Bren School of Environmental Science & Management
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Bioeconomic Modeling of Salmon Farming Practices in Southern Chile

A group project submitted in partial satisfaction of the degree requirements for the Master of Environmental Science & Management

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The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the envrionmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than on discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

Christopher Costello, Faculty Advisor
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Abstract

Rising global demand for salmon has led to aquaculture practices that can have important environmental and socioeconomic impacts. After explosive growth of the salmon farming industry in Chile, lax regulations and a lack of scientific information resulted in ecological degradation and, in 2007, an outbreak of a salmon virus that caused a virtual industry collapse. As the industry rebuilds and expands into Chile's pristine southernmost region, the Magallanes, there is a need to identify management practices that will lead to favorable trade-offs between "outcomes of interest" including ecological health, Concession Profit, and artisanal fishing profits. Our project offers a bioeconomic model that predicts the magnitude of those outcomes caused by individual salmon farming concessions. Our model identifies practices that have the strongest effect on the outcomes and should therefore be targeted for changes in management. We also used the model to predict the outcomes of concessions already approved for the Magallanes, demonstrating the model's ability to aid managers in choosing between future concession applications. Then, we identified combinations of farming practices that can lead to more overall benefit than those approved concessions. Lastly, we identified model parameters that warrant future research in order to improve the reliability of the model's results. Importantly, our model provides a framework that can be built upon to include greater detail and scope, and can be tailored to describe salmon aquaculture in other parts of the world. Our tool can help managers identify favorable trade-offs that maximize overall benefits from this rapidly expanding global industry.

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Acronyms

AAA – appropriate area for aquaculture
EIA – Environmental Impact Assessment
FCR – feed conversion ratio
GORE – Regional government of the Magallanes (Gobierno Regional Magallanes y Antarctica Chilena)
ILO – International Labor Organization
IPN – Infectious Pancreatic Necrosis
ISA – Infections Salmon Anemia
LGPA – Chile's General Fishing and Aquaculture Law
MATLAB – a technical computing software program (Mathworks, Inc.)
MPA – Marine Protected Area
N – Nitrogen
OECD – Organization for Economic Co-operation and Development
RAMA – Environmental Rules and Regulations for Aquaculture amendment to the
SCUBA – Self-Contained Underwater Breathing Apparatus
USD – United States Dollar
WCS – Wildlife Conservation Society

Executive Summary

Background

Aquaculture, or fish farming, is a rapidly growing industry that has the potential to help meet increasing global demand for seafood (Pomeroy 2008). Production from salmon aquaculture in particular has increased dramatically in the past three decades as demand for this species continues to rise (Naylor & Burke 2005). Salmon aquaculture commonly occurs in offshore farms composed of floating net pens. In this environment, salmon farming can have significant ecological impacts, including nutrient and chemical pollution, competition and predation by escapes with wild fish, and the spread of disease and parasites to wild species.

Chile's salmon farming industry was established in the Los Lagos Region in the south-central part of the country in the late 1970s. The industry experienced explosive growth (Barton, 2010), contributing substantially to national revenue and providing tens of thousands of jobs. By 1992, Chile had risen to become the world's second largest exporter of farmed salmon (Bjørndal & Aarland, 1999), and production from that country continued to grow through its peak in 2007 (Barton & Fløysand, 2010). However, a lack of scientific information on which to base regulations, coupled with weak on-the-ground enforcement, likely contributed to the widespread environmental degradation and poor labor conditions that characterized the industry in that region. In 2007, an outbreak of the infectious salmon anemia (ISA) virus swept through Los Lagos salmon farms and drove the industry to near-collapse (Barton & Fløysand, 2010). To rebuild this economically important industry, the government has begun to encourage large-scale expansion of salmon farming in the more pristine, southernmost region of Chile, the Magallanes (Barton & Fløysand, 2010). Applications for salmon farming "concessions" – particular areas in the coastal ocean that can be leased to aquaculture companies – are currently being accepted and approved for operation in the Magallanes.

Our client, the Wildlife Conservation Society (WCS) of Chile, is concerned that the expansion of salmon aquaculture into the Magallanes will result in undesirable ecological and socioeconomic impacts similar to those experienced in Los Lagos (Claude & Oporto, 2000; Pinto et al, 2005).

Objectives

The main goal of this project is to determine how specific salmon farming practices affect a set of environmental and economic outcomes that are of interest to diverse stakeholders. These stakeholders include artisanal fishers, aquaculture companies, environmental groups, regulatory agencies, and more. The specific objectives of this project include the following:

- Construct a model that captures the mathematical relationships that link salmon farming practices to various outcomes of interest.
- Identify the range of possible outcome values that are expected to occur based on currently approved farming practices in the Magallanes.
- Identify the salmon farming practices that have the strongest effect on each outcome of interest.
- Highlight tradeoffs between important pairs of outcomes.
- Model the impacts of each approved salmon farming concession for the Magallanes and rank them in terms of outcome values.
- Develop recommendations to the regional government in the Magallanes (GORE), the industry association (SalmonChile), and aquaculturists about changes to farming practices that could prioritize particular stakeholder interests.
- Identify areas where research to gather more accurate data would lead to the greatest improvement of the model's reliability.

Constructing the Model

Through an extensive literature review and stakeholder interviews conducted in Chile, we identified seven "outcomes of interest" that capture the most important potential impacts of the salmon aquaculture industry in the Magallanes. Our outcomes of interest are Ecosystem Health (comprised of Species Health, Species Richness, and Species Abundance), Area Affected by Pollution, Probability of ISA Transmission, Expected Regulatory Costs of Labor Law Violations, and Concession Profit. We then created a model that takes nine "inputs" – farming practices or conditions over which aquaculturists have some degree of control – and calculates their the resulting value of each outcome of interest. The nine inputs are: Number of Juvenile Salmon at Start of the Production Cycle, Number of Net Pens in Concession, Number of Months per Production Cycle, Number of Chemical Treatments, Equipment Quality, Number of Wage Violations, Number of Hours Violations, Water Current Speed, and Depth of the Seafloor. The model is composed of seven sub-models, which are made of mathematical relationships and parameters that translate input values into the resultant outcome values. The seven sub-models are described here:

- Nutrients' Effect on Ecosystem Health: predicts the effect of nutrient effluent on species richness of benthic marine life surrounding the farm.
- Chemicals' Effect on Ecosystem Health: predicts how chemical use affects the abundance of benthic species in the area surrounding the salmon farm.
- Escaped Salmon's Effect on Ecosystem Health: predicts the number of escaped salmon as a function of type of farm technology and models their effects on pelagic species abundance and health.
- Probability of Inter-Farm ISA Transmission: estimates the probability of ISA spreading to a farm if a neighboring farm is already infected with the virus.

- Harvestable Salmon and Concession Profit: calculates the number, weight, and value of harvestable salmon, on-site operational costs, and profit to the concession (which takes into account the expected costs of collapse due to an ISA outbreak and of fines due to labor violations).
- Expected Regulatory Costs for Labor Violations: predicts the total potential and total expected cost of fines incurred for violating labor laws.
- Economic Effects on Artisanal Fishing and Tourism: predicts changes in profits based on salmon farming's impacts on the various native species that are valuable to these two industries.

We gathered data from the environmental impact assessments (EIAs) of the 32 approved concession proposals for the Magallanes and used these values to represent as many of our model inputs and parameters as possible. The average values for each input and parameter found in the EIAs were used as "default" values to represent the "average" salmon farm approved to be implemented in the Magallanes, and the ranges in these values were assumed to represent the total possible range of values for salmon farming practices to be expected in the Magallanes. Each run of the model represents a possible management decision – a combination of input values that can be selected by the industry (or required by the government). The outcomes that the model calculates are the resultant outcome values that can be expected after one cycle under the input farming conditions.

Analysis and Results

We performed five main analyses using our model and the EIA data.

Default Values:

With input and parameter values set to their defaults, we found the following values for our outcomes of interest, which represent the impacts of the "average" approved salmon farm in the Magallanes after one harvest cycle:

- Ecosystem Health Index = 1.97 (on a scale of 1-3)
- Area Affected = 19,210 km^2
- Concession Profit = $2,700,000 USD
- Probability of ISA Transmission = 0.0006
- Profits to Artisanal Fisheries = 0.87 (fraction remaining)
- Profits to Tourism = 0.48 (fraction remaining)
- Expected Regulatory Cost of Labor Violations = $1,480 USD

Input Ranges

To identify the range of possible values for each outcome based on approved farming practices, we ran our model varying the inputs concurrently across their ranges found in the approved concession EIAs. This process amounted to over 60,000 model runs. For each outcome of interest, we plotted frequency histograms to illustrate the distribution of values and to determine the full ranges of outcome values that can be expected based on approved farming practices.

We found a wide range of outcome values for every outcome of interest, implying that, depending on the combinations of inputs chosen for implementation in the Magallanes, there could be very preferable or very negative impacts.

Efficiency Frontiers

To isolate important trade-offs between pairs of outcomes, we generated scatter plots illustrating pairs of outcome values associated with each of the model runs from the input range simulation. We identified the outer bounds of these plots – the efficiency frontiers – which represent combinations of inputs that maximize total benefit to both outcomes. We use these graphs to inform recommendations to improve aquaculture practices in the Magallanes.

One notable finding from these plots is that, if aquaculturists wish to grow large numbers of salmon (in the range of 1-2,000,000 starting smolt), they can alleviate some of the negative environmental impacts by increasing the number of net pens within each farm (thus distributing fish more sparsely) and upgrading to copper cages.

Approved Concession Rankings and Efficiency Frontier

We used the model to predict the outcomes associated with 21 currently approved Magallanes concessions based on the input conditions stated in their application EIAs. We ranked these concessions based on their performance for each outcome, and then compared all the concessions with a scatter plot based on the outcomes Ecosystem Health and Concession Profit.

We found that most of the 21 concessions fall inside of the efficiency frontier for these two outcomes. We identified three concessions that make distinctly different tradeoffs between maximizing Ecosystem Health and Concession Profit. We identified potential for improvement in these approved concessions by comparing this efficiency frontier with that of the input ranges simulation: The simulation showing the outcomes from all possible combinations of input values leads to hypothetical concessions that are more efficient than those along the efficiency frontier of the 21 approved concessions.

Elasticity matrix

We created an elasticity matrix to identify “leverage points”, or input values that, when adjusted, have strong effects on a given outcome value. We performed this analysis by systematically adjusting each input value by a given percent and calculating the resulting proportional change in each outcome. The elasticity matrix identifies inputs that managers can alter that will result in the greatest improvements on certain outcomes.

We found that the Number of Salmon at Start of cycle was overall the most impactful input, likely because this input is used in several of the sub-models. Number of Slice Treatments, Number of Net Pens, Depth, Current Speed, and Equipment Quality were also important leverage points.

Sensitivity Analysis

In order to test our model’s robustness and identify potential areas of research that could lead to improved precision of our model results, we conducted a Monte Carlo sensitivity analysis. We first performed a base run consisting of 1,000 model runs in which parameter values were selected at random from within their ranges while holding input values at their defaults. This process identified the full range of expected outcome values due to parameter uncertainty. Next, to find how strongly each parameter affects each outcome, we performed 1,000 more runs for each of the 34 parameters, systematically isolating each one at its midrange value. In addition to testing the robustness of our model, this sensitivity analysis highlights parameters where small adjustments result in large changes in the outcomes of interest.

We found that the parameter values for N Content in Feed, N Richness Elasticity, Mortality Due to Disease, Probability of Disease Inside and Outside of Pens, Distance Between Farms, Economic FCR, Other Operational Costs, Price Per Kilogram of Salmon, and the Number of Escapes to Halve Native Cetaceans, Predators, and Prey had the greatest impact on our outcome ranges. The accuracy of our model would benefit most from an improved understanding of these parameter values.

Recommendations to the industry

Our model results lead to some recommendations for the salmon farming industry and its regulators in southern Chile, including the following:

Focus on upgrading net pen technology: Our analysis predicts that upgrading to the newest technology – copper cages, which prevent 100% of salmon escapes – would increase Concession Profit as well as provide benefits to other outcomes of interest, including Ecosystem Health and Profits to the Tourism Industry.

Decrease the amount of juvenile salmon at the start of the production cycle: Our model shows that Smolt at Start has the strongest influence on Ecosystem Health. These results highlight the opportunity to impose limits on this starting number of salmon, if a goal is to balance ecological impacts with industry profits.

Utilize this model to assess future concession applications: Aquaculture managers can use this model to assess and rank future applications for salmon farming concessions in the Magallanes. Rankings can be calculated to reflect various stakeholder interests, and can be especially useful in illustrating tradeoffs. These rankings and the resultant efficiency frontiers can also be used to identify issues on which particular concessions could focus in order to improve their performance on one or more outcomes.

Caveats

While we believe that our model provides reasonably reliable results that can help guide salmon aquaculture management in southern Chile, it comes with some important caveats. For example, the model does not capture the cumulative effects of salmon farming over space or time. The model also has distinct conceptual boundaries in its level of detail and scope. Therefore, the model can be utilized in its present state, but also serves as a framework for future enhancements. Likewise, the model could be modified to model offshore aquaculture in different parts of the world.

Conclusions

With the continuing rise of global demand for salmon, aquaculture is a clear alternative to augment wild harvest. However, offshore salmon farming can have significant ecological and socioeconomic impacts, and there will have to be tradeoffs between these impacts as the industry continues to grow. Our model offers a tool for salmon farming managers to help predict and manage the industry's impacts by avoiding "trial-and-error" management; tools like this will be crucial as salmon aquaculture increases in intensity and expands to new regions of the world.

Problem Statement

The Chilean salmon aquaculture industry was introduced in the Los Lagos Region in the late 1970's (Barton & Fløysand, 2010). The industry experienced explosive growth, and by 1992, Chile provided more farmed salmon to the world market per year than any other country, second only to Norway (Bjørndal & Aarland, 1999). Initially, the industry provided Chile with increased job opportunities and economic growth, but this rapid growth and weak regulation lead to environmental degradation and poor labor conditions. In 2007, an outbreak of the infectious salmon anemia (ISA) virus in the Los Lagos region led to a drastic decline of salmon production from that country, driving the industry to a near-collapse and leaving substantial impacts on the environment and economy of that region (Barton & Fløysand, 2010).

To reduce the risks of re-infection and further environmental contamination in Los Lagos, the industry has begun to expand to the Magallanes region of Chile (Barton & Fløysand, 2010). This southernmost region contains relatively pristine, sparsely populated fjord ecosystems that currently support tourism, artisanal fishing, and other important ecosystem services (Iriarte, González, & Nahuelhual, 2010). Many stakeholders including the regional government, non-profit organizations, tourism operators, fishers, and local residents are concerned that the expansion of salmon aquaculture will result in undesirable impacts similar to those experienced in the Los Lagos region (Claude & Oporto, 2000; Pinto et al, 2005). However, industry leaders assert that the expansion of the salmon farming industry will bring increased job opportunities and economic prosperity to the Magallanes, and that increased stringency of regulations and monitoring will minimize any negative environmental and social impacts (SalmonChile, 2009).

This industry viewpoint has evidently had influence at the political level. The regional government of the Magallanes (GORE) has responded to this pressure by allowing the implementation of large-scale salmon farming in their region. There are a number of salmon farms that have already begun operations in the Magallanes, and proposals for more are continually being approved (Gobierno de Chile, 2010). Our client, the Wildlife Conservation Society (WCS) of Chile, wishes to collaborate with GORE to establish management practices that minimize the negative impacts of aquaculture in the Magallanes. WCS wishes to support aquaculture strategies that will balance the expansion of the industry with environmental conservation and community livelihoods in this region (Wildlife Conservation Society, n.d.)

Project Significance

The expansion of the salmon aquaculture industry into the Magallanes region has increased interest in re-evaluating some salmon farming practices. There have been many efforts to model the interactions between salmon aquaculture operations and biological and economic systems (Cacho, 1997; Mccausland et al, 2006; Nobre et al, 2009; Sylvia et al,1996); however, bioeconomic models like these have traditionally aimed to optimize production without focusing explicitly on preserving environmental integrity or employee welfare (Pomeroy et al, 2008). Despite the rapid growth of the industry in the Magallanes region and the effects that this escalation will undoubtedly have on the region's ecosystems and economy, there have been no applications of bioeconomic modeling of salmon aquaculture in that region. This project addresses this need by quantifying the complicated interactions between salmon farming practices and their associated impacts and offering an important tool for weighing the environmental and socioeconomic implications of various management decisions.

This project was prompted by WCS's concerns about the potential impacts of expanding the salmon farming industry into the Magallanes region of Chile. WCS anticipates that monitoring and enforcement will prove to be inadequate in the Magallanes as they were in Los Lagos despite recent increases in stringency of national salmon farming regulations (Barton & Fløysand, 2010). They believe that these shortcomings in on-the-ground management will contribute to a lack of incentive for the industry to operate in a way that sustains environmental and socioeconomic well-being. To strengthen these incentives, WCS is interested in providing recommendations on farming practices that minimize environmental harms without jeopardizing the profitability of the industry. This project addresses those trade-offs by offering a model that predicts the extent of impacts that certain aquaculture practices will incur, both on the profitability of farming operations and on environmental and human welfare. Additionally, the results of our analyses are used to develop recommendations to the industry that are beneficial to multiple stakeholders. Ultimately, we hope this model will be used as a tool for developing best management practices and salmon farming regulations that will promote social and environmental sustainability as well as economic profits for the Magallanes region.

Project Objectives

The goal of this project is to assess how the modification of specific salmon farming practices affects a set of environmental and economic outcomes of interest to diverse stakeholders including managers, aquaculturists, environmental groups, Magallanes locals, and others. To do so, we developed a model parameterized with data from the environmental impact statements (EIAs) of approved salmon farm concession proposals and from scientific literature. Farming practices include the length of the harvest cycle, number of chemical treatments, water current speed and depth, equipment quality, and other conditions over which aquaculturists have some control. The outcomes that we considered are Ecosystem Health, Concession Profit, Profits to Tourism, Profits to Artisanal Fisheries, and Probability of ISA Infection. We aim for our analysis to be used by managers, environmental groups, and aquaculturists to identify the tradeoffs in environmental and socioeconomic impacts brought on by different farming practices. In order to provide that analysis, we achieved the following specific objectives:

- Construct a model that links salmon farming practices to various outcomes of interest
- Develop an elasticity matrix that describes how a percent change in each input affects the percent change of each outcome. This analysis allows us to identify the range of outcome values that can be expected from proposed practices, and to identify the inputs that have the greatest effect on each outcome.
- Predict the extent of impacts caused by each approved salmon farming concession in the Magallanes and rank them in terms of their outcome values.
- Identify areas where research to gather more accurate data would lead to the greatest improvement of the model's reliability.
- Develop recommendations to the GORE, the industry association SalmonChile, and aquaculturists on business practices that maximize profitability while minimizing environmental and social threats.

Project Background

Global Farmed Salmon Industry

About 16% of protein consumed by humans worldwide is derived from seafood; however, harvest from wild fish stocks has not been able to keep pace with ever-increasing human population and the associated increase in demand for seafood. This deficit is evidenced in indications that over half of the world's capture fisheries are currently fully exploited, and about 25% are overexploited, depleted, or recovering from depletion (Jiang, 2010).

Aquaculture, or fish farming, has the potential to bolster global fish production without increasing fishing pressure on wild stocks (Naylor & Burke, 2005). This is a welcome prospect in the case of salmon, as demand for this carnivorous species continues to increase, especially in wealthy nations (Naylor & Burke, 2005). In fact, the market for salmon exemplifies the rise of the aquaculture industry: In 1980, wild commercial fisheries produced more than 99% of salmon consumed worldwide (J Eagle, 2004; Naylor & Burke, 2005), but since the advent of large-scale salmon farming in the following decade, this contribution has dropped to about 40%. Meanwhile, production from salmon aquaculture climbed to near 60% of world production. World farmed salmon production surpassed wild harvest for the first time in 1999 (Eagle, 2004). This redistribution of global salmon production has occurred while the amount of wild harvest remains relatively stable, indicating that salmon aquaculture has increased the size of the salmon market. Indeed, the amount of wild and farmed salmon produced worldwide has more than doubled since the mid-1990s, with farmed salmon production at 1,800,000 tons in 2001 (Eagle, 2004).

In addition to being able to produce large quantities of salmon to supplement capture fisheries, salmon farming has several advantages over those fisheries. Aquaculture can be more cost-effective than fishing, and some regions can benefit from the jobs created with the introduction of this industry (Windsor & Hutchinson, 1990). Cultivation also gives the aquaculturist the ability to control the characteristics of the fish produced, ensuring a consistent product. In addition, salmon farming

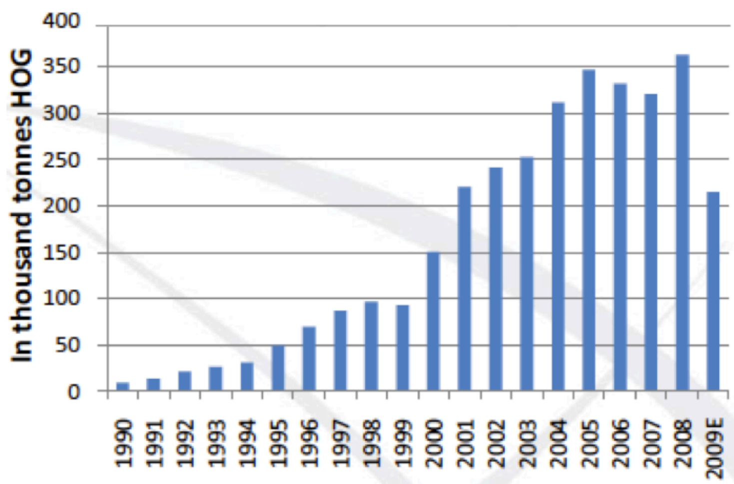


Figure 1: Chilean market of farmed Atlantic Salmon (Marine Harvest, 2010)
HOG: Head On Gutted, 2009 is Expected

allows for year-round production at a pace controlled by the aquaculturist, whereas wild fisheries produce at inconsistent rates through time (Windsor & Hutchinson, 1990). However, there are some serious concerns with large-scale salmon farming with respect to ecological impacts, resource depletion, and human health. As a major player in the global salmon farming industry, it will be in Chile's best interest to make informed decisions about salmon farming in that country.

Development of Chile's Salmon Farming Industry

Southern Chile offers many conditions favorable for salmon farming. For example, water temperatures in southern Chile are warmer on average than Northern

Hemisphere salmon farming nations, leading to comparatively shorter harvest cycles. Their location in the Southern Hemisphere also allows Chilean farms to harvest salmon when Northern Hemisphere farms are out of season (Marine Harvest, 2010). The geophysical structure of southern Chile's expansive coastline also offers ideal conditions for salmon aquaculture, including complex fjord habitats with protected inlets, freshwater input for hatching and growing smolt, and regular tidal flushing. These environmental conditions offer some important competitive advantages of farming salmon in Chile, which contributed to the initiation of the industry in the early 1980s.

Figure 2: Map of Chile – regions of aquaculture

The salmon farming industry in Chile was established with support from the Japanese International Cooperation Agency and the Chilean innovation group, Fundacion Chile in order to stimulate economic growth. The industry was initiated in the Lakes District in the Los Lagos region in the south-central portion of the country (see Figure 2), which offered a stable labor force and ideal environmental conditions (Oyarzun, Campos, & Huber, 1997). When the government first began approving salmon farming operations in 1984, there were few regulations that pertained to this industry (Barton & Fløysand, 2010; Leon-Munoz, Tecklin, Farias, & Diaz, 2007). By the 1990's, Chile's salmon farming industry had grown to become a producer at the global scale: In 1991, Chile produced approximately 10,000 tonnes of salmon, worth US$ 159 million (Ibieta, Tapia, Venegas, Hausdorf, & Takle, 2011; SalmonChile, 2007). Production dramatically increased through 2008, when total harvest peaked at 379,000 tonnes, valued at US$ 2.2 billion (see Figure 1) (Ibieta et al., 2011; SalmonChile, 2007).

This explosive growth provided Los Lagos with important economic benefits, including employment opportunities in this region that previously had one of the country's highest unemployment rates. By the industry's peak in 2008, over 50,000 people were working directly or indirectly for the industry. In turn, Chile's low minimum wage and Los Lagos' large labor force helped to enable the rise of the salmon aquaculture industry in that country (Barrett, Caniggia, & Read, 2002).

Farmed salmon quickly became the second largest Chilean export in an economy historically dominated by copper mining. In 2007, farmed Atlantic salmon exports from Chile made up nearly 40% of US salmon consumption, representing 12.94% of non-mining related exports and 38.75% of food exports from Chile (Ibieta et al., 2011; Knapp, Roheim, & Anderson, 2002). However, the world soon learned about the environmental and socioeconomic issues of Chile's salmon industry in March 2008, when the New York Times published a highly critical article about the country's salmon farming industry (Barrionuevo, 2008). Following this publication, US demand for Chilean salmon dropped over 30%, and the industry found itself unprepared for the crisis that was unfolding. (Barton & Fløysand, 2010; Ibieta et al., 2011)

ISA Crisis

In 2007, an outbreak of the infectious salmon anemia (ISA) virus in the Los Lagos salmon farms led to the near-collapse of Chile's salmon farming industry. ISA is an influenza-type virus that affects only certain species of fish, is highly infectious, and leads to fish mortality (O. Miller & Cipriano, 2003). The ISA virus was first diagnosed in Chile in July of 2007 at two farms owned by the Norwegian company Marine Harvest, the largest global producer of farmed salmon and the second largest exporter operating in Chilean waters (Arengo, Diaz, Ridler, & Hersoug, 2010). The virus quickly spread to farms throughout the region. By December of 2007, ten farms reported ISA infections, eight of which were owned by Marine Harvest, and within a few months, the virus had spread widely throughout the production region (Carvajal, 2009). According to the Chilean subsecretary of fisheries, by March 2009 over one hundred farms were in sanitary rest and all production was postponed (Carvajal, 2009; Sernapesca, 2009).

Chile's salmon farms were at high risk of an outbreak like that which took place in the Los Lagos region in part because of that country's lax regulations regarding farming practices. Some problematic farming techniques included high fish densities in the pens, farms with multiple generations of fish raised concurrently, and farms in close proximity to one another. During this period of industry crisis, the technical manager of Marine Harvest, Adolfo Alvial, admitted that the ISA crisis was a symptom of the greater problem of weak regulation (Carvajal, 2009).

The ISA outbreak amounted to significant socioeconomic impacts, including the loss of 20,000 jobs by July 2009, and approximately US$ 3 billion between 2008 and 2011 (Arengo et al., 2010; Asche, Hansen, Tveteras, & Tveteras, 2010; Soares, Green, Turnbull, Crumlish, & Murray, 2011). Farmers also lost profit when they harvested their stock at lower fish weights in anticipation of ISA infection. In 2008, the average harvest weight per fish dropped to 2.5 kg compared to the average historical weight of 4.5 kg (Barros, 2010). Although farmed salmon stocks in Chile decreased through 2009 to about one tenth of their peak numbers, they have since begun to rebuild, even in the Los Lagos region (Asche et al., 2010; Ibieta et al., 2011).

