**6,062.74**	**11,850.48**
Depreciation cost per year ($'000s)			89.32	401.61	783.22
Energy cost[b]			**37.80**	**189.00**	**378.00**
Labor cost[c]			**334.74**	**473.68**	**647.36**

[a]Data regarding the capital costs and equipment needed are taken from Wright and Arianpoo (2010).
[b]Data for energy usage is from Liu et al. (2016). We use a unit price of $0.07 per kilowatt hour, as is common in Canada (Wright & Arianpoo, 2010).
[c]Data on wages came from Wright and Arianpoo (2010) as well as Liu (2008), with each farm comprising of a workers, a manager, and a vet technician.

Table 6. Net present value under the base-case scenario for each production quantity, the net present value for each production quantity when genomic technologies are incorporated, and the value of the genomic technologies.

Base case (without genomic technologies)		With genomic technologies		Value of genomic technologies ($'000s)
Production quaatity (tonnes)	Net present value ($'000s)	Production size (tonnes)	Net present value ($'000s)	
100	−2,156	115	−642	1,515
500	−1,593	575	5,980	7,573
1,000	−591	1,150	14,555	15,147

and 1,000 tonnes. The tonnage of coho salmon produced does not offset the high capital costs needed.

Net present value: with genomic technologies

To estimate the value of the genomic technologies, we calculate the NPV of the production of coho salmon while incorporating the changes on each of the economically important biological traits, as described in Table 4. The change in NPV as flesh quality, mortality, growth rate and feed conversion ratio vary from the base-case scenario (without genomic technologies) will signify the economic value of marker-assisted selection and genomic selection technologies.

Results indicate that GS and MAS can make the production of coho salmon in a recirculating system profitable at a production level of 575 tonnes similar to current production of coho salmon in BC. The value of the genomic technologies, in a recirculating system producing 115 tonnes of coho, could be around $1,515,000, accrued over a period of 10 years. Although the NPV at 115 tonnes did increase over the period of 10 years when compared to the base-case scenario, it did not become positive with genomic technologies. In the 1,150 tonnes land-based recirculating system, the genomic technologies can be valued at around $15,147,000 over a period of 10 years. Standardizing the results indicate the value of the genomic technologies may be around $13,170 per tonne of coho salmon produced.

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, we calculate the NPV of the production of coho salmon modifying one trait while keeping the remainder constant.

The results indicate that, using the values from Table 4, flesh quality is the biological trait that has the largest impact on NPV of coho salmon 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 $6,280 per tonne of coho salmon 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 NPV, potentially adding $5,160 per tonne of salmon produced, which accounts for 42% of the total value. Disease resistance, which affects mortality, will only improve production to the point where a positive NPV is attained at higher production quantities, if targeted alone (Table 7).

Table 7. Net present value and the value of the genomic technologies for each of the three biological traits, at different production quantities.

Production quantity (tonnes)	Net present value ($'000s) with genomic technologies			Value of genomic technologies ($'000s)		
	Flesh quality	Mortality	Growth rate	Flesh quality	Mortality	Growth rate
100–115	−1,434	−2,078	−1,578	722	78	578
500–575	2,018	−1,204	1,297	3,612	390	2,891
1,000–1,150	6,633	188	5,191	7,224	779	5,782

Table 8. The net present value (NPV) at each production quantity, and the estimated value of the genomic technologies, with a 17.5% and 12.5% change in price.

Production qunatity (tonnes)	NPV with 12.5% increase in price ($'000s)	Value of genomic technologies ($'000s)	NPV with 17.5% increase in price ($'000s)	Value of genomic technologies ($'000s)
100	−1,555	602	−1,313	843
500	1,415	3,008	2,622	4,215
1,000	5,425	6,016	7,840	8,431

Sensitivity analysis

There is some uncertainty in the appropriate value of the parameters chosen in Table 4. To address these uncertainties, we 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 color 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. We show the value of the genomic technologies, which is equal to the change in NPV when market price includes a 12.5% and 17.5% price premium. The sensitivity analysis is performed using a higher and lower base value than the base of 15%, 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.

The results indicate that a price increase of 17.5% ($8.40/kg) would still yield negative net profits at a production quantity of 100 tonnes. Managers would therefore have to focus on additional biological traits or increase their production to a higher quantity. With a price increase of 12.5% ($8.04/kg), the farm would yield positive net profits at a production quantity of 500 tonnes and 1,000 tonnes (Table 8).