Shift to the Magallanes

After the ISA crisis in Los Lagos, the Chilean government imposed a two-year moratorium on issuing salmon farming permits in the Magallanes region to the south, where a few farms were already operating. Similar to Los Lagos, the Magallanes region offers ideal environmental conditions for salmon production; in contrast to Los Lagos, this region is characterized by pristine coastal environments and sparse human population. The Magallanes also has a skilled labor force with a rich tradition in fishing. However, the unemployment rate in the Magallanes is extremely low, limiting the available workforce (Gobierno de Chile, 2010). Currently, tourism is the main economic activity in the Magallanes. Because many tourists visit this region to experience the rich natural environment, the expansion of the salmon aquaculture is seen as a potential threat to that economic activity (Gobierno de Chile, 2010).

The Chilean government, eager to rebuild the economically important salmon farming industry, lifted the moratorium in 2011; since that time, 28 salmon farming permits have been approved in the Magallanes region (SEIA, 2012). The national government aims to gradually release 200 salmon farming concessions and create 3,000 new jobs by 2014 (Gobierno de Chile, 2010). Salmon farming companies are responding to the opportunity as well, as evidenced by the 1,644 applications received by November of 2010 (Gobierno de Chile, 2010).

Despite government and industry support, there are some major challenges involved in this expansion to the Magallanes. Perhaps most importantly, building the required infrastructure and supporting industries in this sparsely populated region will require a great deal of effort due to the small amount of existing infrastructure in this region (Ibieta et al., 2011). Building infrastructure will amount to large start-up costs, which will be coupled with high costs of transportation to and from this geographically isolated region (Asche & Bjorndal, 2011). There are environmental and socioeconomic hurdles to overcome in order to establish this industry in the Magallanes region; nevertheless, the high demand for farmed salmon could lead to a profitable industry.

Salmon Farming Practices in Chile

The salmon farming process in Chile is carried out in five main stages: freshwater, saltwater, harvesting, processing, and distribution (Marine Harvest, n.d.). Salmon eggs are harvested in freshwater, where they develop for 12 to 18 months before being transferred into saltwater cages. Once the salmon reach the developmental stage of smolt, they are transferred into floating offshore net pens in saltwater fjords, channels, and waterways (Marine Harvest, 2010). This is the farming stage on which our project focuses. In southern Chile, salmon farms are implemented in spatially explicit clusters called “concessions”. Salmon aquaculture concessions may only exist within Appropriate Areas for Aquaculture, or AAAs, which are larger coastal areas identified by a commission comprised of Subpesca and other governmental groups. Each concession is leased by a single aquaculture company, and can contain many farms in any configuration within the concession. Each farm in turn is composed of a collection of net pens that hold the salmon (see Figure 3).

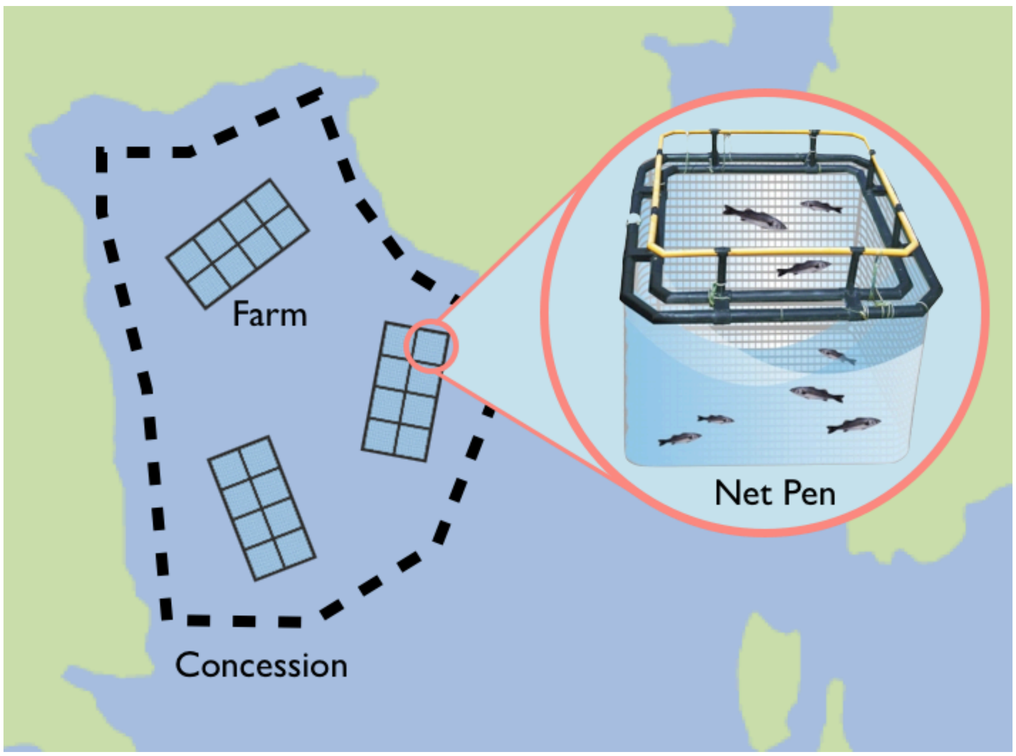


Figure 3: A concession, farm, and net pen

Net pens are made of a combination of steel and plastic, and vary in size, shape, and depth. Generally, net pens are either rectangular or circular in shape, and the number of net pens in a farm can vary, depending on the size of the harvest capacity of the concession. Many farms contain between 8 and 32 net pens. In the net pens, the salmon are kept at stocking densities around 15–25 kg of salmon per cubic meter of water (Marine Harvest, 2008), and are fed several times per day, with feed dispersed mechanically or by hand. Once they reach their market weight of 4.5-5.5 kilograms (normally 12 to 18 months after entering the net pens), they are harvested and transported to a processing facility to be prepared for distribution (Marine Harvest 2010).

The labor force on salmon farms is comprised of SCUBA divers, facility managers, and general laborers responsible for maintenance, feeding, and other aspects of the daily operations. The number of workers employed on a farm varies depending on the size of the farming operation, with common employment between 5 and 40 people. These positions can be permanent or temporary, with SCUBA divers generally being hired as subcontractors. Many salmon farm workers come from rural backgrounds, and relocate to salmon farm sites from great distances (Arengo et al., 2010).

Environmental Impacts

Offshore net-pen salmon farms can lead to a variety of impacts on the surrounding marine environment. The most commonly identified environmental impacts of offshore salmon farming result from nutrient pollution, escaped salmon, chemical use, interaction with predatory birds and marine mammals, and the dependency on wild fish and other products to make salmon feed (Nash, Brubridge, & Volkman, 2005; Ocean Conservancy, 2011). While all of these potential impacts are worth consideration, some have greater relevance in the Magallanes region of Chile due to this region's unique set of ecological and political circumstances.

Nutrient Pollution

Nutrient pollution from salmon farms has the potential to cause significant impacts on marine ecosystems. Nutrients (especially carbon, nitrogen, and phosphorous), sunlight, and oxygen comprise the three main building blocks of primary production of marine plants like phytoplankton and algae (C. B. Miller, 2004). Marine primary producers can grow and reproduce until they become limited by the depletion of one of those three ingredients. Whether sunlight, nutrients, or oxygen is limiting depends on the background conditions in the particular marine environment, which can fluctuate over space and time and respond to environmental and anthropogenic perturbations (Smith, Tilman, & Nekola, 1999).

When marine primary producers are nutrient-limited, their productivity is limited by the availability of an individual nutrient. Marine primary producers generally require carbon, nitrogen, and phosphorous in a ratio of 106:15:1 (C. B. Miller, 2004) in order to grow and reproduce. In marine systems, nitrogen (N) is commonly the limiting nutrient, meaning that primary producers tend to deplete N resources before carbon and phosphorous resources are drawn below their required concentrations (Smith et al., 1999). In these N-limited environments, the addition of N to the system stimulates rapid growth of primary producers until sunlight, oxygen, or another nutrient becomes limiting.

Nitrogen is delivered to the marine environment from salmon farms primarily by way of uneaten food pellets and salmon feces. Liquid waste from employee quarters and organic matter from fouling organisms on the net pens can also lead to nutrient loading from salmon farms, but these two sources contribute comparatively insignificant amounts of nutrients (Nash et al., 2005). It is common practice for farmed salmon to be fed by distributing pellets over net pens, either by hand or more commonly by an automated machine, two to three times per day (K. Brooks, 2003); any pellets that are not consumed fall through the open net weave and sink to the sea floor (Islam, 2005; Kutti, Hansen, Ervik, Høisæter, & Johannessen, 2007). The proportion of feed lost has been considerably reduced over the past few decades, with losses generally less than 5% with modern feeding technology (K. Brooks, 2003). Of the feed consumed, salmon are expected to excrete about 15% in the form on feces (Salmon Aquaculture Dialogue, 2010). The C:N ratio in salmon feces has been found to be around 5:6, with variation depending on the type of feed blend used (Chen, Beveridge, Telfer, & Roy, 2003). This ratio demonstrates the contribution of farmed salmon feces to elevated N concentrations in the marine environment that can stimulate primary productivity.

Although both the amount of fish in the farm and the amount of feed delivered influence the total effect of nutrient enrichment, the factors with the greatest influence on nutrients' effects are water depth and current speed (K. Brooks, 2003), which can vary widely between salmon farming sites. These two factors weigh greatly in determining the distance that nutrient-laden particles travel from the farm before settling to the seafloor. The settling rate of these particles also plays a part in determining the dispersal distance of that particle, but this rate is less variable among farms than currents and depth. The combination of local currents, settling rates of food pellets and feces, and water depth determines the size of the area impacted by nutrients from salmon farms and the distribution of varying nutrient concentrations on the sea floor (Silvert & Sowles, 1996).

Salmon feed settling rates have been reported between 8-11 cm/sec, and feces settling rates are a slower 2-8 cm/sec due to their lower density (Chen et al., 2003; Hevia, Rosenthal, & Gowen, 1996; Tironi, Marin, & Campuzano, 2010). Empirical evidence shows that nutrient loading from salmon farms is greatest directly under and in the immediate vicinity of the farm, with concentrations diminishing with increased distance (Black, Hansen, & Holmer, 2008a; K. Brooks, 2003; Islam, 2005). Therefore, salmon farms located in areas of faster currents and/or deeper water can result in lower nutrient concentrations on the sea floor due to greater dilution. These conditions can lead to moderate impacts over relatively large areas. Conversely, farms in areas of slow currents and/or shallow water can be more prone to acute effects over smaller areas because the nutrient effluent is concentrated within in the immediate vicinity of the farm.

Primary productivity stimulated by N enrichment from salmon farms can lead to a chain of processes that can affect the ecological structure of the enriched marine environment. In the presence of increased N in a previously N-limited environment, primary producers flourish until sunlight, oxygen, or another nutrient becomes limiting. At low to moderate levels, N enrichment can stimulate growth that supports elevated abundance and/or species richness (Kutti et al., 2007). However, the impacts of high levels of nutrient enrichment can cause adverse impacts on marine biota (Kutti et al., 2007; Marine Aquaculture Task Force, 2007; Nash et al., 2005). Eventually the algae and phytoplankton resulting from this bloom dies and sinks to the sea floor, where they are decomposed by aerobic bacteria. Increased metabolism by these benthic bacteria requires increased amounts of oxygen, leading to depleted oxygen concentrations, and, in extreme cases, anoxia (Smith et al., 1999). Since all coastal marine organisms depend on oxygen, oxygen depletion leads to death or relocation of marine species that previously inhabited the affected area (Smith et al., 1999). Although some hearty species may persist in hypoxic or anoxic waters, oxygen depletion causes changes in species assemblages. Species diversity and abundance generally decline with increasing oxygen depletion (Goldburg, Ellion, & Naylor, 2001). Such changes in species assemblages induced by nutrient loading from salmon farms can disrupt local ecology and have adverse impacts on the resources on which humans depend for livelihoods and sustenance, including wild fish and benthic animals like mussels and clams.

Escaped Salmon

Another primary concern about large-scale offshore salmon farming are the salmon that escape into the surrounding environment (Buschmann et al., 2009). Salmon farms in Chile have historically reported far higher escape rates than other countries, with more than 10 million Atlantic salmon escaping into Chile's coastal waters every year ("Farmed Salmon Escapes," 2012). Escaped farmed salmon can lead to three main impacts on native ecosystems: the spread of disease and parasites across great distances; predation and competition with native species; and diminished genetic quality of wild populations by interbreeding with native salmon (Rosamond Naylor et al., 2005). Escapes also incur negative economic consequences to aquaculturists when they lose large numbers of fish, which translates into loss of profit. Additionally, some argue that escaped salmon carry human health costs, since they may be consumed by native fishery species or caught by artisanal fishermen and eaten by people before the antibiotics used on the farm have had adequate time to dissipate. However, these effects are difficult to trace and have not received great attention in the literature (WWF, 2009).

Escaped salmon pose a threat to wild species by transmitting diseases and parasites that flourish in the salmon farm environment. New diseases can be introduced into salmon farms through imported smolt or feed, but farms can also amplify concentrations of native diseases and parasites, which breed in the densely packed net pens (Buschmann et al., 2009; Ocean Conservancy, 2011). There is evidence that sea lice – copepods that attach to and feed on the skin of salmon and other fish – have infected wild fish populations in coastal Chile (Buschmann et al., 2009). Researchers have also found evidence in central Chile's wild marine life of various diseases associated with salmon aquaculture including Furunculosus, Infectious Pancreatic Necrosis (IPN), Rickettsial Septicemia, and ISA. While the source of these diseases is difficult to discern, correlative evidence suggests that they can be traced to salmon aquaculture operations in central Chile (Jensen, Dempster, Thorstad, Uglem, & Fredheim, 2010; Rosamond Naylor et al., 2005; WWF, 2009).

It should be noted that increased attention has been given to the allowable density of salmon in Chile's farms since the 2007 ISA crisis, as evidenced in the maximum fish densities reported in the Magallanes EIAs. Nevertheless, escaped salmon, which may be more likely to be infected with diseases or parasites than wild populations due to their relatively denser living conditions, can drive high transmission rates to wild species (Ocean Conservancy, 2011). Disease transmission to wild species can also occur in the absence of escapes by way of water movement through the net pen system, but with escaped salmon as a vector, disease and parasites can be transported farther into the native marine ecosystem (Jensen et al., 2010; Soto, Jara, & Moreno, 2001).

In addition to increasing the likelihood of spreading disease, escaped salmon threaten marine ecosystems by preying on native species and/or competing for habitat and food. It is difficult to tease apart the combined impacts of escaped salmon on native species resulting from disease, competition, and predation, especially in a region with as little baseline ecological information as southern Chile. However, one study following a catastrophic escape event in Chile suggests that escaped salmon reduced native fish populations through competition and/or predation (Buschmann et al., 2009). It is unlikely, though, that escaped Atlantic salmon are able to establish persistent invasive populations in southern Chile due to their specialized food preferences and the region's inhospitable environmental conditions (Soto et al., 2001). Southern Chile has no native salmon populations, so one of the main concerns with salmon farming – the threat of diminishing the genetic quality of high-value wild salmon through interbreeding – does not apply to this region of the world.

Escapes can enter the environment by way of low level "leakage" through holes in the netting and loss during maintenance, and large-scale escapes due to weather-related events (Rosamond Naylor et al., 2005). The two main factors affecting the escape rates of farmed salmon are the type of the cage technology (particularly its ability to withstand strong currents and major storms), and the amount of human error during routine site maintenance and fish handling (Buschmann et al., 2009; WWF, 2009).

Since the inception of Chile's salmon farming industry in the early 1980s, there have been significant improvements in the quality of aquaculture technology, the amount of required staff training, and the engineering of farming facilities based on site-specific currents and other geophysical conditions. When the industry first emerged in central Chile, it was largely carried out by individuals and small companies that used discarded fishing nets and foam and plastic debris to construct floating salmon pens (Kol, pers. Comm., 2011; Molina, pers. Comm., 2012). At that time, nets were weak and prone to fouling, which resulted in the build-up of feces, feed, and chemicals within the pens as the net holes became obstructed (Molina, pers. Comm., 2012). In addition, the locations of farms were determined based on logistical considerations, such as proximity to ports, without consideration for local bathymetry or currents (Jensen et al., 2010), and nets were moored to the sea floor at two ends only. The combination of these design characteristics led to the net pens being prone to tipping and capsizing during strong currents or storms, resulting in high escape rates (Molina, pers. Comm., 2012).

As the industry began to expand and larger corporations, including foreign enterprises, entered the market, the industry saw rapid advances in farm technology and design. Aquaculturists began purchasing nets manufactured specifically for salmon farming that were built to better withstand snagging and tearing from attacks by native predators like sea lions (Molina, pers. Comm., 2012). Later, the practice of painting or impregnating the nets with antifoulant chemicals became commonplace. This practice serves to increase water flow and reduce the need for cleaning and maintenance, activities that introduce opportunities for human error that lead to fish escapes (Molina, pers. Comm., 2012). Around this same time, the use of predator nets became common practice in Chile. Predator nets consist of an additional netting layer outside of the salmon containment net to protect against sea lions, and a second net covering the top of the pen to inhibit invasion by sea birds. Over time, these nets have been improved to better protect farmed salmon while also reducing incidental mortality of native predators (WWF, 2009).

The next major advance was to increase the number of moorings per farm and arrange them in grid or ladder patterns so that farms were connected to the sea floor at regular intervals around their entire perimeter. These improved mooring techniques reduced the risk of tipping and capsizing, thus reducing salmon loss during extreme weather events and strong currents (Jensen et al., 2010); Molina, pers. Comm., 2012).

Additionally, aquaculture companies began to invest in scientific studies to assist in the engineering of their farms to best fit local geophysical conditions, thereby minimizing drag on the nets from currents. The quality of these studies has continued to improve such that the modern design and placement of farms is meticulously engineered to balance the benefits of high water flow while reducing the risk of capsizing (Jensen et al., 2010); Jensen, pers. Comm., 2012; Molina, pers. Comm., 2012). With each of these technological advances, increased staff training has been implemented with the intent of reducing salmon escapes. Greater emphasis on employee training leads to increased profitability of the farms and reduced impacts on the surrounding coastal environment (Molina, pers. Comm., 2012).

Chemical Pollution

Chemicals including pesticides and antifouling paints are used in aquaculture to maintain fish health, thereby increasing farm profits. Pesticides like SLICE® are applied to control diseases and parasites that might otherwise flourish in the salmon farm environment (Ocean Conservancy, 2011). Antifouling paints are used on net pens to prevent the establishment of fouling organisms like barnacles and algae that slow the flow of water through the nets, thereby threatening salmon health. Other important chemicals are also used on salmon farms include disinfectants, antibiotics, and detergents. Salmon aquaculturists use these chemicals to control the spread of disease and parasites both within individual farms and between separate farms (Burridge, Weis, Cabello, & Pizarro, 2008). The potential for infection to spread between farms is of great concern to salmon farmers; the consequences of poor disease control were seen in the 2007 collapse of the Chilean salmon farming industry as a result of the ISA virus (Aldrin et al., 2011).

The chemicals used to suppress the spread of disease and parasites, while protecting farmed salmon and – to some extent, wild fish – from infection, can have adverse effects on native marine life (Nash et al., 2005). Pesticides are perhaps the most toxic chemicals used in salmon aquaculture, and have become widespread due to the need to control sea lice (Ocean Conservancy, 2011). SLICE, one of the pesticides used most commonly in Chilean salmon aquaculture to combat sea lice, is composed of the active ingredient emamectin benzoate and an assortment of inert chemicals. SLICE is administered in salmon feed, and as a result, those chemicals are released into the marine environment when uneaten feed pellets sink through the net pen walls. Additionally, the fish metabolizes less than 80% of SLICE. The residual chemicals that are not metabolized are therefore excreted into the environment by way of feces (River, 2007). Chemical residues from pesticides like SLICE have been shown to harm marine life, especially on the early life stages of shrimp, lobster, and other crustaceans (Ocean Conservancy, 2011). In a region with a productive crustacean fisheries such as the Magallanes, the effects of chemical pollution have the potential to cause socioeconomic consequences that reach beyond the aquaculture industry (Oficina Tecnica de Borde Costero, 2011).

Parasites such as sea lice are not the only type of infection that farmed salmon face; fouling by algae and invertebrates of the woven net pens also poses a threat to farmed salmon health by decreasing the water flow that acts to cleanse the farms of waste and replenish dissolved oxygen needed for fish respiration (Burridge et al., 2008). Paints containing copper compounds that act as antifoulants are commonly used to deter these organisms from colonizing (Buschmann et al., 2009). In southern

Chile, net pens are usually removed from the water and repainted once every 6 months, and copper precipitates found in the sediments in the vicinity of salmon farms are assumed to have leached from these painted nets (Buschmann & Fortt, 2005). These heavy metal precipitates have been associated with loss of biodiversity in the benthic environment surrounding salmon farms (Buschmann & Fortt, 2005). Copper is especially toxic to the embryos and gametes of marine species, an effect that can have widespread effects on marine ecosystems (K. M. Brooks & Mahnken, 2003). Alternative water-based antifouling paints are available, but have comprised only a small portion of total antifoulant sales in Chile (Bravo et al., 2005).

Another class of extensively used chemicals comprises the antibiotics used to stave off diseases. Salmon farmers in Chile have historically used antibiotics to an extent that far exceeds their use in other salmon farming nations. Although the effects are difficult to measure, this country has received criticism for the potential impacts on the environment and humans of excessive antibiotic use (Buschmann et al., 2009). When administered through feed, antibiotics enter the marine environment virtually unchanged by way of feces, which can lead to antibiotic resistance in marine bacteria. Bacteria resistant to the chemical oxytetracycline, which is used to prevent bacterial pathogens, are common in the waters surrounding salmon farms in Chile (Miranda & Zemelman, 2002). There is concern over the possibility of transferring antibiotic-resistant bacteria to humans who consume farmed salmon that are treated with, or wild fish that are exposed to, antibiotics (Ocean Conservancy, 2011).

The spread of disease and parasites between salmon farms can be driven by water movement and operational procedures (McClure, Hammell, & Dohoo, 2005; Scheel, Aldrin, Frigessi, & Jansen, 2007). The distance between farms influences the probability of an infection spreading from one farm to another, with more closely-spaced farms at higher risk of transmission (Jarp & Karlsen, 1997; Scheel et al., 2007). Operational procedures that can lead to the spread of infection between farms include duties that require personnel or equipment to move between farms. For example, divers that clean the net pens and remove mortalities commonly service more than one farm during a day, and can therefore act as a vector for disease transmission by transporting viruses and parasites like sea lice on their gear (McClure et al., 2005; Scheel et al., 2007). In addition, the biomass of salmon contained in a farm has an impact on the susceptibility of viral, disease, and parasite infection, with greater biomass resulting in an increased probability of transmission between farms (Scheel et al., 2007).

Physical Interaction with Marine Predators

High concentrations of captive fish, fish feed, and the physical structure of offshore salmon farms attract a range of coastal predators including sea lions, fish, and marine birds (WWF, 2009). Sea lions can be attracted by farmed salmon, as well as by the wild fish that are also drawn to the farms, and become entangled in net pen nets and drown. This effect has been observed in Chile, where salmon farming has led to increased mortality of sea lions (Ocean Conservancy, 2011). Diving birds such as cormorants and herons suffer a similar fate when they dive into open net pens in hopes of feeding on the aggregation of farmed fish (Nash et al., 2005). In Chile, sea lions are at even greater risk because farm workers have been known to harass and even shoot and kill sea lions that attempt to damage nets or consume farmed salmon (Nash et al., 2005). Some salmon aquaculture facilities in Chile employ acoustic deterrents to keep marine mammals away (EIAs). However, these deterrents have been shown to damage the hearing capabilities of marine mammals as well as alter feeding and breeding regimes (Ocean Conservancy, 2011).

The threats from entanglement and lethal deterrents have diminished in Chile over recent years due to the introduction of predator nets (Molina, pers. Comm., 2012). These nets keep sea lions away from caged salmon, reducing the risk of entanglement and effectively eliminating the need for aquaculturists to use firepower to keep the predators from endangering their farmed stock (Buschmann et al., 2009). Similar nets installed over the top of salmon net pens keep diving birds at bay (Molina, pers. Comm., 2012).

Farmed Salmon Feed and Resource Depletion

A fundamental goal of aquaculture is to relieve harvesting pressure from wild fish stocks, but this goal can be hampered by aquaculture's reliance on marine fish as a component of feed (Buschmann et al., 2009). As predatory species, salmon require a large amount of animal protein, essential amino acids, omega-3 fatty acids, vitamins and minerals, and energy to live and grow. In the wild, salmon acquire this diet primarily by preying on small fish (Buschmann et al., 2009). To satisfy these dietary needs in farmed salmon, forage fish including sardines, menhaden, and anchovies are harvested in great quantity to supply the global aquaculture industry with the fish meal and oil that are primary ingredients in fish feed. With about 30% of the world's wild fishery landings turned into fish meal and oil, some argue that wild stocks of forage fish are in jeopardy of over-exploitation as a result of the rise of aquaculture (Ocean Conservancy, 2011). It is not currently well known how large-scale harvest of pelagic forage fish affects marine ecosystems, but what is understood is that these small fish play the important ecological role of transferring energy from their prey, plankton, to larger marine fish and marine mammals (Ocean Conservancy, 2011). Therefore, over-exploitation of wild forage fish stocks for the purpose of feeding farmed salmon has the potential to alter marine ecosystem functioning and undermine efforts to alleviate pressure on wild stocks.

Although wild salmon rely on smaller prey fish to fulfill their dietary needs, farmed salmon feed is not comprised entirely of fish products; non-fish animal-derived meals and plant products can supply some of this protein requirement (Goldburg et al., 2001). Over the past decade or so, salmon feed developers have responded to industry needs and the limitations of wild fish stocks by developing feed blends that minimize the amount of wild fish content (Goldburg et al., 2001). At present, many Chilean salmon farmers prefer blends composed of a mix of vegetable (43%), animal (15%), and fish (42%) meals and oils. This mix offers a balance of relatively low cost and sufficient nutrition (Ocean Conservancy, 2011).

The high nutrient content in these dry feed blends, coupled with improved management practices, has enabled some Chilean salmon farmers to achieve an economic food conversion ratio (FCR) of as low as 1.2:1 (Salmon Aquaculture Dialogue, 2010). This means that 1.2 units of feed are purchased for every unit of salmon produced (and as such, lost feed, salmon escapes, and mortality are incorporated into this ratio). This is a significant improvement over Chile's common FCR of 1.9:1 reported in 1997 (Salmon Aquaculture Dialogue, 2010), an improvement that was achieved by altering feed composition ratios and developing feeding technologies to reduce feed loss. Two technologies used in Chile to reduce the amount of feed loss are automatic feeders that apply specific amounts at appropriate times of day, and underwater cameras that allow aquaculture employees to monitor feeding activity and stop adding feed when fish are satiated (Salmon Aquaculture Dialogue, 2010).

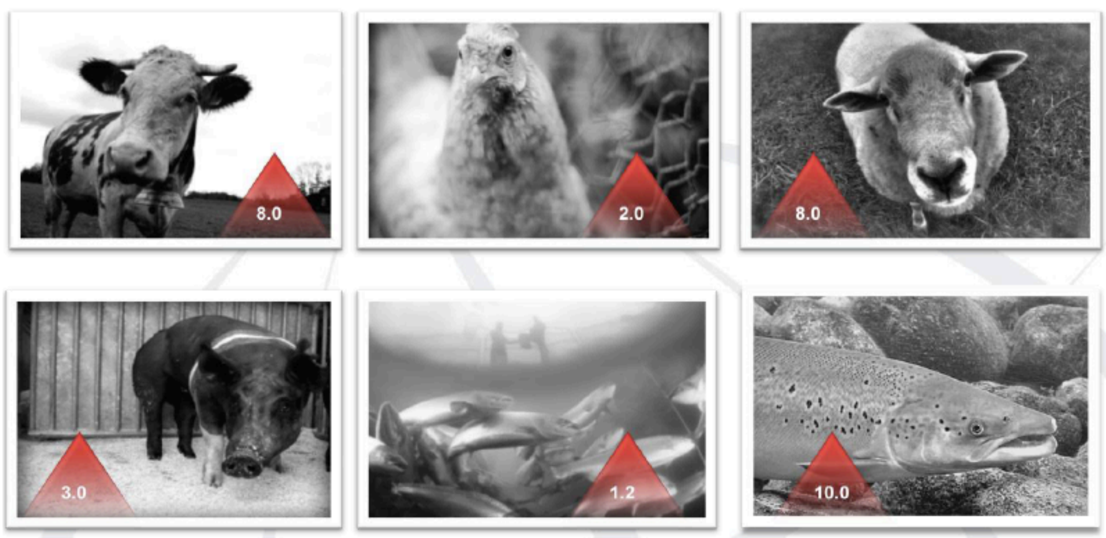


Figure 4: Feed Conversion Ratio Comparison of various livestock species (Marine Harvest, 2010)

Despite these improvements, not all FCR's in Chilean aquaculture facilities maintain a FCR of 1.2:1. Generally, they are closer to the national average of 1.3:1, with some as high as 2:1 due to Chile's relative lack of management and high mortality and escape rates (Marine Aquaculture Task Force, 2007). Even Chile's best ratio is less desirable than those in other major salmon farming countries including Norway, which has an average FCR of 1.1 (Marine Aquaculture Task Force, 2007).

However, to put salmon farming in the context of global livestock production, it should be noted that a farmed salmon FCR of 1.2:1 is superior to that of terrestrial farmed species including cattle (8:1), sheep (8:1), pork (3:1), and poultry (2:1) (Figure 4) (Marine Aquaculture Task Force, 2007). Notably, wild salmon have a much higher FCR (10:1) than farmed salmon, which can be attributed in large part to the comparatively greater amount of energy that wild salmon expend to carry out day-to-day actions. On the other hand, farmed salmon is greatly outperformed by farmed herbivorous fish like catfish, carp, and tilapia, whose FCRs are between 0.23:1 and 0.47:1 (Marine Aquaculture Task Force, 2007).

Labor Impacts

In addition to the environmental impacts associated with salmon farming in Chile, the industry has also been characterized by poor worker conditions and repeated labor violations (Marine Aquaculture Task Force, 2007). According to the National Directorate for Labor, about two-thirds of the salmon farming companies in Los Lagos have violated labor laws. Out of a total of 572 programmed inspections between 2003 and 2005, 404, or 70%, found violations of labor statutes (O'Riordan, 2007). The majority of labor violations in salmon aquaculture are related to worker health and safety. Working conditions in Chilean salmon farms have led to higher than average levels of injury and death than those of other industries (SalmonChile, n.d.). In 2005, the accident rate in Chile's salmon farming industry was 10.6%, 3% above the national average and the second highest of all Chilean industries (Asociación Chilena de Seguridad (ACHS), 2005; SalmonChile, n.d.). Facilities that process farmed salmon have demonstrated some of the most dangerous conditions in the industry, where the work can lead to tendinitis, muscle cramping, inflammation, (Allsopp et al, 2008) and fungal infections (Barrett et al, 2002). Although Chilean law requires companies to investigate and mitigate health problems at their facilities, there is little enforcement of these laws, and companies commonly dispute the connection between health problems and working conditions (Barrett et al, 2002)

Chronically low wages are another labor concern associated with Chile's salmon aquaculture industry, with the per capita income of the average salmon farming job at a level near the national poverty line (Arengo et al., 2010; Barrett et al., 2002; Pinto et al., 2005; R. Pizarro, 2006). Wages vary widely depending on position within a company, with managers earning about 100 times the salary of a production line worker (Arengo et al., 2010; Barrett et al., 2002; Pinto et al., 2005; R. Pizarro, 2006). The standard form of payment in the industry is a combination of either hourly wages or a base salary that are below the national minimum wage, plus production bonuses. Those bonuses can bring total payment up to the minimum wage level (Phyne & Mansilla, 2003). This incentive-based system requires high worker productivity to achieve minimum wage standards. This system is likely to result in wage violations because the legal minimum wage may not always be attainable within regular working hours (Arengo et al., 2010).

After health and safety violations, non-compliance with maximum work hours standards results in the second highest number of violations in the Chilean salmon farming industry (Arengo et al., 2010). The most common infractions include: exceeding the maximum of two hours of overtime per day; failure to give two Sundays off per month; and compulsory overtime (Arengo et al., 2010). During peak season at salmon farms, employees work 10-12 hours per day. If an employee misses work for sickness or childcare, he or she might be required to make up the time on Sundays or with unpaid overtime (Arengo et al., 2010). Anecdotal evidence from farm and factory workers in Los Lagos exemplifies the kind of hardships those workers face. Fish packers with the aquaculture firm Yadran claim that, even after 12 years or more with the company, they received minimum wage with no opportunity for promotion (Barrett et al, 2002). According to a trade union organizer, women often have no washroom facilities, and often complain of cystitis. Worker testimony suggests that salmon aquaculture firms do not consider these conditions to be work related, and though the firms are required by law to investigate health conditions and work-related illnesses, there is no enforcement of these laws (Barrett et al, 2002).

Some of these failures to adhere to labor standards can be explained by the lax regulations in place in Chile. The majority of salmon aquaculture firms operating in Chile are foreign-owned, and foreign countries are expected to adhere to the standards of the company's home country even when operating outside of that country. However, lack of oversight in Chile leads some companies to fall short on this expectation. Many foreign-owned companies have received international criticism for the number of violations incurred for noncompliance with labor laws in Chile (Gutiérrez, 2005). A report by Chile's National Labor Directorate for the Chamber of Deputies' Fisheries Committee details some 80 fines incurred by Marine Harvest in the Los Lagos region, with punitive costs amounting to more than $135,000[1] (O'Riordan, 2007). Chile and Norway have both ratified the labor conventions of the International Labor Organization (ILO), and their national labor legislations contain strong labor provisions. However, weak enforcement in Chile has lead to non-compliance by national and international firms (Arengo et al., 2010). In addition, lack of employment alternatives in areas where the industry is developed can undermine the bargining power of employees to seek higher wages and improved working conditions (Arengo et al., 2010).

[1] Calculated based on exchange rate from February 19th, 2012 of 481.17 CLP to 1 USD, accessed on February 19th, 2012 at <http://www.exchange-rates.org/history/CLP/USD/T>

Regulations

The Chilean aquaculture industry is regulated by the national Ministry of Economy, Development, and Reconstruction. Within this ministry, the Under-Secretary of Fisheries (Subpesca) is the administrative authority that grants salmon farming concessions, and the National Fisheries Service (Sernapesca) is the branch of Subpesca that is charged with carrying out control and enforcement on those concessions (Arengo et al., 2010).

The General Fishing and Aquaculture Law (LGPA), which became effective in 1991, replaced all previously existing legislation governing aquaculture (Leon-Munoz et al., 2007). This law, in its amended version, continues to govern salmon aquaculture in Chile today. At its inception, the LGPA required Subpesca to define geographic areas as AAAs within which salmon farming concessions could be granted (Wilson, Magill, & Black, 2009). In 1997, the aquaculture law was strengthened to include the System for Environmental Impact Assessment, which required applicants to submit an EIA as part of proposals for salmon farming concessions. The EIA had the potential to be an effective tool because it required companies to detail their compliance with environmental regulations and describe a plan to monitor and mitigate any impacts on the environment. However, the effectiveness of the EIA was limited because there was no regulatory mandate obligating concession managers to carry out the monitoring or mitigation that they proposed.

The Environmental Rules and Regulations for Aquaculture (RAMA), an amendment to the LGPA passed in 2001, offered the first substantive requirements for assessment, mitigation, and remediation of environmental impacts of salmon farms. RAMA required concession proposals to include a Preliminary Site Characterization, which provided site-specific environmental information and established annual environmental monitoring. This monitoring, which focused on the aerobic conditions in the benthic sediments below net pens, gave regulators the ability to slow or halt salmon production at concessions with low oxygen levels (Ibieta et al., 2011). The effectiveness of RAMA is summarized in a 2005 report by the Organization for Economic Co-operation and Development (OECD), which considered the regulatory system in Chile to be established and influential, but recognized that it lacked financial resources and trained staff. The report also noted that there was no effective way to collect data on the Preliminary Site Characterization and aerobic conditions, which compromised the enforcement and effectiveness of the system (Leon-Munoz et al., 2007; OECD, 2005). Stakeholders including local fishers and other natural resource users also recognized the potential of the improved regulatory system, but lacked confidence in its ability to protect their interests (Wilson et al., 2009).

The weak enforcement that has characterized Chilean salmon aquaculture regulations has led many aquaculture companies to flout local environmental and labor regulations in favor of maximizing profitability (Buschmann et al., 2009). Some other key factors limiting the effectiveness of RAMA include lacks of: consideration for cumulative impacts of many farms in one area; attention to science-based research, and coordination between government and industry (Buschmann et al., 2009).

It could be argued that these shortcomings in aquaculture management contributed to the ISA crisis in 2007 (Barrionuevo, 2008). In a coordinated effort to manage the economic, environmental, and social crisis following that viral outbreak, the national government established a special commission called the Salmon Working Group (P. Carvajal, 2009). This group worked toward reforms in aquaculture regulations in the LGPA pertaining to sanitary conditions, environmental standards, and smolt imports. The Salmon Working Group proposed a set of recommendations to Congress in 2008, many of which were incorporated into the amended LGPA legislation (P. Carvajal, 2009). In addition, SalmonChile, Chile's salmon industry association, established 52 best management practices aimed at avoiding another disease crisis, almost all of which were incorporated into the new regulation (Alvial, 2011). A moratorium was placed on all salmon farming in Chile while this new legislation was being crafted and after it passed. The government gradually began to issue concessions in the Magallanes region after that time.

The amended General Fishing and Aquaculture Law (LGPA) came into effect in April of 2010, and continues to govern the salmon farming industry in Chile. One major change to the new legislation is the establishment regulations on the spacing and timing of concession operations. Concessions are to be separated by a minimum of 1.5 nautical miles, and farms must be at least three nautical miles apart (Ibieta et al., 2011). In addition, fallow periods of three months are required between every 24-month period of continuous production (P. Carvajal, 2009). Another significant change is that concession permits can be revoked for violating specific regulations, including environmental and labor laws (Marine Harvest, 2010; Ovalle, 2010). Also with the new legislation, a framework allows government and industry to collaborate to implement the new directives on environmental and sanitary regulations (Ibieta et al., 2011).

Regulation of Chile's salmon farming industry has improved significantly since the inception of the industry. Despite the industry's self-regulation and lack of attention to environmental and social welfare that has so far characterized Chile's salmon farming regulations, the current regulation shows great evolution stemming from lessons learned during the crisis (Alvial, 2011). Time will tell whether these improved directives will lead to sustainable environmental and socioeconomic salmon farming practices in the Magallanes.

Bioeconomic Modeling of Salmon Aquaculture

A key objective of this project is to evaluate the potential ecological and socioeconomic impacts of salmon aquaculture in the Magallanes region of Chile. Bioeconomic modeling uses conceptual and mathematical models to predict impacts over cross-disciplinary boundaries such as these. For aquaculture, economic modeling allows for a methodological approach to study the interactions between the biological, physical, technological, economic, and institutional components of aquaculture systems, and to identify key linkages between those components (Griffin et al, 1984; Pomeroy et al, 2008). Generally, economic models are applied to aquaculture systems to assess the potential costs and benefits of alternative production strategies, the selection of sites for farming, or varying policy or regulatory frameworks (Jin, 2003; Pomeroy et al, 2008). Specific parameters that are commonly evaluated in economic models for aquaculture assessment include stocking densities, animal behavior and health, use of antibiotics and vaccines, disease resistance, nutritional requirements, feed conversion ratios, growth rates, regulations, and impacts on groups seeking to utilize the same area for other activities (Cacho, 1997; Jin, 2003; Nunes et al, 2011)

Bioeconomic modeling of aquaculture can be tailored to predict the impacts specific to salmon aquaculture. Bioeconomic analysis of salmon farming in the Magallanes will provide managers with a tool to help decide between alternative management strategies and to modify their farming practices to improve impacts on important outcomes of the industry. By integrating various elements of existing economic models and scientific information, this project develops a model with a unique set of inputs and outcomes that link salmon farming practices to their environmental and socioeconomic impacts.

Data Constraints and Project Scope

The large-scale offshore salmon farming industry in southern Chile holds great research potential. In particular, analyses of the effects of this industry could be thorough in two ways: depth, or the level of detail on specific effects, and breadth, or the scope of the project. In other words, increased comprehensiveness would be achieved by delving deeply into each salmon farming impact to maximize accuracy, and by extending analyses to the many indirect influences that this industry has on the economic and environmental conditions of the Magallanes and beyond. These extensive analyses would require enormous amounts of detailed data and modeling that is not within the means of the present study, and so we built some boundaries for this project's detail and scope. While offering a valuable tool for aquaculture managers in the Magallanes, our model is meant to be neither comprehensive nor exact, and should therefore be treated as a framework that predicts effects within conceptual boundaries.

Limited availability of data is a significant hurdle in the way of accurately modeling the exact effects of salmon aquaculture in the Magallanes region of Chile. At present, there is very little background data describing characteristics like biodiversity, nutrient levels, ecosystem services, and regulatory enforcement. Even if this region-wide data were available, the conditions that they describe could vary widely throughout the region, which means that information to the detail level of an individual salmon farm would be necessary to achieve reliable model results.

In addition, there is a general lack of detailed information in the literature describing certain ecological processes. For example, the impact of diseases and antibiotics on wild species is difficult to discern from field studies and, as a consequence, is poorly understood. Without such data, we had to either wager informed estimations based on limited information (as in the case of disease impacts on wild species) or omit the effect from our model altogether when there was not enough information on which to base estimations (as in the case of antibiotics).

In addition to the scarcity detailed information on background conditions and ecological processes, we lacked some types of information about individual approved salmon farms. Specifications like the distance between farms within the same concession were not included in the concession applications. Without this information, we were unable to provide analysis on some important issues such as the cumulative ecological effects caused by many salmon farms in a small area. In addition, we chose to model the impacts of farming practices over the time scale of one harvest cycle, so the cumulative effects over longer time scales are not captured in our model results.

To carry out our project in the face of these difficulties, we constructed our model to incorporate parameters and mathematical relationships describing as many of these areas of uncertainty as we believed were supported by adequate information. These parameter values, while providing basic relationships that we believe to lead to realistic results, can be viewed as placeholders for a time when better information is available. Until then, our results are still valuable, in part because in most cases they predict impacts on the basis of percent change rather than attempting to calculate the actual change in outcome values resulting from particular changes to the inputs. We can also use the model to identify areas where better information will have the greatest leverage in producing reliable model results. A sensitivity analysis of our parameter values identifies the portions of the model that have the greatest impact on the model outcomes; those parameters are the subject areas that warrant research effort for the goal of improving the reliability of the model.

A second important limiting factor to our project is the scope of the impacts that it predicts. The impacts of salmon farming in the Magallanes could be traced many levels into the complex socioeconomic and environmental web that underlies the industry; our analysis focuses in on a central subset of that network. In particular, we model first-order effects on ecosystem health and profits to the tourism and artisanal fishing industries, and on outcomes of interest to the concession proprietor including profit and expected regulatory costs due to violations of labor standards.

Each of the model outcomes predicts an impact within defined conceptual boundaries. Measurement of ecosystem health extends only to the area affected by farm effluent and salmon escapes, and does not include any impacts on the wild fisheries harvested to produce salmon feed. Profits to tourism and artisanal fishing are modeled with a simple relationship based on the change in Ecosystem Health because an in-depth analysis of those two industries is outside the scope of this project. Profit to the aquaculture enterprise is based on the profit that the company can expect to gain from a single concession, but does not incorporate financial transactions after the fish are processed. The expected regulatory cost due to labor violations is based on the number of violations, without speculating on farming companies' behavior in the face of altered management routines like increased auditing.

Even with these constraints on data and scope, our model offers a valuable tool for those interested in the impacts of offshore aquaculture facilities, including managers, aquaculturists, local politicians and resource users, and environmentalists. The model can be used to predict the extent of some important socioeconomic and environmental impacts of implementing a salmon farming facility in a given location based on the specifications provided by the concession proprietor, and to compare the modeled outcomes of many concession proposals. Our model can be used as a framework that offers valuable results on its own, and it can be refined and expanded in the future to improve its accuracy and broaden its scope.

Methodology

The primary aim of this project is to predict the impacts of carrying out salmon aquaculture using different farming practices. This tool can be used to identify changes in farm management that could minimize the negative social and environmental impacts with minimal sacrifices to industry profit. We began by identifying, through extensive literature review as well as stakeholder interviews carried out in Chile, nine "outcomes of interest" which we determined to capture the most important impacts of salmon aquaculture for a variety of stakeholders in Chile. We then created a mathematical model, first in Microsoft Excel and later transferred into MATLAB, that takes nine "inputs" – practices (including environmental conditions) over which aquaculturists have some degree of control – and predicts the effects of various levels of these inputs on the outcomes of interest (see Figure 5).

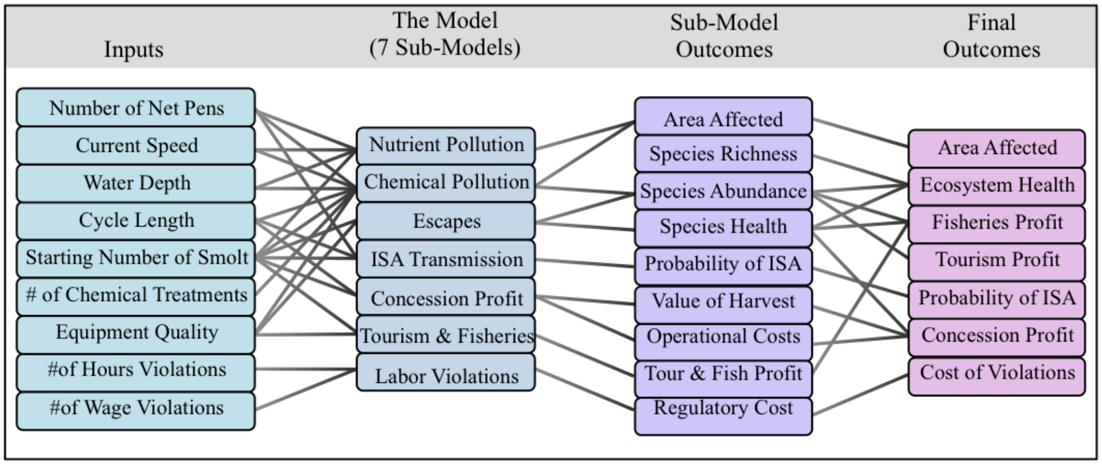


Figure 5: Flowchart describing the steps taken to calculate final outcomes based on input values. Lines indicate dependencies between steps

The model inputs are:

- Number of Salmon Smolt at the Start of the Cycle
- Number of Net pens in the Concession
- Length of Harvest Cycle (months)
- Equipment Quality (represented as an index)
- Number of SLICE Treatments per Cycle
- Number of Wage Violations per Cycle
- Number of Hours Violations per Cycle
- Current Speed (based on farm placement)
- Water Depth (based on farm placement)

The outcomes of interest are:

- Ecosystem Health – an index comprised of the following:
    - Species Richness
    - Species Abundance
    - Species Health
- Area Affected by Pollutants (in square meters)
- Concession Profit (in US dollars)
- Probability of an ISA Transmission (given presence of ISA at a neighboring farm)
- Profits to Artisanal Fisheries (in fractional change)
- Profits to Tourism Industry (in fractional change)
- Expected Regulatory Cost of Committing Labor Violations (in US dollars)

In order to predict the effects of each input on each outcome, we divided the model into seven sub-models: Nutrients, Chemicals, Escapes Based on Technology Used, Concession Profit, Expected Cost of Labor Violations, Probability of ISA Transmission, and Effects on Artisanal Fishing and Tourism. These sub-models, which are described in detail below, use input values to calculate the effects of those inputs on the related outcomes. These sub-models rely on mathematical relationships based on scientific literature and parameter values gathered from the literature and other sources, including the approved salmon farming concession EIAs for the Magallanes.

The Sub-Models

Nutrients' Effect on Ecosystem Health

A sub-model was constructed to predict the effect of nutrients flowing out of salmon farms on the surrounding marine biota. Due to the lack of data on complex biogeochemical processes underlying nutrient limitation in Chilean fjords, we assumed from the outset that N is the limiting nutrient in the waters surrounding salmon farming sites, and that this nutrient continues to be limiting throughout the harvest cycle. Accordingly, this sub-model is built upon a mathematical relationship formulated by Gao et al. (2006) that describes the change in benthic species richness based on the amount of added N density in a marine system near Hong Kong, China. The relationship is:

$$H' = 0.44 + 3.79/TKN$$

where *H'* represents Shannon Index of Species Richness (Shannon, 1948), and *TKN* represents Total Kjeldahl Nitrogen (the sum of organic nitrogen, ammonia, and ammonium). It is assumed that *TKN* comprises all organic and inorganic forms of N originating from salmon food and feces that enter the environment as a result of salmon farms. Because information on the existing species richness in Magallanes coastal waters was not available, we calculated the point elasticity of Gao et al.'s model so that the sub-model outcome will predict the percent change in species richness instead of actual amount of change. We calculated the elasticity at an N concentration of 4.18 mg/g, which is the average N concentration reported by Gao et al. over the course of N loading from salmon farms in that study. The elasticity yields a 2.8% decrease in H' with every 1% increase in excess N.

With the relationship between excess N and species richness established, we estimated the total mass of N entering the marine environment over one harvest cycle in Chile. This equation is essentially the sum of N originating from the two main sources, uneaten food and salmon feces:

$$N_{total} = E \times FE \times NC_{food} \times FCR \times HS + NC_{feces} \times (1 - FE) \times FCR \times HS$$

where *E* is the percent of feed consumed by farmed salmon that is ejected into the environment by way of salmon feces, which is assumed to be 15% (Black et al., 2010). *FE* is the percent of feed applied to salmon farms that is eaten by the salmon, which is assumed to be 97% based on estimates reported in the approved concession EIAs. NC_{food} is the N content of salmon feed by weight, which is assumed to be 6.24 g N/kg feed (Black et al., 2010). *FCR* is the economic food conversion ratio, which is assumed to be 1.25 based on the average of the values reported in the concession EIAs. *HS* is the tonnes of salmon expected from one farm during one harvest cycle. This value is calculated by dividing the tonnes of harvestable salmon estimated in the Harvestable Salmon model (described below) by the number of farms in the concession. Because we did not have information on the number of farms in each concession, we estimated the number of farms using the number of cages in the concession (as reported in the EIAs), assuming that each farm is composed of 8 cages. NC_{feces} is the percent N content by weight in salmon feces, which is assumed to be 6.5% (Barton, 1997).

Next, we incorporated the spatial effects of particle movement due to water currents and depth to predict the farthest distance N travels in the direction of the prevailing current before reaching the seafloor. This distance, *d*, is assumed to be the maximum distance that particles containing N travel in the direction of the current. It is also one of the terms necessary to calculate the size of the total area of benthic environment over which N is distributed, or the "impact area". This dispersal model is based on an equation posited by Silvert & Sowles (1996),

$$d = \frac{CS \times D}{\frac{SS_{feces} + SS_{feed}}{2}}$$

where *CS* is current speed, *D* is water depth, and *SS* is settling speed. Average current speed and water depth measurements were obtained from approved concession EIAs for the Magallanes region. Settling speeds for salmon food pellets and feces were estimated by calculating the average settling speeds reported in two studies (Chen et al., 2003; Tironi et al., 2010). We used the average of the settling speeds of feed pellets and feces from these two studies to estimate the settling speed of all nutrient-containing matter entering the marine environment from salmon farms.

Next, we estimated the amount of N reaching the seafloor at varying distances from the farm within the impact area. N deposition was assumed to follow a normal distribution, with decreasing N loading at increased distances from the pen. Although non-normal distributions that result in N loading concentrated away from the net pen may arise from complicated local patterns in fluid dynamics, this assumption is based on empirical and modeling studies that describe organic matter dispersion from salmon farms that is concentrated near the farm and diminishes with increasing distance (Black, Hansen, & Holmer, 2008). The impact area was divided into elliptical rings, each separated by 5 m on the major axis, that radiate from the point that represents the farm. For mathematical purposes, the farm is assumed to be at the center of the ellipse, although the farm is actually located at the end of the ellipse that is in the lee direction of the current; these two farm positions result in identical numerical outcomes. Therefore, *d* is equal to twice the length of the major axis of this elliptical impact area. We next used a cumulative distribution function for our normal distribution with a mean of 0 and standard deviation of 1/6*d* to determine the proportion of the N effluent that falls within each elliptical ring. We multiplied that proportion by *N* to find the actual amount of N falling within each ring.

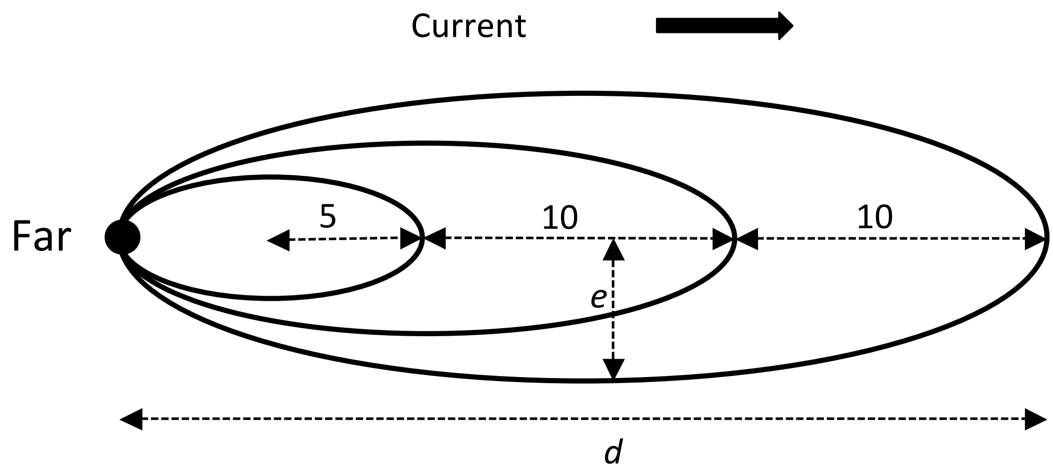


Figure 6: Diagram of pollution dispersal. Conceptual diagram of the dispersion model in a hypothetical location with a maximum dispersal distance (*d*) of 30 m. The 10-m spacing between rings reflects the placement of the farm at the left of the impact area ellipse instead of in the center.