Mortality

High rates of mortality may lead to a smaller harvest size as less fish reach their harvest weight, 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, we 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

Table 9. The net present value (NPV) at each production quantity, as well as the associated value of the genomic technologies, when mortality changes to 12.50% and 7.50%.

Production quantity (tonnnes)	NPV with mortality at 12.50% ($'000s)	Value of genomic technologies ($'000s)	NPV with mortality of 7.5% ($'000s)	Value of genomic technologies ($'000s)
115	−2,118	38	−2,038	119
575	−1,405	189	−1,000	593
1,150	−214	377	595	1,186

(10%). The average of the differences is 2.5% so the sensitivity analysis includes mortality estimates of 12.5% and 7.5%.

Results show that if mortality were to be as high as 12.5% per year, a farm would not yield positive profits at a production of 1,150 tonnes or lower, with a loss of -$214,000 after 10 years (Table 9). If managers could achieve a mortality rate of 7.5%, only a production quantity of 1,150 tonnes would show a positive NPV.

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, we measure the NPV if the growth rate resulted in a market weight of 3.025 kg and 2.675 kg over a period of 12 months, which gives a range of 350 grams with the base case of 2.85 kg as the average.

The results show that, if a harvest weight of 2.675 kg can be attained over the 12 month growth cycle, then the NPV only becomes positive at production capacity of 1,150 tonnes. If the harvest rate is raised to 3.025 kg, the NPV will be positive at a production capacity of 575 tonnes (Table 10). Profits would not be incurred over 10 years even with a harvest weight of 3.025 kg in a farm producing 115 tonnes. Managers would have to opt for larger production outputs or target additional biological traits when selecting for broodstock

Discussion and summary

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 higher profits accruing to the farm itself. The technologies used for selective breeding may have great economic value and may offset the high capital and operational costs of a recirculating system at a production capacity of 575 to 1,150 tonnes, generating substantial profits. When selecting for broodstock, farms would yield

Table 10. The net present value (NPV) at different production quantity, and the estimated value of the genomic technologies 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 qunatity (tonnes)	NPV with market weight of 2.675kg ($'000s)	Value of genomic technologies ($'000s)	NPV with market weight of 3.025 kg ($'000s)	Value of genomic technologies ($'000s)
115	−1,866	290	−1,285	872
575	−142	1,451	2,764	4,358
1,150	2,311	2,903	8,125	8,716

higher profits when targeting flesh quality, which accounted for 52% of the increase in profits. On the other hand, targeting the growth rate accounts for 42% of the increase. The results also indicate that the land-based farms presented in the study would not see positive profits at any production size without the use of the genomic technologies.

As is mentioned in Bjørndal and Tusvik (2017, 2019), there are few published economic analysis focusing on recirculating systems, in part due to it being a novel technology and in part due to many facilities failing in their production. As a result, some of the parameters used in this study relating to the technology, biology, and economic components come with uncertainty. It should be highlighted that the evaluation presented in this paper was deterministic and does not include a probability distribution of potential outcomes. There are several economic and technical risks involved in land-based farming that should be noted, even with the implementation of marker-assisted selection and genomic selection. Previous studies have shown that land-based farming require expensive capital and operational costs that are either higher or similar in comparison to ocean-based pens. Boulet et al. (2010) concluded that a recirculating system requires four times the initial investment as open-net pens, within Canada. King et al. (2018) found that RAS would require twice as much of an investment than a sea-based system in Tasmania. These are similar to the findings of Liu et al. (2016), which compared the environmental and economic performance of a closed-containment recirculating facility and open-net sea pens both producing 3,300 tonnes of Atlantic salmon.

The high startup costs make land-based farming a risky venture, and operations can be curtailed by several technical, biological, and market-based factors. King et al. (2018) states that recirculating systems pose a great financial uncertainty, in comparison to sea-pen production systems. The study found that the initial investment costs may be prone to increase to allow road access to the facility, meet local building regulation requirements, or clearing land space to build the facility (King et al., 2018). Land-based farms require a higher energy input and a power failure can result in the loss of a year-class. Ammonia, carbon dioxide, and oxygen must all be maintained within certain parameters and rely on the biofilters and the removal of solid wastes in a timely manner. If the equipment is not properly working, the technical malfunctions lead to biological imbalance in the water, with toxic compounds such as ammonia and nitrite becoming detrimental to fish health and welfare (Badiola et al., 2012). The loss of biomass, and therefore the loss in profits, may be large enough to stop future production of a RAS facility, even if the biological or technical risks are tended to.