Because the relationship presented by Gao et al. (2005) depends on the density of N in marine sediments, we calculated the N density added to each ring as a result of the salmon farm. These calculations were based on the area and volume of each elliptical ring, the background N density, and the density of the marine sediment. Ring areas were calculated using *d* and *e*, the distance of particle diffusion in a direction perpendicular to the current direction. The distance *e* was calculated using a modified version of the equation used to calculate *d*:

$$e = \frac{\ln(CS) \times D}{\frac{SS_{feces} + SS_{feed}}{2}}$$

The modification of incorporating the natural log of CS reflects the tendency for particles to diffuse farther in the directions perpendicular to the current when currents are slower, and travel less distance in these directions when currents are faster. See Figure 6 for a conceptual diagram of the dispersion model. Ring volumes were calculated using the ring area and Gao et al.'s sediment sampling depth of 14 cm, and the background density was assumed to be 3.25 mg/g as reported by Gao et al. for Hong Kong marine systems. This background N density is a reasonable estimation of that found in Chile based on the similar density found in a study performed off of Conception, Chile (Farías, 2003). The density of marine sediment was assumed to be equal to the standard density of dry sand, 2.00 kg/m3 (ASI, n.d.) based on a study showing that shallow to mid-depth benthic substrates in the Strait of Magellan are composed mostly of sand (Montiel, Quiroga, & Gerdes, 2011).

The total and background N densities were used to calculate the percent change in N density experienced by each ring as a result of the salmon farm. Next, we used the elasticity of -2.8 to calculate the percent change in species richness in each ring. The percent change in species richness was capped at -100% such that, in any ring for which this calculation resulted in a change in species richness of <-100%, the result was assumed to be -100% because any greater decrease in species richness would be impossible. We then added the negative percent change in species richness in each ring to 100 to determine the percent of species richness remaining in each ring.

We calculated each ring's contribution to the overall species richness remaining within the entire impact area by multiplying the proportion of the impact area each ring comprises by the percent of species richness remaining in that ring. Finally, we calculated the sum of those weighted contributions to find the total

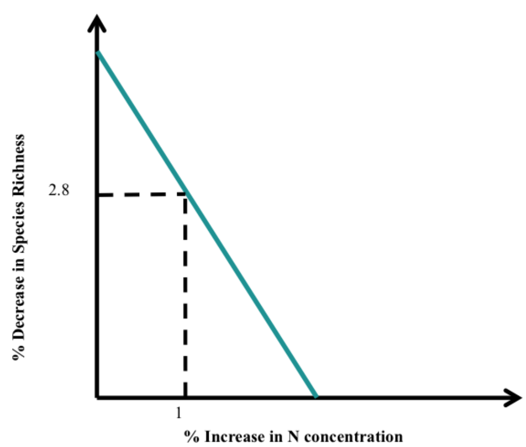


Figure 7: Nutrients' effect on Ecosystem Health

percent of species richness remaining throughout the impact area. Because the interpretation of this outcome relies in part on the size of the impact area that varies depending on current speed and water depth, the sub-model result was standardized by reporting the size of the impact area and the percent species richness remaining within 100 m of the farm in the direction of the current. Standardizing in this way also allows for comparison between this outcome and those of the SLICE and copper sub-models, and between impacts that occur over different sizes of areas. This sub-model outcome was combined with the sub-model outcomes describing chemicals and disease impacts to calculate the Ecosystem Health final outcome. Figure 7 illustrates the sub-model's impacts on the outcome of Species Richness.

Chemicals' Effect on Ecosystem Health

To describe the impacts of chemical use in salmon farms on the marine environment, we modeled the effects of the common pesticide SLICE® and copper-based antifouling paints. We selected these two chemicals to model due to their extensive use in Chile and the availability of relevant data (Bravo et al., 2005). The goal of this sub-model is to describe the impacts of varying amounts of these chemicals on benthic species in the area surrounding salmon farms.

Calculating Total SLICE Input

First, we calculated the amount of chemicals that enter the marine environment and become distributed on the sea floor as a result of salmon farms in Chile. Similar to the Nutrients model, we chose to focus our model on the impacts of chemicals on benthic species. The amount of SLICE per treatment is calculated using the common dosage of 50 micrograms per kilogram of fish for seven consecutive days (River, 2007). Therefore, the total amount of SLICE used per cycle is:

$$Total\ SLICE\ Input = W \times N_f \times D \times S$$

where W = the weight of one salmon, N_f = total number of fish per farm, D = dosage of SLICE, and S = number of treatments per cycle. For W, this model calculates the average weight of one salmon over the length of the cycle by averaging the weight of individual fish in each month from the Harvestable Salmon model. Therefore, for longer cycle lengths, the average weight of individual fish is larger. We use the average number of fish per farm over the entire cycle to calculate the average weight, which allows us to estimate the amount of SLICE used without knowing when in the cycle the treatments are applied. We argue that this is a good estimation with the assumption that treatments are applied throughout the harvest cycle.

We assumed that 85% percent of SLICE is released into the environment: 5% in uneaten food and 80% in feces (River, 2007). We further assume that all excess SLICE is deposited in the sediments rather than remaining in the water column due to its high affinity to bind to soil particles (River, 2007). An additional simplification of the model is that it does not reflect decay of the chemicals over time.

Calculating Total Copper Input

To calculate the transfer of copper into the environment, we assumed that all concessions described as Technology Class 3 use copper-based antifouling paints on their aquaculture nets. We assume a constant leaching rate from net surfaces of 60 micrograms per square centimeter per day to find the total amount of copper released into the environment:

$$Total\ Copper\ Input = l \times C \times dpm \times SA_n \times N_n$$

where l = leaching rate, C = number of months per cycle, dpm = days per month, SA_n = painted surface area of one net, and N_n = number of nets per farm. Because we could not determine the actual painted surface area of a given net, we used a simple calculation to estimate SA_n:

$$SA_n = (SA_b - SA_t) \times F_n$$

where SA_b = the surface area of the outside of a box, representing a rectangular net, SA_t = the area of the top of the box, and F_n describes the fraction of the net that is actually a painted surface. We estimated that F_n is 0.1, meaning approximately 10 percent of the 5-sided rectangular net is a painted surface. This estimation allowed us to predict the total amount of copper leached from the aquaculture nets over the length of one cycle.

Modeling deposition of SLICE and copper onto the seafloor

We modeled the dispersion of SLICE and copper onto the benthos in a similar fashion as the Nutrients sub-model (see Figure 6). Because SLICE is a component of salmon feed, we assumed the same settling speeds and averaged the settling speed of feed and feces to determine the maximum distance that SLICE travels from a salmon farm. For copper, we could not find a reliable estimate of settling speed, so instead we used the value for feces, 4 cm/s, due to the small size of leached copper particles (Chen et al., 2003; Tironi et al., 2010). We assumed that the distance calculated using the average settling speed, current speed, and depth is the maximum distance traveled by food and feces from the farm. Also like the nutrients model, we assumed a normal distribution of particle deposition into concentric elliptical rings emanating from the salmon farm, with a mean of 0 and a standard deviation of 1/6 of the maximum distance (Chen et al., 2003; Tironi et al., 2010). Like in the Nutrients sub-model, we estimated the width of the elliptical impact area (the length of the minor axis) by using the same equation used for distance, but taking the natural log of the current speed. We were then able to use the total input of chemical to determine the concentration of copper and SLICE deposited within each ellipse.

Modeling Effects on Benthic Species

Once we had calculated the concentration of copper and SLICE in marine sediments surrounding a salmon farm, we could then estimate its impacts on benthic fauna in the impact area. We based these calculations a study conducted by Mayor et al. (Mayor et al., 2008) on two different non- fisheries target species in a region of Scotland where salmon aquaculture is carried out. This study recorded the number of individuals that died when placed in sediments containing known concentrations of chemicals, including copper and SLICE. The species they studied, *Corophium volutator* and *Hediste diversicolor,* a polychaete and crustacean respectively, have similar sensitivities as benthic species studied in other regions of the world, so we believe that it is reasonable to base our model for Chile on these species (Mayor et al., 2008). We ran a logistic regression on their results and created an equation that models the fraction of mortality due to any given concentration of copper or SLICE:

Effects of *SLICE*:

$$Fraction\ Mortality\ of\ Polychaetes = 1(1 + e^{1.15-0.002 \times [SLICE])})^{-1}$$

$$Fraction\ Mortality\ of\ Crustaceans = 1(1 + e^{1.22-0.002 \times [SLICE])})^{-1}$$

Effects of *Copper*:

$$Fraction\ Mortality\ of\ Polychaetes = 1(1 + e^{3.3 - 3.541 \times 10^{-5} \times [Copper])})^{-1}$$

$$Fraction\ Mortality\ of\ Crustaceans = 1(1 + e^{1.5 - 9.866 \times 10^{-6} \times [Copper])})^{-1}$$

where *[SLICE]* and *[Copper]* = the concentration of SLICE and copper in the sediments. Using these equations, we were able to calculate the fractional mortality of

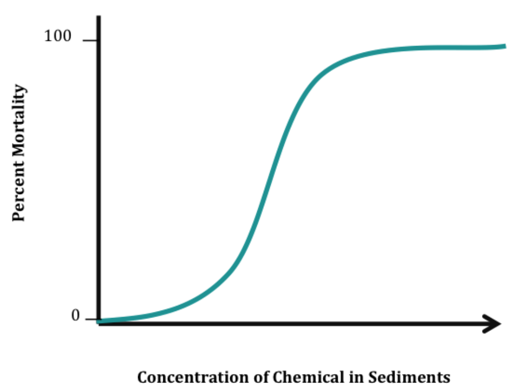


Figure 8: Chemicals' effect on Ecosystem Health

both types of species in each elliptical ring. We calculated the weighted average mortality within the ellipse created by a maximum dispersal distance of 100 m for both copper and SLICE. The averages were weighted by area to account for the fact that smaller rings have less area and thus contribute less to the overall average than rings comprising more area. By subtracting the resulting fractional mortality from 1, we were able to show the fraction of each benthic species remaining. We then averaged the effects of SLICE and copper on both crustaceans and polychaetes to determine the percent of abundance of these two species that remains after chemical loading. The fraction of crustaceans remaining over the total impact area was used in the calculations for Profits to Artisanal Fisheries and Tourism. Finally, the impacts of copper and SLICE within the ellipse reaching100 m from the farm are combined with results from the Nutrients and Disease sub-models to give a final measure of Ecosystem Health, an index that equally weights the results of the three sub-models. Figure 8 illustrates the sub-model's impacts on the outcome of Species Abundance.

Probability of Inter-Farm ISA Transmission

Because the ISA virus is such an important concern for the Chilean aquaculture industry, we included the risk of infection by that virus in this study. This sub-model, which is based on farmed salmon biomass and distance between farms, estimates the probability of ISA spreading to a farm if a neighboring farm is already infected (see Figure 9). The first step in this model was to construct a probability matrix (see Table 1) that describes the probability of ISA spreading from one farm to another during the time of two months, based on various starting conditions of those two farms.

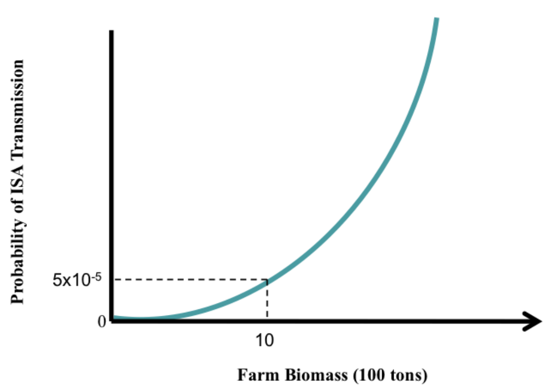


Figure 9: Probability of inter-farm ISA transmission

Table 1: Probability matrix for the transmission of ISA between neighboring farms

Probability Matrix							
	Month 2						
Month 1		1,1,0	1,0,1	0,1,1	2,0,0	0,2,0	0,0,2
	1,1,0	0	0.8371	0.1629	0	0	0
	1,0,1	0.0001	0.8364	0.1627	0.0007	0	0
	0,1,1	0	0.0008	0	0	0	0.9992
	2,0,0	0.1363	0	0	0.7008	0.0265	0
	0,2,0	0	0	0	0	0	1
	0,0,2	0	0.0008	0	0.0000	0	0.9983

Pink: Situation in which one farm's salmon are slaughtered
Red: Situation in which both farm's salmon are slaughtered

The numbers separated by commas (i.e. 1,0,1) describe three possible "states" that a single farm can be in: A, B, or C. The number is each position (A, B or C) refers to the number of farms in each state. The three states are:

A = Infected/Undetected,

B = Infected/Detected

C = No Infection (salmon are healthy or have been slaughtered)

For example, a situation in which both farms are uninfected is described as 0,0,2. This matrix shows all possible combinations of states in the two farms for month 1, shown in the first column, and all possible combinations in month 2, displayed in the first row. The values in the table represent the probability of a shift from one combination of states to another over the course of a month. For example, the probability of two farms in state 1,1,0 in one month changing to state 1,0,1 in the following month is 0.837. To create this matrix, we made the following assumptions:

- Detection of the ISA virus takes seven months from initial infection, equating to a monthly probability of detection equaling 0.163:

$$1 = (p + p(1-p) + p(1-p)^2 + p(1-p)^3 + p(1-p)^4 + p(1-p)^5 + p(1-p)^6)$$

- The true detection time ranges between six and nine months; however, because salmon facilities in Chile test their farmed salmon for disease frequently, we assumed detection will occur at the low end of the range (Scheel et al., 2007). The monthly probability of an infection remaining undetected will be the inverse, 0.837.

- The baseline probability of infection per month (i.e. from infected smolt) is 0.0008, obtained from data collected in Norway (Scheel et al., 2007). The inverse of this probability, which represents the probability that an uninfected farm will remain uninfected, is 0.9992.
- The probability of a farm shifting from Infected/Detected to No Infection is always 1 because regulations require all salmon in infected farms to be slaughtered (Odebret, 2011).

In this sub-model, we focus on scenarios in which one farm is uninfected and the other is infected (and might or might not be detected). We also assume that both farms are part of the same concession. Therefore, from the matrix we are only concerned with three combinations of state changes highlighted below (see Table 2).

Table 2: State changes of interest

Probability Matrix							
	Month 2						
Month 1		1,1,0	1,0,1	0,1,1	2,0,0	0,2,0	0,0,2
	1,1,0	0	0.8371	0.1629	0	0	0
	1,0,1	0.0001	0.8364	0.1627	0.0007	0	0
	0,1,1	0	0.0008	0	0	0	0.9992
	2,0,0	0.1363	0	0	0.7008	0.0265	0
	0,2,0	0	0	0	0	0	1
	0,0,2	0	0.0008	0	0.0000	0	0.9983

By summing the probabilities of these three state changes and the baseline probability of infection, we get the probability of the uninfected farm becoming infected with ISA:

Baseline Probability of Infection: 0.0008

1,0,1 → 1,1,0: 0.0001

1,0,1 → 2,0,0: 0.0007

\+ 0,1,1 → 1,0,1: 0.0008

= 0.0024

We then incorporated a stochastic model for ISA transmission developed by Scheel et al. (Scheel et al., 2007) that calculates the risk of ISA transmission based on fish biomass, distance between farms, a transmission indicator, and a network indicator. The transmission indicator term equals 1 when one farm has ISA and the other is susceptible to infection, and equals 0 in all other conditions. The network indicator refers to whether aquaculture workers and boats are traveling between the two farms, which increases the likelihood of transmission. If the same workers and boats are visiting both farms, the network indicator is 1; if not, the indicator is 0. Our model assumes a network indicator of 1 because the neighboring farms are always within the same concession. The Scheel et al. model is:

$$\lambda_{ji}(t) = \lambda_b(t)\exp\left(\alpha n_j(t) + \beta_1 n_i(t)\right) \times \left[\exp\left(-\phi d\left(x_j, x_i\right)\right) + k_{ji}\exp(\gamma)\right] I_{ji}(t)$$

Or more simply,

$$\lambda_{ji}(t) = \lambda_b(t) e^{biomass\ term}\left(e^{distance\ term} + k_{ji} e^{local\ network\ term}\right) I_{ji}(t)$$

where (Scheel et al., 2007) is the rate of transmission, $\lambda_b(t)$ is the baseline rate of transmission, k_{ji} is the network indicator and I_{ji} is the transmission indicator. Assuming that the coefficient estimates for the biomass, distance, and local network terms calculated by Scheel et al. in Norway hold true in southern Chile, we were able to use EIA data from Chile to find proportional changes in the transmission rate of ISA based on farm biomass. However, we had to assume a constant distance between farms because information on farm configurations within concessions was not available. Lastly, we multiplied the proportional change in transmission rate by the probability of the uninfected farm becoming infected with ISA (calculated above) to give our final outcome, Probability of ISA Transmission Given Presence at a Neighboring Farm.

Translating the risk of ISA into loss of Concession Profit

To estimate the monetary effects that an ISA outbreak poses to the aquaculture industry, we used the Probability of ISA Infection to calculate profit losses. Our model first assumes that once a farm becomes infected, there is a 5% chance that the infection will spread throughout the entire farm, causing an outbreak. We multiply this percent by the Probability of ISA transmission calculated above to determine the probability of an ISA outbreak given presence at a neighboring farm. We assume if an outbreak occurs, the fish must either be killed or harvested. If the salmon become infected with ISA within the first seven months of the cycle, the concession incurs all costs of that loss and no profit. After seven months we assume that the salmon are at an adequate weight for harvest without incurring any financial losses.

The loss of profit due to ISA risk is:

$$Profit\ Losses\ Due\ to\ ISA = (1 - P_{outbreak}) \times C_m \times M$$

Where C_m is the monthly cost of operations (calculated in the Harvestable Salmon Model), $P_{outbreak}$ is the Probability of ISA outbreak given ISA at a neighboring farm, and M is months. Again, we used seven months assuming infection after this time would still allow aquaculturists to harvest for full profit.

Escaped Salmon

Technology Classes

To create a sub-model predicting the number of escaped salmon as a function of the type of technology used, we first completed a literature review and sought expert advice to determine how technology and management have developed since the emergence of the salmon farming industry in Chile. From these sources, we were also able to estimate the escape rates (the percent of farmed salmon that are expected to escape within one harvest cycle) corresponding with each technological phase of the industry's development, and the maintenance costs associated with each technology. We use this information to model escaped salmon's effects on disease spread to, and competition/predation with, native species. In addition, we used a simple model to predict the economic effects of these escapes on the profits to the salmon aquaculture, artisanal fishing, and tourism industries.

We defined four distinct technology classes, each representing a combination of technologies used during the evolution of the industry, and each associated with a particular average escape rate. We calculated the number of salmon that are predicted to escape from one concession using the starting number of smolt multiplied by the escape rate corresponding to the technology class being used. The technology classes are defined as follows:

- **Class 1:** Represents conditions commonly found early in the emergence of the salmon aquaculture industry in Chile (1980s). Corresponds with reported **escapes at 30% per cycle** (Naylor et al., 2005; Molina, pers. comm., 2012).
    - Weak or damaged netting frequently made from discarded fishing nets – prone to holes allowing leakage of salmon.
    - Moored at two places only - one on either end of the farm - making pens vulnerable to capsizing in strong currents or during severe weather conditions (see Figure 10).

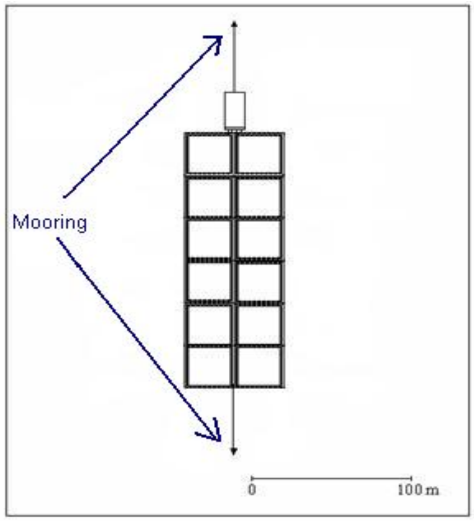


Figure 10: Class 1 Moorings

- No scientific assessment of the environmental conditions in the planned farm locations; farms not engineered to minimize escapes during major storms.
- Minimal staff trainings on proper maintenance and fish handling techniques to minimize escapes.

- **Class 2:** Represents conditions at the start of industry expansion (early 1990s). Corresponds with **20% escapes per cycle** (Naylor et al., 2005; Molina, pers. comm., 2012).
  - New nets designed and purchased specifically for salmon aquaculture meant fewer holes and less salmon leakage.
  - Use of predator nets reduces leakage due to rips and holes and wild predator mortality.
  - Moored in a "grid" or "ladder" pattern to prevent capsizing in major storms (see Figure 11).

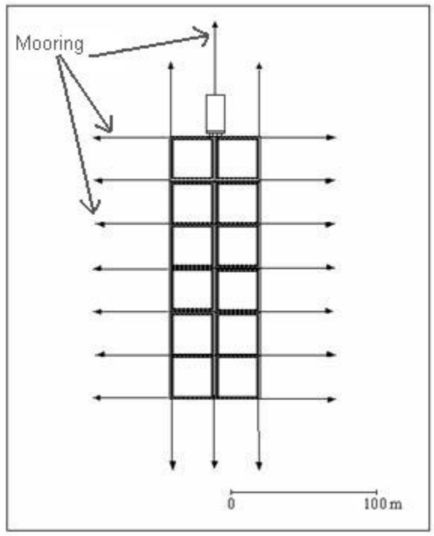


Figure 11: Class 2 and 3 Moorings

- Early attempts to engineer farms to be suitable for the specific hydrodynamic conditions of the planned location.
- Introduction of staff trainings on maintenance and fish handling practices.

- **Class 3:** Represents the current most widely available aquaculture net pen and mooring technology. Corresponds with approximately **5% escapes per cycle** (Naylor et al., 2005; Jenson, pers. comm., 2012; Molina, pers. comm., 2012).
  - Stronger net material such as Kevlar and polyethylene further reduce holes leading to leakage (Hvalpsund Net, 2011).
  - Nets coated in antifouling paint (usually copper-based), reducing the need to clean or replace the nets (a common opportunity for escapes). However, this period also experienced an increase in average density within the pens which increased the need for maintenance (Naylor et al., 2005; Molina, pers. comm., 2012).
  - Stronger and better-designed predator nets further reduce leakage and wild predator mortality.
  - Continued use of the grid or ladder mooring patterns.
  - Better engineering and design based on more thorough studies of the currents and seafloor conditions (Jensen et al., 2010).
  - Increased staff trainings on maintenance and fish handling practices.
- **Class 4:** Represents a potential next step in large-scale salmon aquaculture - the use of solid copper cages in place of net pens. This technology hypothetically corresponds with **0% escapes per cycle** (Molina, pers. comm., 2012).
  - Copper cages replace nets entirely; impervious to rips and predators

- Copper does not succumb to bio-fouling so no cleaning or replacement is required
- Moored to one point on the seafloor, drastically minimizing drag from the currents (see Figure 12).

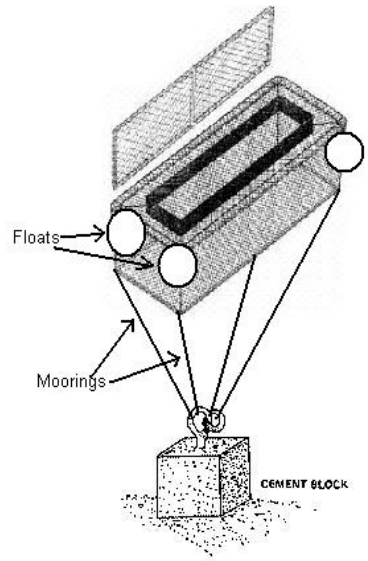


Figure 12: Technology Class 4

- Continued improvements in engineering and site-based design.
- Staff will need to be trained to use this entirely new technology, which operates quite differently from the traditional net pens.

A number of assumptions went into the process of defining these technology classes. We assumed that: there is a constant escape rate for each class across all areas and seasons; these classes are distinct from each other with no overlap in any one farm; and all farms within a concession have the same class characteristics. The process of identifying maintenance costs associated with each technology class also involved significant extrapolations and assumptions due to limited data availability. One result of these assumptions is that our analysis of cost does not capture the variation in costs that can occur depending on the conditions of each concession site.

Based on a number of expert interviews and data gathered from the EIAs of approved salmon aquaculture concessions in the Magallanes, we estimated maintenance costs for each technology class (see Table 3). Using the estimates of escape rates in combination with the estimated maintenance and training costs, we calculated the predicted monetary impacts of escaped salmon for one cycle of aquaculture for each technology class. As maintenance and training costs rise, revenue losses due to escaped salmon fall (due to a smaller percentage escaping with better technology).

Table 3: Technology Class maintenance costs

Class	Tightening Moorings	Cleaning/ Repairing/ Replacing Nets	Staff Training (at hourly worker wage)
1	$2000 US per net pen, twice per cycle (based on diver wages)	$400 US per net pen, twice per month	0 hours per cycle
2	$6000 US per net pen, twice per cycle (cost increase due to more moorings)	$400 US per net pen, twice per month	10 hours per cycle
3	$6000 US per net pen, twice per cycle	$400 US per net pen, once per month (less need due to antifoulant paints and stronger materials)	20 hours per cycle
4	$2000 US per cage, once per month (due to the configuration of these cages, moorings can be tightened in less time)	Completed by diver, so costs included in the $2000/cage/month	40 hours per cycle

Predation and Competition

To calculate effects of predation on and competition with native species from escaped salmon, we first used the Lotka–Volterra equations[2] to describe the interactions between native predator and prey species in the absence of the escaped salmon. We then added in the number of escaped salmon as an additional predator-level pressure. Escaped salmon exert pressure in the form of predation on native prey species and in the form of competition on native predator species. A limitation of this model is that it does not include the more complicated interactions between more than two species – dynamics that undoubtedly play out in nature. We examined the effects of escapes on three trophic levels: predator-level fin fish, prey-level fin fish, and

2 The Lotka-Volterra equations describe the dynamics of interactions between two predator and prey species.

cetaceans. We assumed that cetaceans interact with the escaped salmon similarly as do the predator level fin fish, with a few modifications, explained below.

We added the pressure from escaped salmon to the basic Lotka-Volterra equations (adjusted to account for density-dependent growth), by adding a term to represent the number of escapes present in the environment, *E* (determined by the technology class and number of salmon added to the pens). We also added a term, β', to represent the rate of predation by salmon on the prey species.

The resulting equations are as follows:

$$\frac{dx}{dt} = x(\alpha - \beta y - \lambda x - \beta' E)$$

and

$$\frac{dy}{dt} = y(\delta x - \gamma - \mu y)$$

where,

- y = number of some predator species (e.g. hake)
- x = number of the predator's prey species (e.g. sardines)
- α = intrinsic growth rate of the prey species
- β = rate of predation on prey by native predators
- λ = density-dependent growth dampener for prey (negative growth rate)
- β' = rate of predation on prey by escaped salmon
- E = number of escaped salmon time zero
- t = time in months
- δ = conversion efficiency between prey and predators (i.e. how much the presence of prey "helps" predators)
- γ = intrinsic mortality rate of the predator species
- μ = density-dependent growth dampener for predators (negative growth rate)

The Lotka-Volterra model depends on a number of assumptions about the environment and the dynamics of the predator and prey populations. As examples, the model assumes that the food supply of the predator population depends entirely on the prey populations; that the rate of change of a population is proportional to its size; that the environment does not change in favor of one species; and that the genetic adaptation is sufficiently slow to not affect the model's predictions.

When the native predators and prey are at equilibrium we find:

$y = (\alpha - \lambda x - \beta' E) / \beta$ when the change in x is 0

and

$y = (\delta x - \gamma) / \mu$ when the change in y is 0 (see Figure 13).

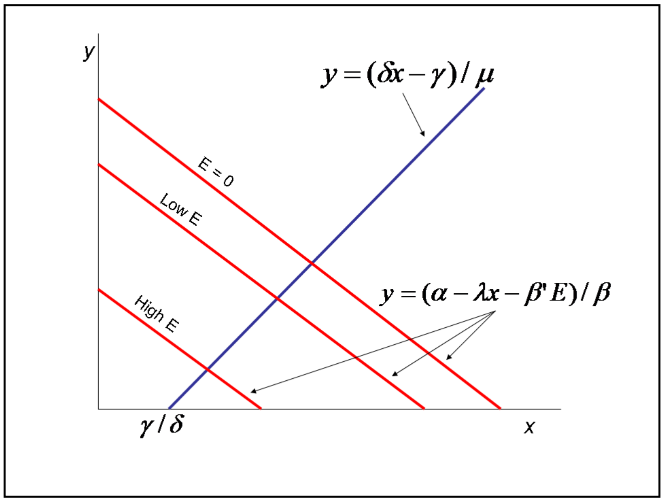


Figure 13: System at Equilibrium

When these two equations are set equal (points in Figure 13 where red and blue lines intersect) and solved for the number of prey and predators, we find the following equations:

$$x = \frac{\alpha - \beta' E + \frac{\beta\gamma}{\mu}}{\left(\frac{\beta\delta}{\mu}\right) + \lambda}$$

and

$$y = \frac{\delta\left(\frac{\alpha - \beta' E + \frac{\beta\gamma}{\mu}}{\left(\left(\frac{\beta\delta}{\mu}\right) + \lambda\right)}\right) - \gamma}{\mu}$$

With these two equations, we solved for the fractional change in the numbers of individuals of each species present with and without pressure from escaped salmon. We found that the relationships between the number of prey and the number of escapes, as well as between the number of predators and the number of escapes, are both linear, such that more escapes lead to fewer individuals of both native species (see Appendix A for more detailed calculations). Therefore, we were able to identify the number of escaped salmon that would reduce both native populations by a specific percentage and then use those numbers to calculate the fractional change that would be expected in *x* and *y* due to the addition of the predicted number of escaped salmon in our modeled cycle.

While actual data on the effects of escaped salmon on native fauna are scarce, especially for southern Chile, there are records of a variety of large-scale escape events in different times and geographies on which we were able to base our analyses (Buschmann et al., 2006; Jensen et al., 2010; Soto et al., 2001; WWF, 2009). We used the number of escapes in each of the events described in these papers in combination with observed percent reductions of native species in the corresponding locations (Soto et al., 2006) to extrapolate an approximate number of escapes in any one cycle that would reduce the native predator and prey species by 50%. We estimated that an escape event of 50,000 salmon would result in a 50% reduction in both the wild predator and prey populations.

Finally, to address the trophic level of cetaceans, we assumed that the system dynamics would behave similarly to the fin fish trophic levels, such that escaped salmon would function as an additional predator in competition with cetaceans for the same food species (although this assumption may only hold true for cetaceans that eat fin fish, as opposed to certain whale species that eat krill only). We also assumed that cetaceans do not eat escaped salmon and that the competition pressure from salmon on cetaceans is lower than on the fin fish. We thus assumed that 100,000 escapes in one cycle would be required to reduce the cetacean populations by half. We were thus able to insert the following equations into our model:

$$Fractional\ Change\ Predator = 1 - \left(\left(\frac{0.5}{50{,}000}\right) \times predicted\#escapes\right)$$

$$Fractional\ Change\ Prey = 1 - \left(\left(\frac{0.5}{50{,}000}\right) \times predicted\#escapes\right)$$

and

$$Fractional\ Change\ Cetaceans = 1 - \left(\left(\frac{0.5}{100{,}000}\right) \times predicted\#escapes\right)$$

These equations were used to calculate the fractional change in the number of individuals of these three trophic levels in response to pressures from the predicted numbers of escapes from one cycle of salmon aquaculture. These calculations give the fractions of the total numbers of individuals of each trophic level that are unaffected by a given number of escapes in any one cycle. Because the number of escapes is negatively correlated with the technology class, the size of the unharmed fraction of each trophic level is positively correlated with the technology class.

These calculated fractional changes in species abundance across three trophic levels were combined to create the “Species Abundance - Water Column” index, which was in turn combined with the results describing benthic abundance from the Chemicals sub-model to create the overall “Species Abundance” index. It is important to note that this method of calculating the fractional changes in species abundance allows for the possibility of improvement at the end of the aquaculture cycle. If the fractional change were positive (implying that the aquaculture activities had a beneficial impact on these species) the resulting Species Abundance index would be greater than 1; if there were no effect, the index would be exactly 1. For example, a Species Abundance index of .85 would imply that 85% of populations of native fauna remained after one harvest cycle, and an index value of 1.15 would indicate that the populations of native fauna increased by 15%. Finally, this Species Abundance metric was combined with the Species Richness and Species Health indices to create the Biodiversity Index. Figure 14 illustrates the sub-model’s impacts on the outcome of Species Abundance.

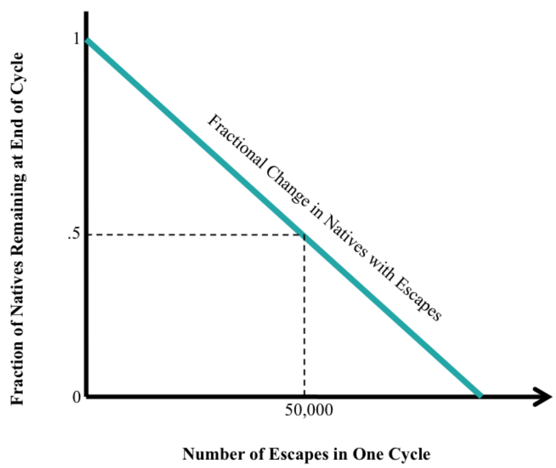


Figure 14: Predation and competition by escaped salmon's effect on Ecosystem Health

Spread of Disease

The second effect of escaped salmon that we modeled was the spread of disease and sea lice, both within the farmed salmon population and to wild species. Our models of the spread of disease between salmon in the same farm and from escaped salmon to native species are based on equations detailed by Anderson & May

(Buschmann et al., 2006; Jensen et al., 2010; Soto et al., 2001; WWF, 2009). Although it is likely that native species contract diseases and sea lice both from escaped salmon and from direct contact and proximity to the salmon farms, we made the simplifying assumption that escapes are the only source of transfer to the native species. We also assumed that no salmon or native species become immune or resistant to the disease. The basic equations used to model spread of a disease within the pens are as follows:

$$\frac{dh}{dt} = G - hm - \phi hs - h \times p$$

and

$$\frac{ds}{dt} = \phi hs - \big(s(m + v)\big) - (s \times p)$$

where,

- *h* = number of healthy animals
- *s* = number of sick animals
- *t* = time in months
- *G* = population growth of healthy animals (0 for salmon because they do not reproduce)
- *m* = natural mortality rate for the healthy species
- ϕ = disease (or sea lice) transmission coefficient
- *p* = percent of salmon that escape based on the technology class

To transform these equations for modeling the spread of disease from escaped salmon to native species, we simply added a term to each equation to incorporate the number of escapes each month that are infected with the disease:

$$\frac{dh}{dt} = G - hm - \phi h(s + Z)$$

and

$$\frac{ds}{dt} = \phi h(s + Z) - \big(s(m + v)\big)$$

where *Z* is calculated as the product of the number of sick salmon in a concession and the percent that escape, as determined by the technology class in use.

We used mortality rates for farmed salmon from scientific literature (Asche & Bjorndal, 2011) and data collected from the concession proposal EIAs. We selected three native species to represent the three trophic levels affected by the spread of these pathogens. We used demographics for hake (*Merluccius gayi*) to represent the predator level, sardines (*Sardinops sagax*) to represent prey, and Commerson's dolphin (*Cephalorhynchus commersonii*) to represent cetaceans. We used mortality rates and transmission coefficients within the range appropriate for the IPN virus. We assumed that the disease transmission coefficient for this virus would be quite small because fish are vaccinated against this disease; if a disease is detected, the fish are administered additional antibiotics by way of food pellets (EIAs). We chose to model the spread of IPN instead of ISA because testing for the ISA virus is performed on a regular basis, and if it is detected all salmon in the farm are immediately exterminated and removed (Allsopp et al., 2008; Marine Harvest, 2010; Scheel et al., 2007). IPN, on the other hand, can sometimes go undetected for many months, and if detected is simply treated with more antibiotics, which is not guaranteed to stem the infection. The probability of one farm contracting the ISA virus from a neighboring infected farm, based on stocking density and proximity, is modeled in the Spread of ISA sub-model.

The spread of sea lice was modeled using essentially the same methods that were used for the spread of disease, with the following adjustments: The equations were amended to allow for salmon to contract sea lice from the native species as well as transmit sea lice to the native species (because sea lice is likely already present in the native ecosystem before aquaculture is introduced); species mortality rates due to sea lice were assumed to be much lower than for the IPN virus because adult salmon can survive even with relatively great numbers of lice; and the transmission coefficient for sea lice was assumed to be much higher than for IPN because low levels of sea lice are quite common throughout aquaculture industries worldwide (Watershed Watch, 2001).

We gathered information on the starting number of smolt from concession proposal EIAs, and assumed that 5% of incoming smolt are infected with the IPN, but only 10 individual smolt are infected with sea lice (based on studies showing that salmon smolt enter the pens relatively free of lice (Heuch & Mo, 2001; Krkosek, Bateman, Proboszcz, & Orr, 2010). We modeled the spread of each infection over the number of months that comprise length of the harvest cycle, as reported in the EIAs. We then calculated the fractional changes in the numbers of healthy individuals of each trophic level due to the spread of disease and sea lice after one harvest cycle by dividing the number of healthy individuals at the end of the cycle by the number of healthy individuals at the start of the cycle (See Appendix A for more detailed calculations). The results represent the proportion of that trophic level that remains uninfected after one cycle. These results were combined to create our overall Species Health index, which was combined with the Species Richness and Species Abundance indices to create our final Biodiversity Index. Again, any positive impacts that aquaculture might have on the health of these three trophic levels would be represented in a Species Health index greater than 1, no effect would result in an index of exactly 1, and a decline in species health would be represented as a proportion less than 1. Figure 15 illustrates the sub-model's impacts on the outcome of Species Health.

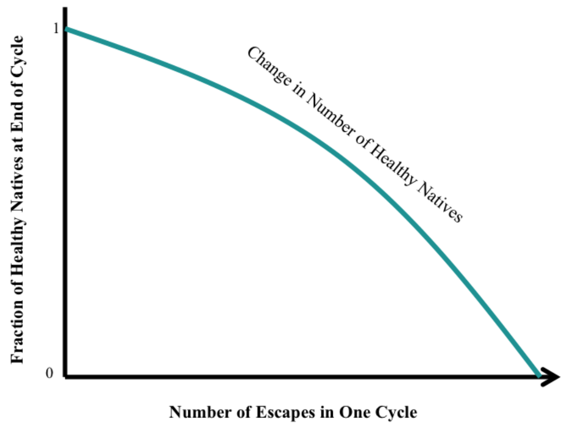


Figure 15: Spread of disease by escaped salmon's effect on Ecosystem Health

<u>Expected Regulatory Costs of Labor Violations</u>

To capture the expected costs to the industry as a result of poor labor practices, a sub-model was constructed predicting the total potential and expected cost of fines incurred for violating labor laws. Labor violations were categorized into "wage" violations and "hours" violations. Wage violations were defined as instances where any law regulating wage was violated, including the following:

- failing to pay for overtime
- making deductions from wages that were not agreed upon between parties
- making illegal deductions and offsets of wages (unfair wages)
- general failure to pay wages

Hours violations were defined as instances where any law regulating the legal number of working hours was violated, including the following:

- failing to grant two Sundays of rest in a calendar month
- exceeding the legal hours in a working day
- exceeding the legal hours in a work week
- exceeding the maximum of two extra working hours per day
- distributing the regular work of 45 hours in more than six days, or less than five

- failing to grant a break during the working day
- exceeding the maximum of 10 legal working hours per day

The total potential cost of fines incurred for violating wage and hours violations cumulatively (*TPC*) was calculated using the formula:

$$TPC = (v \times fc) + (h \times fh)$$

where *v* and *h* represent the number of wage violations and the number of hours violations within a production cycle period, respectively. The terms *fc* and *fh* represent the average fine amount in US dollars issued by the Chilean government for wage-based and hours-based labor violations, respectively.

The lack of detailed information for each violation made it difficult to determine a relationship between the amount of a fine and the severity of the violation for which it was assigned. Therefore, we determined that an average of all fines for a particular category of labor violation was the best way to determine a probable potential cost incurred by any violation in that category, regardless of its severity. These averages were calculated from fines complied from a public database of labor violation records obtained from the Chilean Ministry of Labor's labor inspection website. The labor violation records for 11 salmon aquaculture companies were queried, categorized according to whether the violation was wage-based or hours-based, and then averaged (see SEIA, 2012). It is important to note that *fc* and *fh* are averages calculated from fines for violating Chilean labor regulations only; they do not include any fines associated with violating international statutes or labor codes, such as those defined by the OECD, ILO and NAFTA[3].

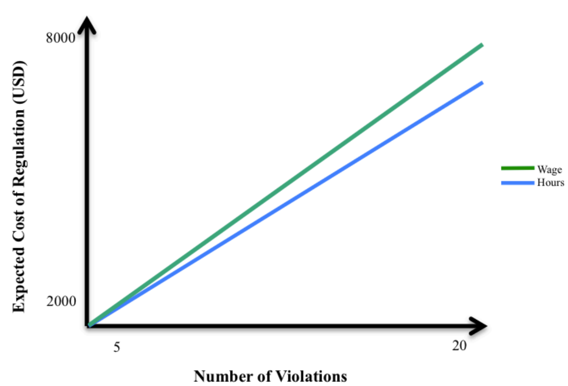


Figure 16: Number of Violations effect on Expected Cost of Regulation

3 Chile is a signatory and member nation of the OECD, ILO and NAFTA treaties.

The total expected cost of fines incurred for violating wage and hours violations cumulatively (*TEC*) was calculated by multiplying *TPC* by a probability of detection constant (*P(dt)*):

$$TEC = TPC \times P(dt)$$

where *P(dt)* is equal to 0.12. This value is based on a statistic stating that only 12% of all salmon farming facilities are actually inspected for regulatory compliance (J. R. Barton and Fløysand). This assumes that the probability of being detected for violating a labor law is dependent on inspection only. The result of this formula gives the total expected cost of violation of any salmon farm in this region, assuming that the concession is in non-compliance with at least one wage or hours law. Figure 16 illustrates the sub-model's impacts on the outcome of Expected Cost of Regulation.

<u>Concession Profit</u>

To determine the profit that a concession generates in a cycle, it was first necessary to calculate the value of harvestable salmon and on-site operational costs incurred throughout the harvest cycle. A model was constructed to predict both of these components of Concession Profit. Both of these aspects of profit are dependent on factors affecting the number of farmed salmon, including losses due to mortality and escapes, number of salmon at the start of the cycle, and length of the cycle.

Modeling Harvestable Salmon Revenue

We constructed the Harvestable Salmon sub-model to determine the number of salmon that are available for harvest at the end of a cycle, as well as their weight and value to determine concession revenue. We based our model of biological growth on equations developed by Guttormsen (2008) and Asche and Bjorndal (2011), which were developed specifically for farmed salmon. These equations are based on the well-known Faustmann model, developed in 1849 for optimal harvesting of timber. The Faustmann model, which shows that the optimal time to harvest is when the marginal increment in value equals the opportunity cost of investment, is successfully used by salmon farm managers to determine when to harvest salmon (Asche & Bjorndal, 2011; Guttormsen, 2008). We chose to use the equation developed by Asche and Bjorndal (2011) because it reflects a faster growth rate based on improvements to technology and the use of genetically modified smolt – conditions which we believe to hold widely true in southern Chile. The equation is:

$$w(t) = 5.72t^2 - 2.08t^3$$

where w = weight in kg, and t = time in months.

With this established biological growth equation, we next needed to factor in losses due to escapes and mortality. The number of escapes is predicted in a separate sub-model and incorporated here. Mortality in salmon farming can be attributed to five general categories: disease, production, environment, predation, and unknown causes (Soares et al., 2011). We chose to show mortality over the course of a harvest cycle as a percent loss of the number of salmon at start because mortality records do not differentiate between these causes of death. Because mortality does not occur at a constant rate throughout the harvest cycle, we chose to use the step rate method described by Asche and Bjorndal (2011), in which mortality rates change each month of the cycle. Based on detailed information of expected monthly mortalities from the EIAs of approved Magallanes concessions, we applied a decreasing mortality rate, where mortality starts at 2.17% in the first month of production and decreases to 0.3% per month at the end of the harvest cycle (SEIA, 2012). This decreasing mortality rate was confirmed by research on salmon farming in Scotland by Soares et al. (2011). The total mortalities over the course of the harvest cycle are approximately 15% based on the step method, depending on the length of the cycle. This is consistent with the median value of 15% expected mortality based on approved Magallanes EIAs (SEIA, 2012).

To use the result of the Harvestable Salmon sub-model to estimate the Concession Profit, we next calculated the value of the harvest:

$$V(t) = .93b(t) \times .75p(t)$$

where V = Value in US\$, t = time in months, b = biomass in kg, and p = price in US\$/kg of salmon.

We used a conversion ratio of 93% for the difference between the live salmon weight and the final weight of the harvested biomass (Marine Harvest 2010) and assumed that the price of salmon per kilogram is a constant value. We calculated this value by averaging the market price of whole farmed salmon over the past 14 months from present because this the typical length of a harvest cycle in southern Chile. Over this time period, the average commodity price was US$5.87/kg (with fluctuations between $4.13 and $7.92) (IndexMundi, 2012). Assuming a mark-up from farm to the commodity market of 25%, we adjusted the value of the salmon at the end of the harvest cycle to be US$4.40/kg.

Modeling Operational Costs

Next, we modeled the costs of producing one cycle's harvest using the variable costs calculated in the SLICE sub-model and parameters obtained from literature and personal contacts (Bravo pers. comm. 2011; Martinez perss comm.

2011). We calculated the cost of one cycle of production at one concession with the following formula:

$$pc(t) = f(t) + s(t) + c(t) + m(t) + l(t) + i(t) + o(t)$$

where *pc* = cost of production, *f* = cost of feed, *s* = cost of smolt, *c* = cost of chemicals, *m* = cost of maintenance, *l* = cost of labor, *i* = interest and depreciation, and *o* = other operational costs.

The time frame of our measurement of operational costs begins when smolt are transferred to the net pen, and ends when they are removed as adults and ready to be processed. The physical structures of a salmon farm are depreciated over their lifespan, and this is reflected in the model as interest and depreciation on invested capital. We used cost estimates from Ibieta et al. (2010) for smolt, interest and depreciation, and other operational costs because this study is specific to Chile and provided estimates in recent dollar values. The processes we used to determine the cost of maintenance is discussed in the Escapes sub-model.

We calculated the cost of feed with the following equation:

$$f(t) = cf \times fcr \times thw$$

where *cf* = cost of feed per kg, *fcr* = the economic feed conversion ratio, and *thw* = the total harvest weight in kg.

We used the cost of SLICE to calculate the cost of chemicals with the following equation:

$$c(t) = cs \times d \times anf \times awf \times td \times ntc$$

where *cs* = cost of SLICE per kg, *d* = dose per fish, *anf* = average number of fish, *awf* =average weight of fish, *td* = 7 days of treatment, and *ntc* = the number of treatments per cycle which is an input.

We calculated the cost of labor with the following equation:

$$l(t) = mw \times ma \times c \times anw$$

where: *mw* = minimum wage per hour, *ma* = maximum allowable work hours per week, *c* = cycle length in weeks, and *anw* = the average number of workers at a farm.

The Harvestable Salmon sub model calculates a monthly cash flow based on the production costs and the number of months into the harvest. The cash flow calculation is used to show the profits or losses to the concession in any month of the harvest. This calculation is used to determine the cost of an ISA outbreak and costs due to labor violations; both are discussed in detail in their respective sub-model sections. Figure 17 illustrates the sub-model's impacts on the outcome of Concession Profit.

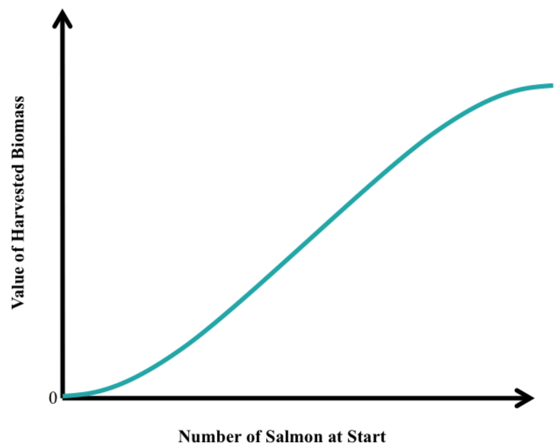


Figure 17: Number of Salmon at Start's effect on Profit to the Concession

Next, we calculated the costs incurred before the salmon are sold on the commodity market, which include processing, transportation, sales, and marketing. To calculate these costs, *a(t),* we used a mathematical relationship established by Forster (1995):

$$a(t) = [pc(t)/(1 - 0.38)] - pc(t)$$

With the relationship established between the production cost and additional costs, we then calculate the total cost of the harvest in per kilogram (*h(t)*) and in total (*H(t)*).

$$\hbar(t) = pc(t) + a(t) + i(t) + lv(t)$$

$$H(t) = \hbar(t) + b(t)$$

where *i(t)*= the cost of an ISA outbreak, and *lv(t)* = the cost of labor violations

Calculating Concession Profit

The preceding equations led to our calculation of the final outcome, Concession Profit.

$$P(t) = V(t) - H(t)$$

where P = profit, V = value of harvest, and H = total cost of harvest.

This value therefore represents the profit that a given concession can expect to accrue based on our estimations of the value of their harvest at the end of the cycle and the costs associated with producing and selling that harvest.

Economic Effects on Artisanal Fishing and Tourism

Due to constraints on the scope of our model, we were not able to predict the actual amounts of the economic impacts of salmon aquaculture on the two other main industries in southern Chile, artisanal fishing and tourism. However, we were able to address these effects in a simplified manner by assessing salmon farming's impacts on the various native species that are valuable to these two industries.

Tourism in the Magallanes is composed mostly of sport fishing and whale watching (Magallanes Minister of Tourism, pers. comm., 2011). To calculate the effects of one cycle of salmon aquaculture on this industry, we simply calculated the average of the fractional changes in species abundance in the water column (i.e. predators and prey, which represent those species that would be targeted by sport fishermen) and cetaceans (representing whale watching interests). Thus, any

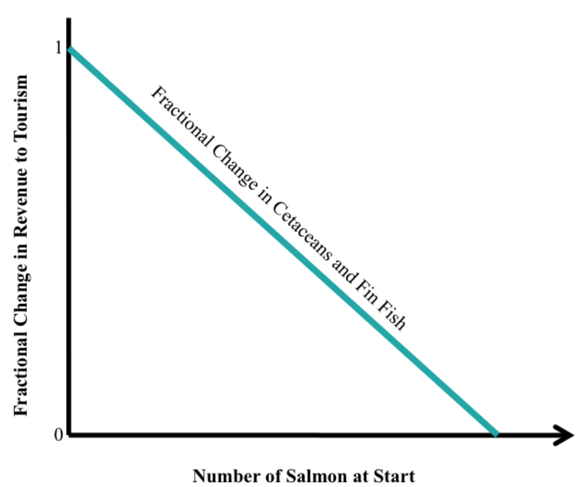


Figure 18: Number of Salmon at Start's effect on Tourism Revenue

reduction in the combination of these three species metrics was assumed to represent a reduction of the equivalent proportion in revenue to the tourism industry. Figure 18 illustrates the sub-model's impacts on the outcome of Profits to Tourism.

We were able to use landings data for the Magallanes region over a number of years to calculate the effects on artisanal fishing in a more sophisticated manner (Fernandez, 2008). We used this data to first determine the percentages of the total landings that each trophic level contributes to total landings. These calculations include trophic levels in the benthos because shellfish and crustaceans are an important source of income for artisanal fishers in the Magallanes. With this information, we were able to calculate an average of the fractional changes in predators, prey, and benthic species after one cycle of aquaculture. This average was weighted by the relative importance of each trophic level to the total artisanal catch.

Because salmon are a coveted catch due to high market prices (Kol, pers. comm., 2011), it has been shown that artisanal fishermen can provide a controlling force on the escaped salmon populations by harvesting them along with traditional target species (Buschmann et al., 2006). Therefore, escaped salmon must be included as an economic gain when calculating the economic impacts on this sector. We calculated the fractional increase in available biomass provided by escaped salmon by first determining how many tons of salmon remain at the end of a cycle, which is equal to escapes less natural mortality and mortality due to disease, at harvest weight. Then we compared this biomass estimate with the total biomass of wild fin fish available, which was extrapolated from the landings data. Therefore, artisanal fishermen see a decrease in the native biomass available for them to catch, but this decrease is partly offset by the increase in escaped salmon biomass. Figure 19 illustrates the sub-model's impacts on the outcome of Profits to Artisanal Fisheries.