However, as evidenced by the loss of 250,000 Atlantic salmon after several open-net pens collapsed in the State of Washington in 2017 (Britten, 2018), the escape of 20,000 Atlantic salmon after a fire at a fish farm in Port Hardy, BC (The Canadian Press, 2019), and the loss of 200,000 Atlantic salmon due to algal blooms on the West Coast of Vancouver Island (O'Malley, 2019), it is clear that open-net pens are subject to technical and biological failures as well. Rearing salmon will include risks whether it is conducted on land or in the sea, and those risks will result in economic uncertainty (Bjørndal & Tusvik, 2019). Communication within the land-based farming industry involving producers, suppliers, researchers, and consultants can be beneficial to improving the technology and efficiency of RAS (Badiola et al., 2012), and could lower the operating costs over time.

Current market conditions are a strong driver for the development of land-based farms in British Columbia. The price of farmed Atlantic salmon has been on the rise and demand has increased globally, often times faster than can be supplied (FAO, 2018b). However, we do not include a marketing component for farmed coho salmon in the study, the results of which are dependent upon the success of the selective breeding program, as well as the prices remaining high. Atlantic salmon has a large dominance in the global market, with over 2.3 million tonnes produced in 2017, in comparison to the 180,000 tonnes of coho salmon produced that same year (FAO, 2018a). Consumer preference may deter land-based farms from rearing coho salmon, even with their shorter life cycle and current high prices. For example, Chile is the second largest producer of Atlantic salmon, and its exports to markets in the US, Japan, and the EU have allowed Chilean production to increase 14% in 2018 (FAO, 2019; Quiñones et al., 2019). Chile is also the largest producer of farmed coho salmon, yet even with an increase in production of 34% in 2018, production quantities are very low in comparison to Atlantic salmon (FAO, 2019) and have been relatively stable since the early 2000s (FAO, 2006). It is possible that the demand has not increased considerably since the market for farmed Chilean coho salmon is less varied, with 90% consumed in Japan (Poblete et al., 2019). Given that there are more markets for farmed Atlantic salmon, Chile may not have had the opportunity to expand their production of coho salmon and has produced much more Atlantic salmon then coho salmon since 1992 (Knapp et al., 2007). Olson and Criddle (2008) reported the average real price of Atlantic salmon dropped 3.06% per year and the average real price of coho salmon dropped 6.95% per year, from 1990 to 2006, likely impacting the profitability and growth of the coho salmon production. Future research on consumer preferences and the proper marketing of farmed coho salmon could be used to supplement the economic analysis presented here. Demand for coho salmon from recirculating systems in BC may spread to markets that Chilean coho salmon do not reach, as it would not be associated with the outbreak of Infectious salmon anemia (ISA) that caused production to drop in 2008 (FAO, 2006; Poblete et al., 2019). This demand may be increased due to recent regulatory changes set by the federal government in Canada, indicating a shift away from producing farmed salmon in open net sea-pens (Trudeau, 2019). In the near-future, Canada may have to rely on alternate production systems, such as the land-based recirculating system, in order to remain a major global producer of farmed salmon.

Furthermore, future research efforts could improve the analysis by including risk and uncertainty components. One approach is to perform a risk analysis by including stochasticity into the bioeconomic model and setting limit reference points (Seijo, 2004; Lhorente et al., 2019). Another approach to deal with uncertainty is the use of decision tables to assess the performance of the genomic improvements subject to different management strategies (e.g. stocking densities, harvesting schedules), and under possible states of nature (e.g. temperature regimes, market behavior). This later framework allows optimal choices to be made by using decisions criteria (Villanueva et al., 2013). Nonetheless, even with the lack of a risk and uncertainty analysis and noting the high NPV at production capacity of 575 and 1,150 tonnes makes it likely that generating positive profits (i.e. NPV $>$ 0) is plausible. Enhanced coho salmon broodstock, as this study shows, may provide new possibilities to achieve positive profits in land-based recirculating systems, which may encourage new investments into this industry.

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Disclosure statement

None.

Note

1. The real interest rate is based on a nominal rate of 8% and an inflation rate of 2.2% (Bank of Canada, 2018).

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