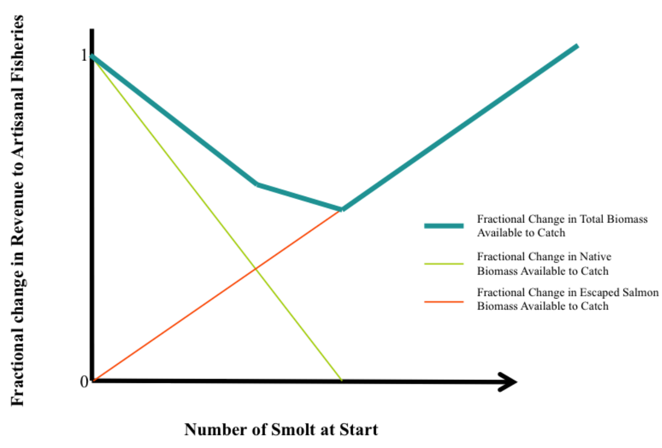


Figure 19: Number of Salmon at Start's effect on Artisanal Fisheries Revenue

Calculating Final Outcomes

Although most final outcome values are simply equal to the results of the sub-models described above, Ecosystem Health required additional steps to combine three sub-model results. Because these three sub-models contained in Ecosystem Health measured different environmental effects (change in Shannon Index, mortality, and species health) we calculated our results as fractional changes that could be combined into a final Ecosystem Health index. The Species Richness, Species Abundance, and Species Health indices are all calculated such that a score of 1 indicates no change, a score of less than 1 indicates a reduction in the species indicator, and a score of greater than 1 indicates an improvement (see sub-models for a more complete explanation).

The final outcome, Ecosystem Health Index, is a summation of the values of the three species indices. As such, a value of 3 indicates no change in Ecosystem Health, while any value above or below 3 would indicate a change in the overall health of the ecosystem. Lastly, we included Area Affected as an outcome, which equals the larger of the areas of impact of nutrient and chemical effluent.

Additionally, to calculate the final outcome for Concession Profit, we combined the outcomes from the Harvestable Salmon sub-model with those from the Probability of ISA sub-model and the Costs of Regulation from Labor Violations sub-model. We first calculated the revenue to the concession after one cycle of aquaculture, as described in the Concession Profit section above, and then subtracted from that value the Operational Costs, the Expected Costs of Collapse due to an ISA outbreak, and the Expected Costs of Regulation from Labor Violations, as calculated in their respective sections above. This calculation provides us with an estimate of the total Concession Profit after one cycle for one concession operating under the specified input conditions.

Analysis

Our modeling tool aims to accomplish three goals: 1) predict the range of effects that can be expected in the Magallanes given the currently proposed concessions, 2) identify "leverage points", or management actions where small changes in farming practices leading to small losses in profits could result in large social and environmental gains, and 3) identify areas where further research would lead to more reliable model results. To accomplish these goals, we gathered data from the approved concession EIAs for both the Los Lagos and the Magallanes regions, and input this information into our model in order to predict the outcomes of various management choices. Each model run represents a possible management decision – a combination of input values that can be selected by the aquaculturist (or required by the government) and the corresponding outcome values that can be expected after one cycle under those conditions.

Concession Data Collection

To obtain a permit to create a new salmon aquaculture facility or augment production at an existing facility within a concession in southern Chile, aquaculture companies submit applications to Subpesca. The application process is managed using an online database system called System of Environmental Impact Evaluation (SEIA), to which we gained access. Applications are subject to compliance with relevant environmental legislation; one of these requirements is that the application must include an EIA of the proposed aquaculture project. The concession-specific input data on which our model relies was obtained from the EIAs of approved concession proposals from the Magallanes region.

In the SEIA database, we were able to search for concession applications that fit certain criteria. Search criteria included status of the application, region, date range of application approval, and type of application. Because we were interested only in aquaculture projects that were approved for operation in the Magallanes region after the 2007 collapse in Los Lagos, we selected "Approved" and "Region XII", and a date range of January 1, 2008 to February 2, 2012 (the date on which we performed the searches). We were only interested in the concession classification that included salmon aquaculture, so we selected "Intensive Fish Farming" as type. After the search was completed, we eliminated any applications that proposed activities other than rearing and harvesting of salmon. We then downloaded the EIA from each salmon farming proposal and mined them for data relevant to our model. We found that all EIAs do not necessarily follow a consistent format, nor did they all contain the same level of detail of data. Nevertheless, most EIAs included information including the planned number of smolt to be imported each cycle, the length of the harvest cycle, number of tons of salmon expected to be harvested from each cycle, ocean current speed, water depth, and more.

Our initial search returned 32 proposals, 21 of which proposed applicable salmon aquaculture projects and contained a sufficient amount of relevant information to use in our model. From the EIAs of these proposals, we were able to find information on all of our inputs as well as several of our model parameters.

Predictions for the Magallanes

Default Values

We created a set of default input and parameter values by averaging the values found in the EIAs from each of the 32 approved aquaculture proposals for the

Magallanes region, and filling in the missing parameters with information from our literature review. Default input and parameter values were calculated by finding the average for each input and parameter found in the EIAs. The ranges of values for each of the inputs found in the EIAs were assumed to capture the full range of values practical for salmon farming in that region. By using average input and parameter values from the approved Magallanes EIAs, we aimed to create a set of values that would be representative of the average conditions that will be implemented in the Magallanes in the near future. Where information was not provided in the EIAs, or where data describing the Magallanes did not exist, we attempted to identify values from other parts of the world where aquaculture is carried out on a similar scale, such as Norway.

Our default values are:

- Number of Salmon Smolts at the start of the cycle: 1,400,000
- Number of Net pens in a Concession: 28
- Number of Months in a Harvest Cycle: 14
- Equipment Quality (represented as an index): 3
- Number of SLICE Treatments per Cycle: 6
- Number of Wage Violations per Cycle: 3
- Number of Hours Violations per Cycle: 2
- Current Speed (cm per second): 11
- Depth (meters): 60

Input Ranges

In order to assess the predicted effects of salmon aquaculture under the conditions proposed for the Magallanes, we transferred our model to the software program MATLAB. We assembled ranges for each of the input values by gathering the minimum and maximum values from the proposal EIAs. These ranges are assumed to represent the full scope of possibilities for industry-scale management decisions. We then ran our model, varying our inputs across these ranges in the following manner: If the input's range was large and continuous (for example, the Number of Starting Smolt ranged from 300,000 to 3,000,000) we selected the lowest value, the highest value, and a midpoint value to represent this input's range. If the input's range was small and discrete (for example, the Cycle length range was 12 months through 18 months) we included every value in its range. This process left us with approximately 61,000 combinations of 32 values. We ran the model in MATLAB once for each of these combinations to produce the range of values for each outcome that can be expected in the Magallanes after one cycle of aquaculture in one concession. We plotted frequency histograms of these values for each outcome to visualize the distributions over the range of possible outcome values.

We then examined the data to identify any interesting tradeoffs (such as the tradeoff between Ecosystem Health Index and Concession Profit). We plotted the outcome values in each of these tradeoff relationships against each other to identify efficiency frontiers where the most efficient management decisions lie. Any points that falls on the efficiency frontier (that is, those that fall on the outermost bound of the distribution) represent a combination of input values that maximize total benefits from the two outcomes being compared. Any point that falls below the frontier represents sub-optimal combination of input values. These relationships can help inform recommendations to improve aquaculture practices.

Case Studies

After completing this assessment of the entire range of possible input combinations, we analyzed the predicted performance of the 21 concessions approved for operation in the Magallanes. We therefore ran the model 21 more times, each time entering the specific combination of input and parameter values listed in the corresponding EIA. Where values were not listed in the EIA of a particular concession, we used our default values. This process allowed us to predict the outcome conditions after one cycle of aquaculture for each of these 21 approved concessions, which we then ranked based on their performance on each outcome. It is important to note that these rankings can be different depending on which outcome of interest the rankings are based.

Elasticity Matrix

We created an elasticity matrix to identify leverage points, or input values that, when adjusted, have the strong effects on a given outcome value. We first ran our model once using the default input values to find the outcome values that result from that default run. Each input value was then systematically adjusted, either by 10% or by the closest appropriate amount. As an example of an input that could not be changed by exactly this percent, a 10% change would have resulted in a value of 30.8 for the number of net pens in a concession. So, we rounded to 31 and then recorded the change in the input as 10.71%. We recorded the percent change in each outcome value corresponding to these changes in the input values. We then calculated the elasticities by dividing the percent change in the outcome by the percent change in the input for each combination of input and resulting outcome.

The only exception to this process was for the Equipment Quality input, which is an index representing the technology class being used (1, 2, 3, or 4). Because each technology class represents a different percent of farmed salmon that escape, we used the percent escapes to calculate the elasticity instead of the class number. The default value for Equipment Quality is 3, indicating a 5% escape rate; a decrease to Equipment Quality 2 means an increase to 20% escapes, and an increase to

Equipment Quality 4 means a decrease of escapes to 0%. So, we calculated the percent change in escapes for both a decrease and an increase in the Equipment Quality input, and then used those percent changes along with the percent change in each outcome to find the elasticities. The resulting elasticity matrix allows us to identify inputs that managers can alter that will result in the greatest improvements on certain outcomes while minimizing loss to Concession Profit. See Appendix C for full results of elasticity matrix.

Sensitivity Analysis

All of the above analyses were conducted while holding the model parameters constant at their default values. Because there is some degree of uncertainty in all of our parameter values, our final step was to carry out a sensitivity analysis on these parameters. Many of our parameter values were taken from studies in other parts of the world, or were extrapolated from limited information available. In addition to testing the precision of our model results, this sensitivity analysis allows us to identify parameters where improved information would be most impactful to improve the accuracy of our model results. Such parameters are those for which small adjustments in their values result in relatively large changes in the outcomes of interest.

We performed a Monte Carlo sensitivity analysis in which we systematically varied each parameter value individually while holding the inputs constant at their default values. For each of the 34 parameters, we ran the model 1,000 times allowing the computer to randomly select one value each time from within the uniformly distributed ranges of each parameter except for the one that was being held constant. This process generated the range of possible values for each outcome that can be thought of as the "base ranges", which we plotted in frequency histograms. Each of these 34 Monte Carlo runs resulted in new histograms for the ten outcomes of interest for a total of 340 histograms. We used those histograms to identify the parameters to which each outcome is most sensitive. These are the parameters that result in the widest outcome ranges when held constant in the Monte Carlo analysis. Therefore, these are the parameters that warrant future research in order to improve our model's reliability at predicting the extent of outcomes of salmon aquaculture in southern Chile.

Results

Predictions for the Magallanes

Default Values

Using the default input and parameter values created by averaging the values reported in the EIAs, we calculated the following outcome values.

- Ecosystem Health = 1.97
  - Species richness = 0.67
  - Species abundance = 0.69
  - Species health = 0.60
- Area affected = 19210 km^2
- Profits to aquaculture industry = $2,716,870 USD
- Probability of ISA Transmission = 0.00057
- Fractional loss of profits to artisanal fisheries = 0.87
- Fractional loss of profits to tourism = 0.48
- Expected regulatory cost for labor violations = $1480 USD

These outcome values represent the "average" effects of one cycle of salmon aquaculture at one concession completed under currently proposed conditions.

Input Ranges

Histograms

By running all possible combinations of our nine inputs across values representative of their ranges (totaling more than 61,000 model runs representing as many aquaculture management decisions), we were able to predict the ranges of all possible values of our outcomes. These outcomes represent the ranges of values that can be expected after one cycle of aquaculture under the range of proposed management strategies for individual salmon concessions in the Magallanes region. We used these outcomes to create frequency histograms that allow us to visualize both the full range of predicted outcome values, as well as which outcome values are most likely to occur. These histograms, with brief explanations, are presented below.

In each of these graphs, the outcome of interest is represented on the x-axis and the frequency with which each resulting value occurred after more than 61,000 model runs is along the y-axis.

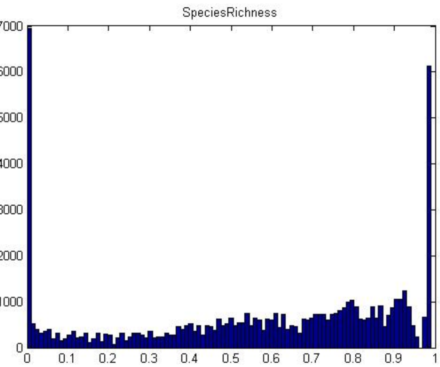


Figure 20: Species Richness (fractional change 0-1)

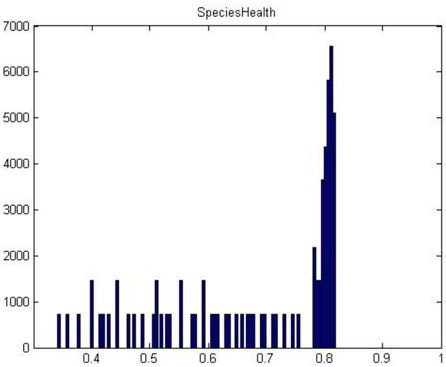


Figure 21: Species Health (fractional change 0-1)

Figure 20 shows that after more than 61,000 model runs of varying input combinations, the fractional change in species richness within a 100-m ellipse of the aquaculture concession is fairly evenly spread across the range of possible values. Model runs where species richness was decreased to zero are the most frequent, with runs where there is no fractional reduction in these species second most frequent. This pattern is likely due to our decision to measure the change in species richness within an ellipse of a set size.

Figure 21 shows that fractional change in Species Health is generally clustered around 0.8, implying that after one cycle of aquaculture, approximately 80% of the individuals in the trophic levels assessed remain healthy (i.e. not infected with IPN or sea lice).

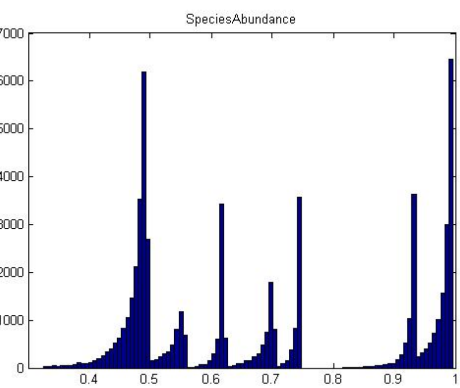


Figure 22: Species Abundance (fractional change 0-1)

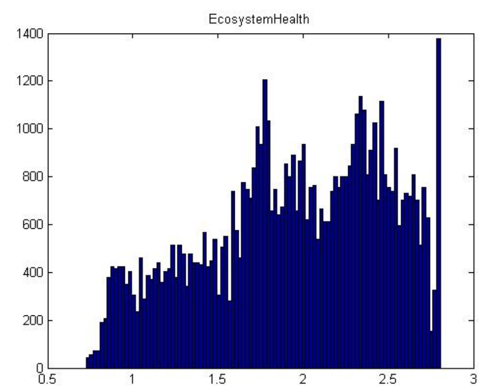


Figure 23: Ecosystem Health (fractional change 0-3)

Figure 22 shows that the Species Abundance index, representing the fraction of individuals remaining alive in each of the trophic levels assessed, is spread across almost the entire range of possibilities, with spikes and somewhat even intervals along the axis. This pattern could be due to the effect of the 4 different Technology Classes resulting in 4 different percentages of salmon escapes.

The Ecosystem Health Index (Figure 23) is made up of the Species Richness, Species Abundance, and Species Health indices and it therefore ranges between 0 and 3. A value of 3 would imply no change in overall Ecosystem Health, and any value lower than 3 represents a fractional decrease in Ecosystem Health. As this graph shows, the predicted results for this outcome are fairly scattered across the possible range, with values above 1.5 more common, and a value of approximately 2.7 being the most frequent.

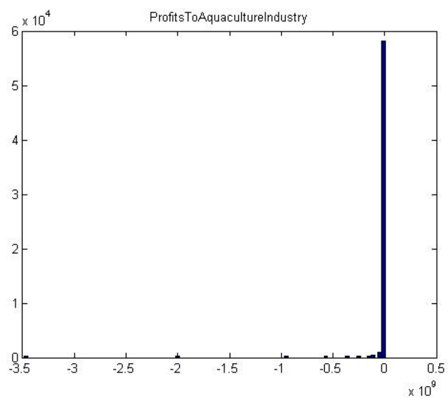


Figure 24: Concession Profit (USD)

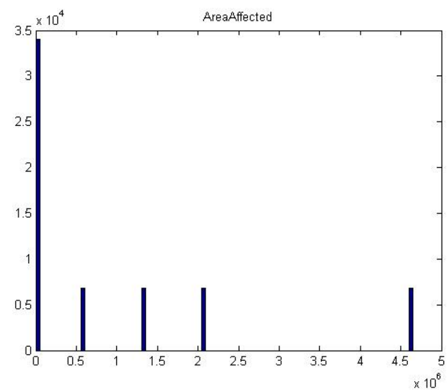


Figure 25: Area Affected (km^2)

Figure 24 illustrates the outcomes for Concession Profit. We found a range of Concession Profit outcome values between approximately \$7,000,000 and -\$3.5 billion. Negative profit values occur when an outbreak of the ISA virus causes the concession to shut down operations mid-cycle and all revenues for that cycle are lost. Because of the scale of this graph's axis, it is not possible to see an accurate range of the possible profit values that are greater than zero because all values between 0 and 10 million dollars are lumped into the same bin in MATLAB. This graph does show, however, that positive profit values are by far the most frequent result, as the probability of a collapse due to ISA is quite small.

Figure 25 reveals that area affected, representing the size of the area over which chemicals and nutrients are deposited on the seafloor during one cycle, varies widely due to changes in depth and current speed. However, very small areas resulted from the majority of the model runs.

Profits to Tourism (Figure 26) represents the fractional change in three trophic levels that are of importance to the tourism industry in Chile. This graph shows that the fractional change in profits to tourism generally follows the same pattern as the Species Abundance graph, with the extremes – complete loss and no change – appearing somewhat more frequently.

Figure 27 represents the fractional change in biomass of native species that are important to artisanal fishermen (weighted according to their historical importance to artisanal fishery catches in the Magallanes) combined with a fractional increase in fishable biomass provided by the escaped salmon. The distribution shows that in most of the 61,000 runs, there was to no change in the abundance of biomass (values between .8 and 1) available to artisanal fishermen after one cycle of aquaculture, and under some of the input conditions there will actually be significant increases (values higher than 1). This is because escaped salmon can take the place of native fin fish as a fishery species.

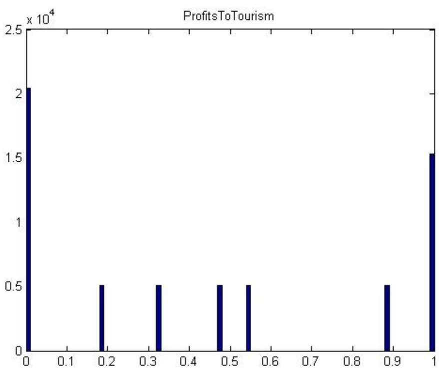


Figure 26: Profits to Tourism (fractional change 0-1)

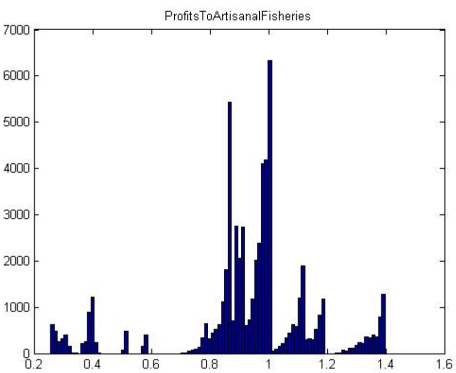


Figure 27: Profits to Artisanal Fisheries (fractional change 0-3)

Figure 28, shows that all values for expected costs of regulation for labor violations are equally likely. This equal distribution is a result of our assumption that the expected regulatory cost is always 12% of the potential cost.

Figure 29 shows the probability that a farm will contract the ISA virus in a given month if that virus is already present in a nearby farm. The probability of ISA transmission between farms is typically very low, but increases with greater farm biomass. From our results we can see that the vast majority of model runs resulted in an extremely low probability of ISA, but that there are cases in which ISA transmission is expected.

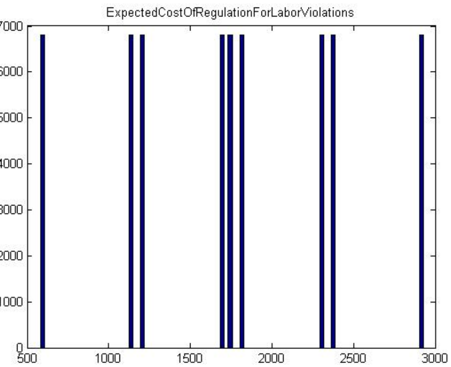


Figure 28: Expected Cost of Regulation for Labor Violations (USD)

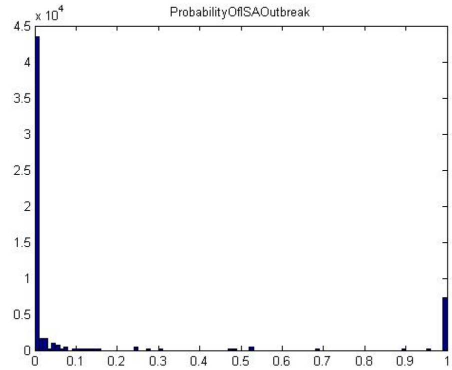


Figure 29: Probability of ISA Transmission

Efficiency Frontiers

We examined some outcomes in pairs to identify interesting tradeoffs and the resulting efficiency frontiers. To identify efficiency frontiers, we plotted interesting pairs of outcomes as scatter plots in which each point represents the values for two outcomes of one model run. Each point can be thought of as one hypothetical aquaculture concession that could exist in the Magallanes.

We examined the following relationships (Figure 30 to Figure 36)

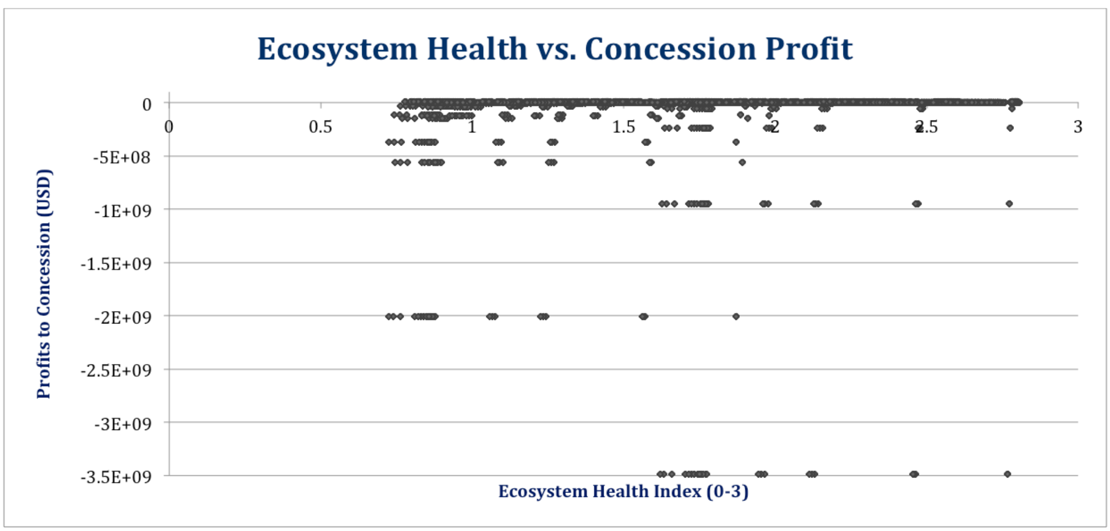


Figure 30: Ecosystem Health vs. Concession Profit

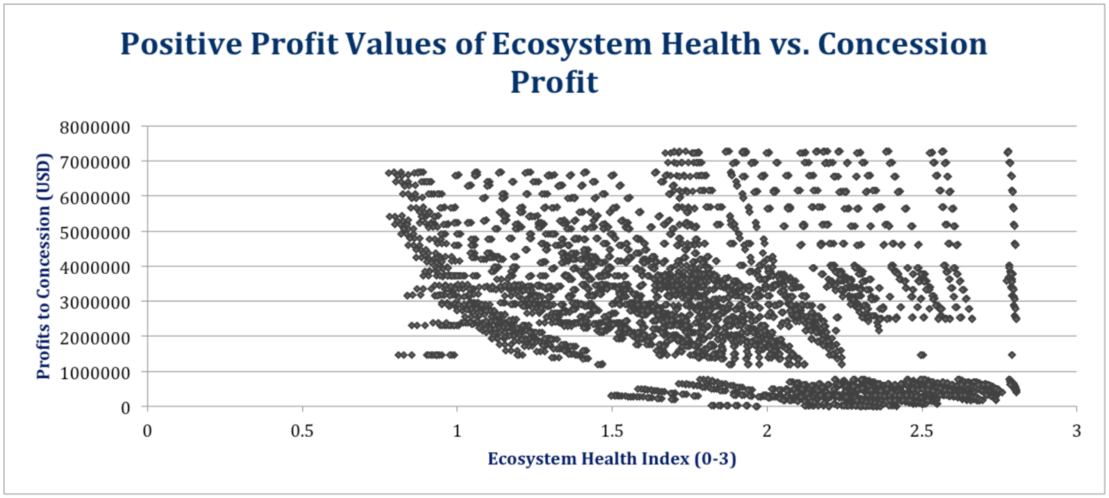


Figure 31: Positive profit values of Ecosystem Health vs. Concession Profit

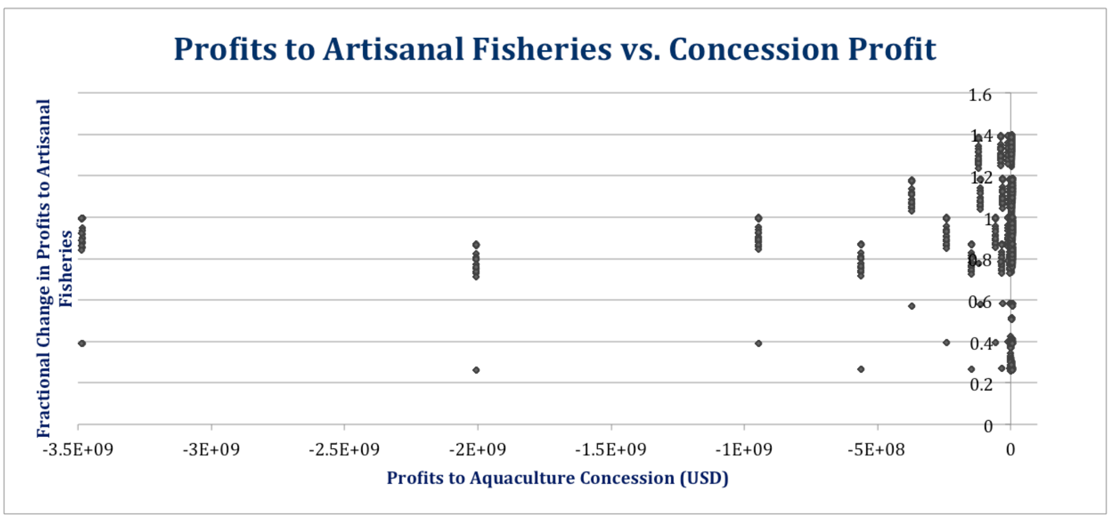


Figure 32: Profits to Artisanal Fisheries vs. Concession Profit

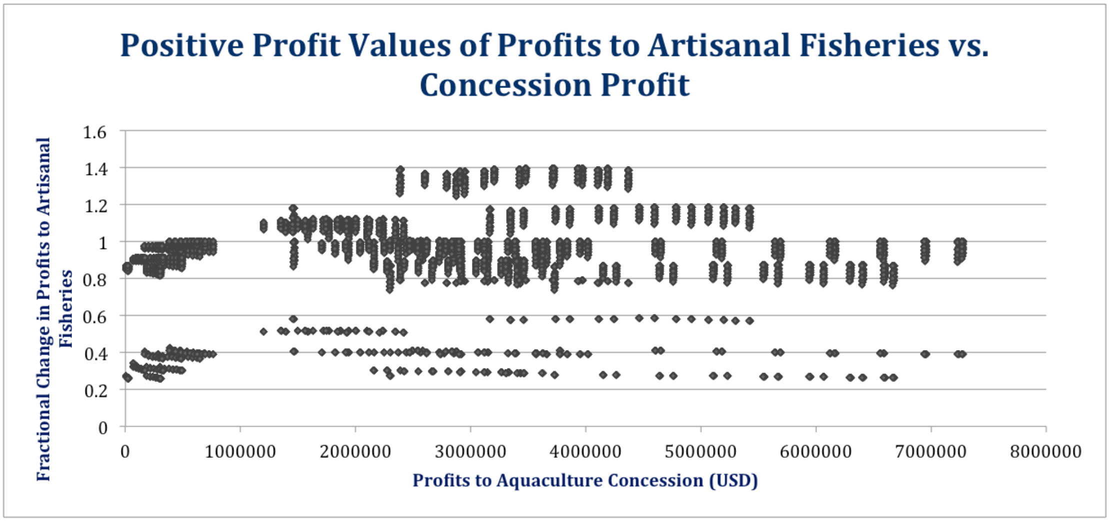


Figure 33: Positive profit values of Profits to Artisanal Fisheries vs. Concession Profit

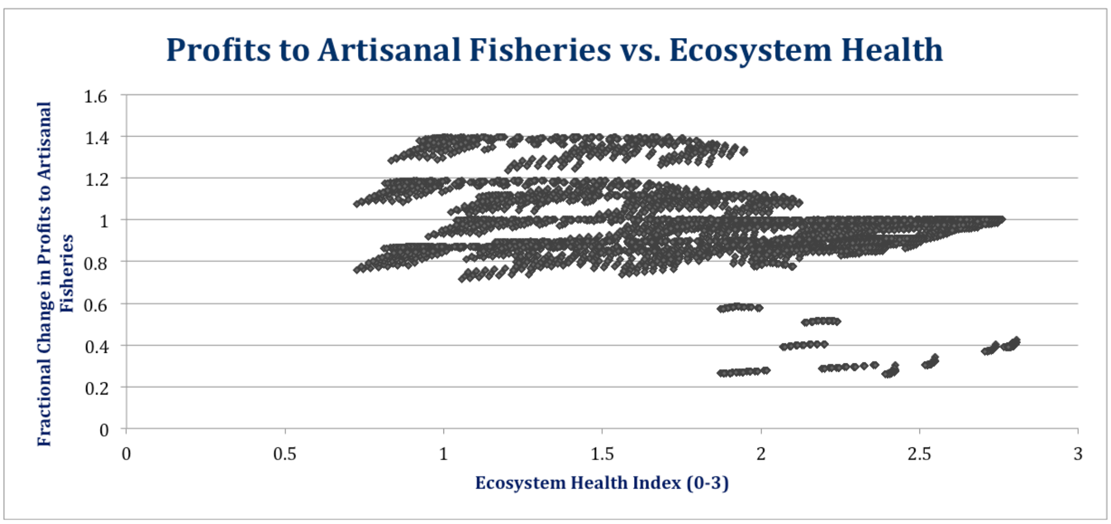


Figure 34: Profits to Artisanal Fisheries vs. Ecosystem Health

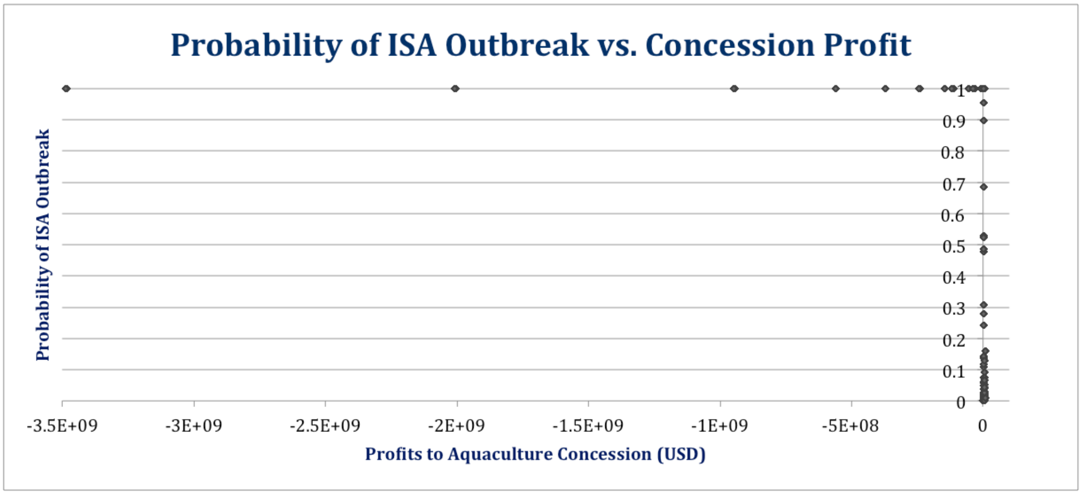


Figure 35: Probability of ISA Transmission vs. Concession Profit

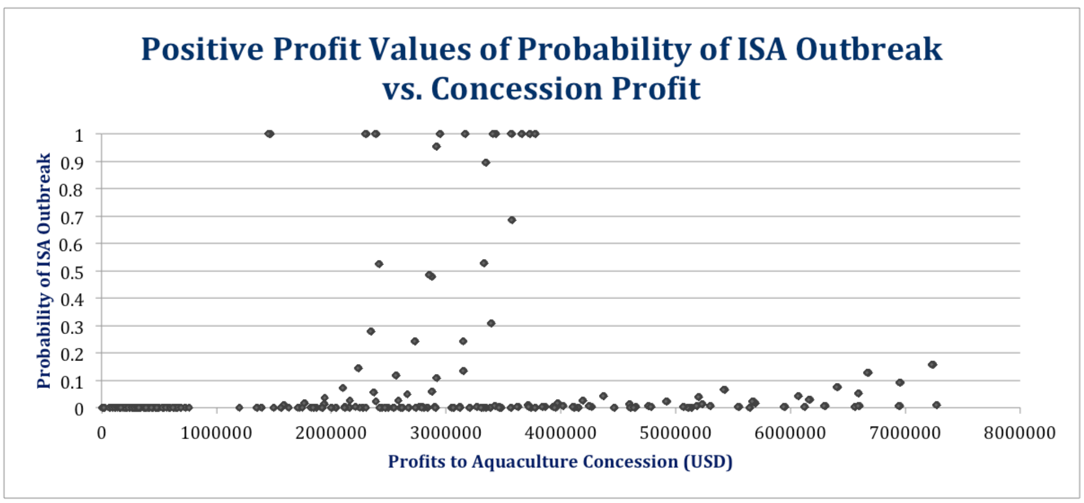


Figure 36: Positive profit values of Probability of ISA Transmission vs. Concession Profit

In all of these graphs, points that fall along the efficiency frontier (i.e. the outer bound of the distribution) represent optimal management decisions based on the input ranges we used. Points along this frontier provide the greatest overall values to both outcomes; however, the distribution of those benefits can vary widely depending on the location along the frontier. In other words, on the frontier, a gain to one outcome results in a necessary loss to the other. Points that are near the middle of the frontier are hypothetical concessions that strike a balance between the two outcomes. Depending on the interests of those evaluating the frontiers, points can be selected that offer relatively more benefit to one outcome than the other. However, in no case should a point be chosen which does not fall on the efficiency frontier if the goal is to maximize overall benefit to both outcomes.

To further explore our model results, we examined the input values that resulted in the extreme high and low outcome values in the above tradeoff relationships. Additionally, we identified the input conditions that resulted in the optimal point or points on these graphs that strike a balance between the two outcomes (those that fall toward the middle of the frontier). Table 4 displays the input values that resulted in the extreme outcome values displayed on the efficiency frontier between Ecosystem Health and Concession Profit.

Table 4: Input values for extreme outcome values from Concession Profit vs. Ecosystem Health Efficiency Frontier

Worst and Best for Ecosystem Health										
Ecosystem Health	Concession Profit	Number of Net pens	Number of Months in Cycle	SLICE Treatments	Equip. Quality	Number of Salmon at Start	Number of Wage Violations	Number of Hours Violations	Average Current Speed	Average Depth of Seafloor
0.725	-2,007,218,190	8	18	8	3	2500000	5	5	80	17
0.725	-2,007,215,850	8	18	8	3	2500000	1	1	80	17
2.804	383,070	32	12	4	4	300000	5	5	3	17
2.804	385,410	32	12	4	4	300000	1	1	3	17

Worst and Best for Concession Profit										
Ecosystem Health	Concession Profit	Number of Netpens	Number of Months in Cycle	SLICE Treatments	Equip. Quality	Number of Salmon at Start	Number of Wage Violations	Number of Hours Violations	Average Current Speed	Average Depth of Seafloor
1.619	-3,486,505,720	8	18	8	4	2500000	5	5	80	17
2.766	-3,486,505,720	8	18	8	4	2500000	5	5	3	17
1.736	7,279,080	32	18	4	4	2500000	1	1	80	17
2.78	7,279,080	32	18	4	4	2500000	1	1	3	17

Ecosystem Health and Concession Profit Maximized with Respect to Each Other										
Ecosystem Health	Concession Profit	Number of Net pens	Number of Months in Cycle	SLICE Treatments	Equipment Quality	Number of Salmon at Start	Number of Wage Violations	Number of Hours Violations	Average Current Speed	Average Depth of Seafloor
2.781	7,267,820	32	18	8	4	2500000	1	1	3	17

Concession EIA Case Studies

We ran our model separately for each of the 21 approved concession proposals to simulate the impacts that can be expected based on each individual set of farming conditions. In order to determine how well each concession performs on each outcome in relation to all other concessions, we created a ranking system from our model results (see Table 5). For a full list of concession names, see Concession Key in Appendix D.

A concession's placement in each column indicates that concession's ranking in relation to all other concessions, with placement closer to the top meaning higher ranking. For example, for the outcome Species Richness, Concession F was ranked first because it resulted in the highest score for species richness. On the other hand, Concession S exhibited the lowest species richness score and was therefore ranked last in that column. Conversely, Concession S scored quite well on the outcome of Concession Profit and was ranked just below Concession R for this outcome.

This ranking process showed that concessions rank differently for each outcome, and there are a few concessions that clearly show tradeoffs between certain outcomes. In comparison with the other concessions, Concession F (displayed in blue) on average scored well for all outcomes except for Concession Profit. On the other hand, Concession R (displayed in green) has the highest score for Concession Profit, but the lowest scores for all other outcomes. The rank of Concession E (displayed in red) was varied across the outcomes. The differences between individual concessions are caused by variations in their input combinations. For the actual values for the ranking of each outcome by concession, see Appendix D.

Table 5: Ranking of 21 approved Magallanes concessions based on their performance on outcomes of interest

Concession Case Study Ranking					
Rank by Concession	**Concession Profit**	**Probability of ISA Outbreak**	**Profits to Artisanal Fisheries**	**Profits to Tourism**	**Ecosystem Health**
1st	R	T	L	L	F
2nd	S	U	U	F	L
3rd	A	L	K	T	E
4th	B	F	T	U	D
5th	C	G	G	G	T
6th	E	H	J	H	U
7th	M	I	I	I	N
8th	N	J	H	J	K
9th	Q	K	O	K	G
10th	D	P	A	O	I
11th	P	O	P	D	H
12th	O	D	C	P	J
13th	H	A	B	A	O
14th	G	B	F	B	P
15th	I	C	R	C	Q
16th	J	E	M	E	M
17th	K	M	D	M	A
18th	F	N	Q	N	B
19th	U	S	S	Q	C
20th	T	Q	N	R	S
21st	L	R	E	S	R

We have excluded the outcomes Affected Area, Potential Cost of Regulation for Labor Violations, and Expected Cost of Regulation For Labor Violations from the ranking system because rankings were not meaningful for these outcomes.

This ranking tool allows management decisions to be evaluated with regard to tradeoffs between multiple objectives. To highlight an important tradeoff and identify its efficiency frontier based on proposed farming practices, we created a scatter plot that illustrates the outcome values for Ecosystem Health and Concession Profit, in which each point is one of the 21 approved concessions (see Figure 37). This plot also identifies concessions that are expected to perform at sub-optimal levels for the two outcomes, and can be used to identify concession proposals that maximize either outcome.

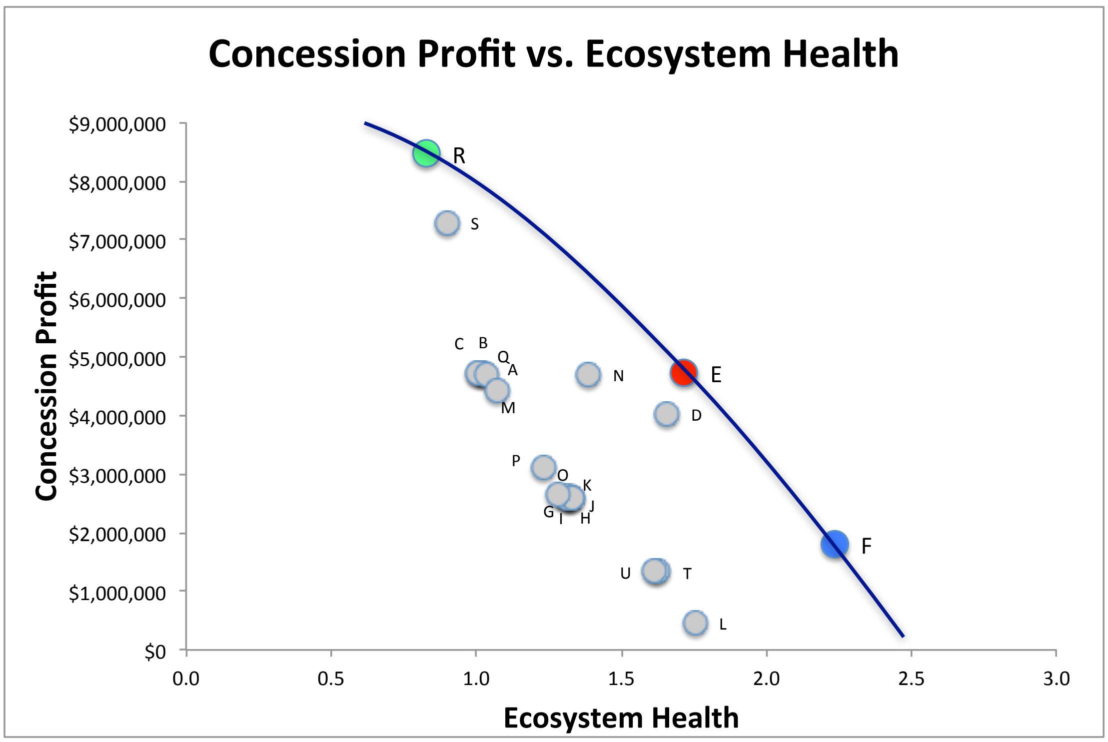


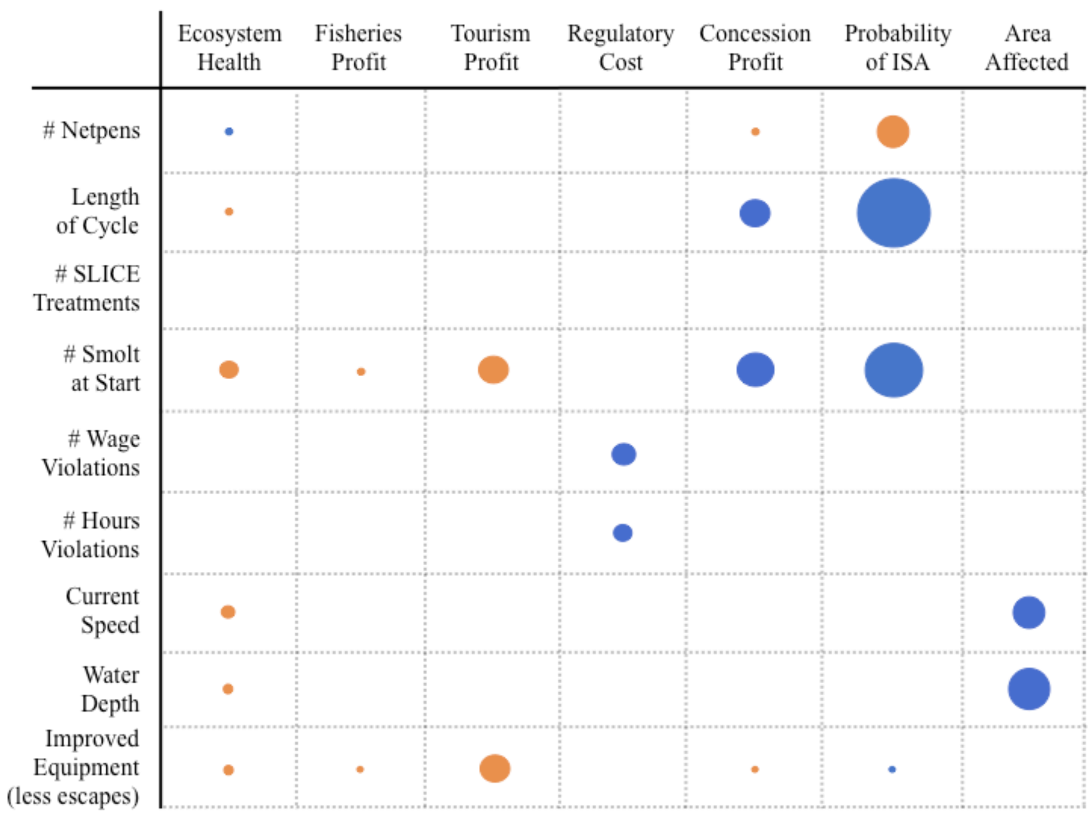
Figure 37: Efficiency Frontier for Concession Profit and Ecosystem Health

An aquaculturist or manager who places a high value on environmental health would favor Concession F, which maximizes benefits to Ecosystem Health. However, this concession is projected to produce relatively little profit. On the other hand, an individual who cares more about profits and less about the environment would chose Concession R, which maximizes Concession Profit. There is one concession, however, that falls between these two points along the efficiency frontier. Concession E proposed a combination of inputs and parameters that strike a balance between optimizing both Ecosystem Health and Concession Profit. This concession provides the greatest overall benefit to both outcomes combined, but neither outcome achieves its maximum possible value. This type of analysis using efficiency frontiers can be a useful tool for determining how concession applications perform in relation to each other.

Elasticity Matrix

The elasticity matrix reveals "leverage points", or model inputs that cause large changes in each outcome (see Table 6). The direction and magnitude of these changes are both of interest for determining which inputs have the most important effects on the outcomes. Because we calculated elasticities by increasing each input value and dividing the percent change in the outcome by that percent increase in the input value, negative elasticities imply that an increase in the input resulted in a decrease in that outcome. Conversely, positive elasticities indicate that the outcome value increases with an increase in the input value. The absolute magnitude of an elasticity reflects the strength with which the input effects the outcome value.

Table 6: Elasticity Matrix describing inputs' impacts on outcomes. Blue circles indicate positive correlations and orange circles indicate negative correlations; elasticity magnitude is represented by the size of the circle, with the greatest value being 5.1 (Length of Cycle's effect on Probability of ISA).



The number of salmon at start is the most influential input overall, affecting nearly all of the outcomes. A 10% increase in the starting number of smolt results in corresponding proportional increases in Concession Profit (1.1) and Probability of ISA transmission (2.3), and decreases in Profits to Tourism (-1.1), Profits to Artisanal Fisheries (-0.1), and Ecosystem Health (-0.4). A longer cycle length also leads to increased Concession Profit (1.2). Depth and Current Speed are positively correlated with Area Affected (1.0 and 1.6, respectively), and negatively correlated with Ecosystem Health (-0.2).

Expected Cost of Labor Violations is dependent on the number of wage and hours violations and is more sensitive to the former (0.6) than the latter (0.4). The largest elasticities were seen in Probability of ISA Transmission, which decreases with Number of Net Pens (-1.7), and increases with Cycle Length (5.1), and the Number of Smolt at Start (2.3). Improved equipment quality (changing from 3 to 4), which results in a decrease in the salmon escape rate, leads to benefits for Ecosystem Health (-0.35), Artisanal Fisheries Profit (-0.12), and Tourism Profit (-1.1), and decreases the probability of ISA transmission (-0.06). These circles are represented with opposite colors as the rest because an increase in equipment quality leads to a reduction of escapes, whereas all other inputs are measured using an increase in their value.

Sensitivity Analysis

The results of our Monte Carlo sensitivity analysis identify the most influential parameters contributing to the variability of our outcomes of interest. The histograms generated by each run represent the range of outcome values that can be expected given the ranges of possible parameter values. With these histograms, we were able to identify parameters that led to highly variable model results (see Appendix F).

Most of the base run histograms closely resemble the bell shape of a normal distribution. Exceptions are Area Affected, Probability of ISA. Probability of ISA exhibits a left-skewed distribution, which corresponds to the fact that this outcome value is very small for most runs, but there are some runs that result in a much larger outcome. Area Affected and Species Richness each have only one frequency bar because it is only affected by the inputs Current Speed and Depth. None of the parameters affect this outcome, so when the inputs are held constant there is no variation in this outcome value.

Parameters that had a noticeable affect are listed below, organized by the outcome of interest that they affected (Area Affected omitted):

Species Richness

- Biomass Farm B
- Cages Per Farm
- Concession Size
- Distance Between Farms
- Feed Settling Speed
- N Content in Feed*
- N Richness Elasticity
- Original N Density
- Sediment Density

Species Health

- Escape Decay
- Mortality Due to Disease*
- Mortality Due to Sea Lice
- Total Salmon Mortality Rate
- Natural Salmon Mortality Rate
- Probability of Disease Inside Pens
- Probability of Disease Outside of Pens
- Probability of Sea Lice Inside Pens
- Probability of Sea Lice Outside of Pens

Species Abundance

- Escape Decay
- Nitrogen Content in Feces
- Feed Settling Speed
- Leaching Rate
- Mortality Due to Disease
- Mortality Due to Sea Lice
- N Richness Elasticity*
- Number of Escapes to Halve Native Cetaceans
- Number of Escapes to Halve Predators
- Number of Escapes to Halve Prey
- Original N Density
- Sediment Density
- Slice Days

Ecosystem Health

- Concession Size
- Distance Between Farms

- Escape Decay
- Fecal Settling Speed
- Feed Settling Speed
- Feed Eaten
- Leaching Rate
- Mortality Due to Disease
- Mortality Due to Sea Lice
- Total Mortality Rate
- Natural Mortality Rate
- N Content in Feed
- N Richness Elasticity
- Number of Escapes to Halve Native Cetaceans
- Original N Density
- Probability of Disease and Sea Lice Inside Pens (two separate parameters)
- Probability of Disease and Sea Lice Outside of Pen (two separate parameters)
- Sediment Density
- SLICE Days

Probability of ISA Transmission

- Biomass Farm B
- Distance Between Farms*

Concession Profit

- Cages per Farm
- Concession Size
- Economic FCR*
- Mortality Due to Disease
- Total Salmon Mortality Rate
- Natural Salmon Mortality Rate
- Number of Workers
- Original N Density
- Other Operational Costs*
- Price Per Kilo*
- Probability of Disease Inside Pens*
- Slice Days
- Cost of Smolt

Profits to Artisanal Fisheries

- Mortality Due to Disease
- N Richness Elasticity
- Number of Escapes to Halve Native Predators

- Number of Escapes to Halve Native Prey*
- Probability of Disease Inside of Pens
- Probability of Disease Outside of Pens*
- Probability of Sea Lice Outside of Pens
- Slice Days

Profits to Tourism

- Biomass Farm B
- Escape Decay
- Mortality Due to Disease and Sea Lice (two separate parameters)
- Total Salmon Mortality Rate
- Natural Salmon Mortality Rate
- Number of Escapes to Halve Native Cetaceans*
- Number of Escapes to Halve Native Predators*
- Number of Escapes to Halve Native Prey*
- Probability of Disease Inside Pens
- Probability of Disease Outside Pens*
- Probability of Sea Lice Outside Pens

Expected Costs of Regulation Due to Labor Violations

- Average Fine for Hours Violations*
- Average Fine for Wage Violations*
- Number of Workers

Parameters with asterisks had the most significant affect on the outcomes under which they are listed.

Parameters that have an affect on four or more of our outcomes of interest include: Escape Decay; Mortality Due to Disease; Mortality Due to Sea Lice; Total Salmon Mortality Rate; Natural Salmon Mortality Rate; N Richness Elasticity; Number of Escapes to Halve Native Predators; Original N Density; Probability of Disease Inside Pens; Probability of Disease Outside Pens; Probability of Sea Lice Outside Pens; and Slice Days. Our discussion will focus on these most impactful parameters.

Increased certainty in parameter values that, when held constant, result in a narrower range of observed values for the outcome in question will lead to greater certainty and increased accuracy of our model results for those outcomes. Changes to the shape of a distribution (e.g. skews, smoothing, shrinking) resulting from holding a given parameter constant suggest the type of results that can be expected for that outcome with greater certainty in that parameter.

For example, the parameter Mortality Due to Disease affects six of our ten outcomes of interest. It has a particularly great effect on Species Health, and therefore impacts all the things that depend on Species Health (i.e. Ecosystem Health, Profits to Artisanal Fisheries, Profits to Tourism) and also noticeably impacts Concession Profit. Below are the graphs for Species Health and Concession Profit from the base Monte Carlo run (Figure 38 and Figure 39):

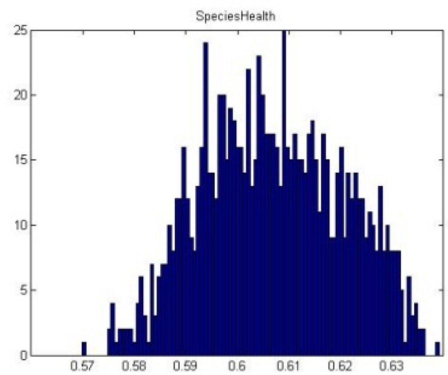


Figure 38: Monte Carlo Base Run for Fractional Change in Species Health (0-1)

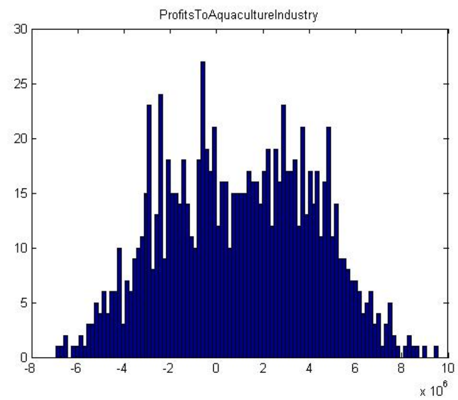


Figure 39: Monte Carlo Base Run for Concession Profit (USD)

Holding Mortality Due to Disease constant at its midpoint value causes the adjustments in these histograms (Figure 40 and Figure 41):

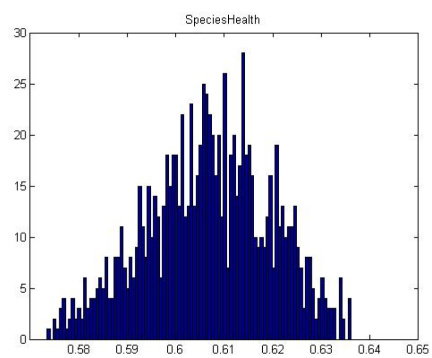


Figure 40: Monte Carlo with Midpoint value of Mortality Due to Disease for Fractional Change in Species Health (0-1)

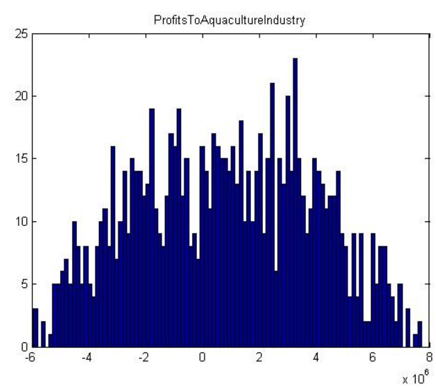


Figure 41: Monte Carlo with Midpoint value of Mortality Due to Disease for Concession Profit (USD)

Certainty about this parameter both compresses the ranges of these outcomes and adjusts their distributions.

Discussion

Predictions for the Magallanes

Default Values

The results for the default model run can be interpreted as follows: The value of 0.67 for the Species Richness Index implies that after one cycle, species richness will have decline by 33% within a 100 meter ellipse of the concession. The Species Abundance Index of 0.69 means that 31% of animals in the assessed trophic levels (predator, prey, cetaceans, and benthos) will have been killed. The Species Health Index value of 0.60 means that 40% of animals in the predator, prey, and cetacean trophic levels will be infected with IPN or sea lice. An Ecosystem Health Index of 1.97 means that overall Ecosystem Health has been reduced 34% as measured by our three species indices. The Area Affected under our default conditions is 19,210 km^2, and profits to the industry are $2,716,870 US. Fractional changes in Profits to Artisanal Fisheries and Tourism are 0.87 and 0.48 respectively, implying 13% and 52% reductions in species important to these industries. There is a 0.057% probability that the concession will contract ISA, given its presence at a neighboring farm. Lastly, the Expected Costs of Regulation are $1,479.48 US.

This combination of outcome values represents a system that, after one cycle of aquaculture at our default input conditions, is moderately affected by the presence of that one concession. Concession Profit are remarkably high after just one harvest cycle, and losses to Artisanal Fisheries are not overwhelmingly negative, in part because these fishermen are able to catch and sell the escaped salmon. Ecosystem Health and Profits to Tourism, however, have suffered relatively large losses, and it is important to remember that all of these values could change significantly after multiple aquaculture cycles over a number of years. Our default values are assumed to represent the “average” conditions that can be expected in the Magallanes based on the currently approved management practices for that part of the world, but the real strength of our model lies in its ability to be used by managers and regulators to make informed decisions about what practices to choose, or which concession proposals to approve. These default values result in outcome values that are not optimal. According to our model, these values can be improved for all ten of the outcomes of interest. The use of our model to inform these improvements is further detailed below.

Input Ranges

Histograms

By completing more than 122 thousand model runs where all inputs were varied across their possible ranges we were able to create frequency histograms representing the entire ranges of possible values for our Outcomes of Interest. Each of these frequency histograms is discussed in detail here.

Species Richness (Figure 20)**:** In most model runs, Species Richness of the benthos decreased by 100%. In other words, there is a complete loss of species richness as measured by the Shannon Index. The clustering of additional runs around a 17% loss could imply that some ideal combination of inputs results in this low impact of 17% and allow for species richness to remain high. Depth and current speed are the only inputs affecting species richness. The large disparity between the results could be indicative of a threshold, where certain input values or a combination of input values for depth and current speed could result in a complete loss. This would mean that placement of a concession with respect to the depth of the sea floor and the existing current speeds are extremely important to benthic species.

Species Abundance (Figure 21): After one production cycle, Species Abundance is highly variable. About half of the model runs show species abundance remaining relatively unchanged, while the other half show drastic decreases in species abundance. Species Abundance is a measure of the fractional change in the *number of individuals* in each of the assessed trophic levels. In our model it is most affected by predation and competition by escaped salmon and chemical output from SLICE treatments. Thus, it is likely that the number of escapes, which is a factor of the Technology Class in place, as well as the number of chemical treatments applied, are having the largest affect on the native species abundance. In runs where one or both of these two inputs were set at higher values the Species Abundance would fair poorly, and where they are set low Species Abundance will be less affected.

Species health (Figure 22): Our results demonstrate that Species Health remains relatively high, with a high percentage (approx. 80%) of individuals remaining free of disease and parasites after one production cycle, in about one quarter of the runs. In the other approximately ¾ of the more than 122,000 model runs Species Health is reduced by between about 25% and 75%. In our model disease and sea lice are only spread to the native species by escaped salmon, which are a factor of the Technology Class in place. Class 1 net pen technology allows a full 30% of salmon to escape in a given cycle, while Class 2 reduces this percentage to 20%. Current net pen technology (Class 3) successfully prevents all but 5% of salmon from escaping in a single cycle, while Class 4 technology (the hypothetical next move for aquaculture in southern Chile) prevents practically 100% of escapes. This input was allowed to vary over this entire range, with each Class being selected an equal number of times, thus, it follows that the model runs which resulted in a high value for the Species Health Index corresponded to those runs where Class 4 was selected, and the other three technology classes resulted in the remaining spread of values.

Ecosystem Health (Figure 23): Ecosystem Health is an index composed of the sub-model results describing species health, abundance, and richness, with each equally affecting the overall projection of the health of the surrounding ecosystem. Despite species health remaining relatively high after a single production cycle, the high frequency of complete losses in benthic species richness coupled with the variability observed in species abundance, results in a varied Ecosystem Health frequency distribution.

Concession Profit (Figure 24): Concession Profit, which were calculated by subtracting operational costs from the revenue gained from selling the salmon, are dependent on nearly every input we assessed. This is because many of the inputs represent variable costs to the industry, and in addition the functioning of those inputs within the aquaculture production system directly affects harvest, and consequently profit. Because every input was varied over a range of values, we expect the effect on profit to vary greatly. Profit is a direct reflection of harvest, and the amount of salmon harvested is largely dependent on the initial number of salmon entering the farm. Therefore, the initial number of young salmon entering the production cycle is likely having the greatest affect on profit, and on the variation in the results.

Area affected (Figure 25): The area affected by salmon farming impacts was determined only by current speed and depth. The resulting area affected had a wide range, but the majority of runs resulted in an area affected of 0 km^2. High current speeds result in a greater impact area due to the fact that higher current speeds carry nutrients and chemicals greater distances from salmon farming operations. Low current speeds transport these same materials at a smaller distance, decreasing the impact area. There are tradeoffs between high and low currents and their affects on the size of an impact area. While high current speeds increase the area of impact, and distribute materials greater distances, resulting in more widespread potential effects, they also dilute material concentrations so that effects at farther distances are likely weaker. Low currents result in smaller impact areas, which are beneficial in localizing the impacts of salmon farming to a smaller area, though the negative effects on ecosystem health within that area are greater. These same tradeoffs exist for varying depths. Greater depths decrease the propensity for settled material to be suspended or mixed into the water column. This however allows for chemicals, nutrients and organic matter from farming operations to accumulate, which may amplify the negative effects on the benthos. Shallow depths can have the opposite effect, where settled materials can be easily re-suspended, carried, and distributed over a larger area, which can minimize negative impacts to the benthos by stopping accumulation.

Profits to Tourism (Figure 26): There is a large range in the effects of salmon farming to profits for the tourism industry. The majority of runs show little to no change, or complete changes to profits. Like profits to the artisanal fisheries sector, these results are based on the fractional changes in the abundance of certain trophic levels, in this case cetaceans, predators, and prey. However, unlike with artisanal fisheries the tourism sector experiences no positive effects from the presence of the aquaculture industry. The tourism industry in southern Chile is largely comprised of sport fishing, but is also contributed to by whale watching, and other ecotourism activities. Profits rely heavily on pristine landscapes and abundance of native marine animals, specifically fin fish and cetaceans. Thus, in our model, as the predator, prey, and cetacean trophic levels decrease in abundance so too do the tourism industry profits.

Profits to Artisanal Fisheries (Figure 27**):** Profits to Artisanal Fisheries is an index for which a value of 1 represents no change. This graph shows that the most frequent result after more than 122 thousand model runs, was little to no change after one production cycle. Artisanal fishing profit is dependent on the abundance of specific commercially important species, represented in this model by the predator, prey, and benthic trophic levels. Any effect that salmon farming has on those abundances will directly affect artisanal fishing profit. However, these effects (which as discussed above are generally decreases) are offset to some degree by the presence of escaped salmon, which the artisanal fishermen are able to catch and sell at a very high market price. This accounts for the relatively high frequency of model runs where the Profits to Artisanal Fisheries comes out greater than 1. However, because these effects are only measured for one production cycle, and because Atlantic Salmon generally do not establish in the waters of southern Chile, it cannot necessarily be expected that this pattern would continue through time. Like Ecosystem Health, the cumulative effects from multiple production cycles would most likely yield a stronger negative effect.

Expected Cost of Regulation for Labor Violations (Figure 28): Potential and expected cost of regulation for labor violations are affected only by the number of violations, the average cost of labor violations (which is assumed to be constant) and, in the case of expected cost, the constant parameter describing the probability of detection. The total regulatory costs for a company in any one cycle will be simply their number of fines multiplied by the average price of one fine. Therefore, the more violations a company commits in one cycle, the greater their total punitive costs will be. Expected cost will always be lower than potential cost, because this outcome incorporates the *probability* of the violations actually being detected by a regulatory agency or monitoring body. In our model this probability is set at 12% per cycle. If this probability of detection were to increase or decrease, the expected cost of regulation for labor violation would change respectively.

Probability of ISA Transmission (Figure 29): The probability of an ISA transmission occurring in a given cycle is naturally low because it is not a common virus in the Magallanes.

Efficiency Frontiers

We found a number of tradeoff relationships between various outcomes of interest that we chose to examine more closely with scatter plots that highlight efficiency frontiers (Figure 30 through Figure 36). Each point on these graphs represents a hypothetical salmon farming concession in the Magallanes. It is easy to see from these graphs that there are many possible management decisions that are not efficient, regardless of which outcomes one cares about. Points that fall toward the bottom left corners represent input value combinations that result in sub-optimal performance for both outcomes. If an aquaculturist (or policy maker) were to use this model as a planning tool, he or she would avoid farming practices that result in those outcome pairs, if their goal is to maximize efficiency. There are many potential input combinations that fall on the efficiency frontier that lead to favorable outcomes for one factor, with less favorable results for the other. In these cases, managers must make decisions based on their values, and difficult tradeoffs might need to be made.

For all graphs where Concession Profit was one of the outcomes of interest being examined, we chose to show both the full graph, on which negative profit values obscure patterns found for positive profit values, as well as a "zoomed in" version where results for all model runs where profits were positive are displayed.

For example, the comparison of the results for Ecosystem Health and Concession Profit from all possible input combinations shows that, within the full range (Figure 30), it is possible to have negative profit values across the whole range of Ecosystem Health values, including when Ecosystem Health is high. Additionally, some of the lowest profit values result in the highest Ecosystem Health scores. This is likely due to the fact that if ISA is discovered early in the cycle, the fish will all be removed before a great deal of damage can be caused to the surrounding environment.

When we focus in on the range of possible positive values for Concession Profit as they relate to Ecosystem Health scores (Figure 31), we can see that there are a number of input combinations that result in very high profits, but significant decreases in Ecosystem Health. There are also a number of results where Ecosystem Health fairs very well, but the Concession Profit are extremely low. What makes this relationship interesting is that there are actually a number of management decisions that lead to relatively high values for both of these outcomes. The points in the upper right corner of the graph represent input combinations that maximize Concession Profit while at the same time leading to only a slight reduction in Ecosystem Health.

In order to better understand the management decisions that led to this optimal set of outcomes, we examined the input values for this model run, as well as for runs that resulted in combinations of the highest and lowest Ecosystem Health and Concession Profit values (Table 4). Examination of these values shows that the number of starting smolt is very influential, with the lowest numbers of smolt resulting in the best Ecosystem Health scores, and the highest number of smolt resulting in the highest Concession Profit scores. However, this is not the only input affecting the outcomes of these hypothetical concessions. The optimal concession input values demonstrate that with slow currents and shallow depths, as well as the use of technology that falls within our Class 4, Ecosystem Health can actually be nearly maximized with while achieving a Concession Profit that is nearly maximized. Three additional inputs that are worth noting are the Number of Net pens and the Numbers of Wage and Hours Violations. Our model shows that higher numbers of net pens are better for both Ecosystem Health and Concession Profit, while lower numbers of violations improve profits without decreasing Ecosystem Health at all. Managers concerned with either of these two outcomes could easily make improvements based on this information.

The second relationship we examined was the trade off between Concession Profit and Profits to Artisanal Fisheries (Figure 32). The relationship displayed on the full graph for these two outcomes shows that conditions resulting in negative profits (caused by an ISA outbreak) generally result in little to no change to profits to artisanal fishermen. This likely occurs because our model does not show cumulative effects, so any negative impacts on native species that might occur due to an outbreak of the ISA virus are not captured.

The zoomed graph for these two outcomes (Figure 33), displaying only positive profit values, is an excellent demonstration of an instance where the efficiency frontier technique can be especially useful. The points that fall along the outer right bound of the distribution represent the most efficient possible combinations of outcomes, and any points inside this frontier are sub-optimal for those two outcomes. However, unlike the relationship between Ecosystem Health and Concession Profit, here there are no points where both outcomes are equally maximized. When Concession Profit are maximized, Artisanal Fisheries profits are low, and vise versa. Interestingly, this same relationship can be observed in the graph comparing Ecosystem Health to the fractional change in Artisanal Fisheries (Figure 34). This is because of the benefit that artisanal fishermen can gain from catching and selling escaped salmon, while escaped salmon decrease both Ecosystem Health index and the Concession Profit. However, points that maximize Concession Profit, and points that maximize Ecosystem Health on their respective graphs all decline when profits to Artisanal Fisheries are hardly impacted, if at all (scores around 1). Managers and regulators can make decisions about management practices based on which of these industries is most valuable to a specific region. An especially interesting area for further exploration would be the creation of a three-dimensional efficiency frontier graph comparing all three of these outcomes. With this tool, one could identify management decisions that maximize Ecosystem Health and Concession Profit with minimal, if any, reductions in Profits to Artisanal Fisheries.

The relationship between the Probability of an ISA Transmission and the full range of Concession Profit can be seen in Figure 35. In this graph, it is especially clear that model runs resulting in negative profits were those in which an infection of ISA occurred and was detected. Figure 36, however, which shows the close-up of the upper right quadrant of this graph, shows that higher values for probability of ISA occur around the midrange values for Concession Profit. The highest and lowest profits are associated with zero probability of ISA transmission. This is due to the relationship between the biomass at the farms and the expected costs of collapse due to ISA. High profits are achieved when biomass is high and risk of ISA is low; however, when biomass is too great there is virtual inevitability that an ISA outbreak will occur, which results in total loss of Concession Profit.

Concession EIA Case Studies

Our ranking results for the 21 Magallanes concessions show how each concession performs on each outcome of interest and how they performed in comparison with each other. We chose to focus on the tradeoffs of two important outcomes, Concession Profit and Ecosystem Health, and we displayed these results in a scatter plot that highlights the efficiency frontier that highlights the tradeoffs between them (Figure 37).

It is clear from this graph that most of the points do not fall along the efficiency frontier. This means that of the 21 concessions, the majority are underperforming on maximizing profit for Ecosystem Health. When we examine inputs of the three points that fall along the efficiency frontier, Concessions E, F, and R, along with inputs for Concession O, which falls far below the efficiency frontier, we can determine key differences that have great effects on the outcomes. When these four concessions are ranked based on their benefit to Ecosystem Health and Concession Profit, the single biggest difference affecting these outcomes is the number of salmon at start (see Table 7). Concession F, which has the least impact on Ecosystem Health, starts the cycle with 840,000 salmon. On the other hand, Concession R has 2,400,000 salmon at start, and ranks first in Concession Profit but low for Ecosystem Health. Concession E, which is a midpoint between Concession F and R along the efficiency frontier, starts with 1,560,000 salmon and balances the outcome values for Concession Profit and Ecosystem Health. Although other factors might affect Ecosystem Health and Profits, including Average Current Speed, Number of Workers, and Number of Months in a Cycle, when there is such a large variation in the Number of Salmon at Start, the impacts of all other inputs and parameters are relatively insignificant. For a full list of input values for each of the 21 Concession EIAs, see Appendix D.

Table 7: Concession EIAs with Input Values

Ranked on concession benefit to Ecosystem Health									
Concession	Number of Netpens	Number of Months in Cycle	Equipment Quality	Number of Salmon at Start	Average Current Speed in cm/second	Feed Conversion Ratio	Percent of Feed Eaten	Number of Workers	Average Depth of Seafloor in meters
F	24	14	3	840,000	4.20	1.20	92	10	60
E	24	18	3	1,560,000	3.96	1.20	95	8	60
O	18	14	3	1,300,000	3.00	1.25	97	5	260
R	20	16	3	2,400,000	25.50	1.10	99.5	36	120

Ranked on concession benefit to Concession Profit									
Concession	Number of Netpens	Number of Months in Cycle	Equipment Quality	Number of Salmon at Start	Average Current Speed in cm/second	Feed Conversion Ratio	Percent of Feed Eaten	Number of Workers	Average Depth of Seafloor in meters
R	20	16	3	2,400,000	25.50	1.10	99.5	36	120
E	24	18	3	1,560,000	3.96	1.20	95	8	60
O	18	14	3	1,300,000	3.00	1.25	97	5	260
F	24	14	3	840,000	4.20	1.20	92	10	60

* Values in gray are default values from the model due to missing data in the EIAs

Efficiency graphs can be used to identify specific adjustments that should be made to move a concession towards the efficiency frontier. When this efficiency frontier is compared with the frontier describing all possible combinations of input values and their outcomes for Ecosystem Health and Concession Profit (Figure 31), it appears that even the most efficient of these 21 real concessions could make significant improvements to both of these outcomes to achieve even greater overall benefit. In fact, none of the 21 concessions are fully maximizing Concession Profit or Ecosystem Health. It may seem strange that managers would not already be optimizing their operations, at least with regards to profits; however, it is our assertion that concessions do not maximize these outcomes because managers simply do not have access to all of the information to make the most informed decisions regarding farming practices. For example, managers might be choosing to employ net pen technology that falls into our Technology Class 3 because it is somewhat cheaper than technology in Class 4. However, if they were knew the financial impacts of the relatively high escape rate, coupled with the relatively low maintenance costs of switching to Class 4, they might in fact choose to make the switch because it seems economically preferable. And in doing so, they could also greatly increase the Species Abundance and Species Health outcome of their concession.

With this tool, managers can see how a proposed concession would perform with its given inputs, and could then make adjustments to the concession to increase

Concession Profit, strengthen Ecosystem Health, or maximize both simultaneously. If a manager wants to improve Ecosystem Health at Concession R, he or she can make modifications to the inputs such as reducing the starting number of smolt and using the model to see what effect this has on Concession Profit. If the starting number of salmon for Concession R were reduced to 2,000,000, while holding all other inputs constant, Ecosystem Health would increase by more than 10% while Concession Profit would decrease by 17%. Additionally, regulators can use our model to rank new concession proposals to help choose which concessions to approve based on which outcomes they value the highest. They could also offer conditional approval to proposed concessions that do not fall on the efficiency frontier, under the stipulation that adjustments be made to the management plan to move this concession's scores towards the frontier.

Though we have chosen to display a tradeoff between Concession Profit and Ecosystem Health, any combination of two outcomes can be examined to view the tradeoff relationship, making this tool highly useful for aquaculturists, policy makers, environmentalists, artisanal fishing and tourism industries, and any number of other stakeholders.

Elasticity Matrix

The number of Smolt at Start is the greatest factor affecting the outcomes of interest. Every environmental outcome is negatively impacted by an increase in Number Smolt at Start, but increased Salmon at Start also corresponds with increased profits, demonstrating that Concession Profit is at odds with many other interests. If it is a priority to preserve ecosystem health, then managers and policy makers could consider incentives for aquaculturists to limit the number of salmon they grow to curb environmental externalities while still ensuring profits to the aquaculture industry.

In addition to Salmon at Start, the increasing Length of Cycle also results in an increase in Concession Profit. Although it might be expected that the industry is already maximizing their profits by harvesting at the optimal time, there are tradeoffs that cause salmon farmers to use sub-optimal cycle lengths. This behavior may result in a minor benefit to the environment, as indicated by the elasticity matrix. An interesting pattern in our results is that the Probability of ISA transmission is increased with concurrent increases in Cycle Length and Number of Salmon at Start. This highlights a potential tradeoff between this outcome and Concession Profit, implying that choices aquaculturists might to increase their profits could also be increasing their risk of their farms contracting ISA.

The Expected Cost of Labor Violations is dependent on the number of violations committed at the aquaculture concession. As such, it is sensible that increased violations lead to an increase in expected cost for those violations. Interestingly, Wage Violations has a slightly larger proportional impact on the outcomes than Hours Violations, perhaps because fines are higher for this type of violation.

Equipment Quality affects many of the outcomes of interest, all in favorable directions. Increasing the Equipment Quality from Class 3 to 4 impacts Profits to Tourism most heavily, with a decrease in the salmon escape rate leading to an increase in tourism profits. This is likely because tourism relies on healthy and abundant populations of native marine species, which are adversely impacted by escaped salmon. Ecosystem Health and Profits to Artisanal Fisheries increased with an improvement in Equipment Quality because native species are not harmed by escaped salmon, which also means that artisanal fishers can catch their traditional target species. All of these benefits occur with a slight increase in Concession Profit. Therefore, switching from technology class 3 to 4 is an improvement that could lead to benefits for all these stakeholders.

Sensitivity Analysis

Our sensitivity analysis revealed that increased certainty about many of our parameter values would improve the precision of our model results. Nearly all of the 34 parameters examined impacted at least one of our model outcomes, and 12 parameters impact four or more outcomes. For the purposes of this discussion, we will focus on the parameters that affect Ecosystem Health and Concession Profit.

The range of values for Ecosystem Health is impacted by 21 of our 34 parameters. This is because this outcome is a combination of the scores for Species Health, Species Abundance, and Species Richness, which are each calculated using many of our model parameters. However, none of these 21 parameters on its own makes a particularly large impact on the range size or shape of the distribution for Ecosystem Health, which is likely because the effects of each are distilled through combination with the others. Closer inspection reveals that holding N Content in Feed, Mortality Due to Disease, and N Richness Elasticity constant at their midpoint values have substantial effects on the distributions of Species Richness, Species Health, and Species Abundance, respectively. When held constant, N Content in Feed narrows the range of the Species Richness outcome values, and increases the frequency of model runs in which this outcome gives a result of the approximate median value of 0.7. When Mortality Due to Disease is held constant, the range for Species Health narrows slightly, the frequency of outcome values near the median (approximately 0.615) increases considerably, and the frequency of outlier values decreases. Similarly, holding N Richness Elasticity constant greatly increases the frequency of the Species Abundance score of approximately 0.695 (the median) and decreases frequency of extreme values. Therefore, further research into the true values for these three parameters can have a large influence on the ability of our model to predict accurate values for these outcomes of interest.

Concession Profit is also affected by a relatively large number of our parameters (13) because it is is calculated by combining several other model results. However, there are four parameters that each have a particularly large affect on the distribution for this outcome. These parameters are Economic FCR, Market Price Per Kilo of Salmon, Probability of Disease Within Pens, and Other Operational Costs. When held constant, Economic FCR causes the range of the Concession Profit distribution to shrink. Interestingly, it also leads to considerable widening and flattening of the distribution. In other words, greater certainty in this parameter allows for variability in other parameters to dictate the resulting Concession Profit value. Holding the Probability of Disease Within Pens or the Other Operational Costs constant has the opposite affect, leading to an increase of midrange values and a more bell shaped distribution.

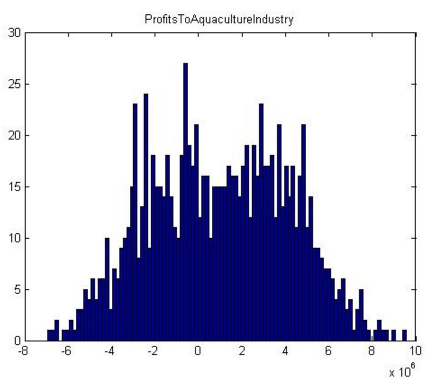


Figure 42: Monte Carlo Base Run for Concession Profit (USD)

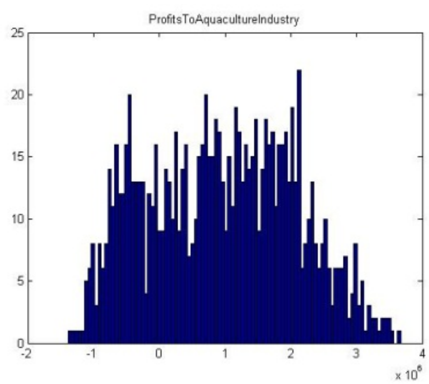


Figure 43: Monte Carlo with Midpoint Value for Price per Kilo for Concession Profit (USD)

The Price per Kilogram of Salmon, when held constant, has a substantial affect on the distribution for Concession Profit (Figure 42 and Figure 43). First, the range is greatly decreased from a spread of -$6,500,000 to $9,800,000 in the base Monte Carlo run to a spread of -$1,400,000 to $3,600,000 in the Monte Carlo run with Price per Kilogram held constant. Additionally, the distribution in the midpoint run is skewed towards the low end of the range, and the frequency of values is more evenly distributed between approximately -$500,000 and $2,000,000. In our model, we used an average price per kilogram of salmon compiled from prices over a recent 14 month period. Isolation of this parameter at its true value at the time of the model run would be a particularly impactful change for managers wishing to use our model to predict the results of their decisions on the profits after completion of one cycle of aquaculture.

Caveats

The model we have constructed has the potential to act as a management tool; however, there are some important caveats pertaining to its use and reliability. Caveats about specific sub-models are discussed in detail in the methods sections of those sub-models, but those more general to the model and its implementation include the following:

Scope and Detail: As discussed in section on data constraints and project scope, our model has boundaries regarding the breadth of its reach and the depth of detail that it includes. Due to the short time frame of this project (one year), we had to make tradeoffs between these two aspects in order to maximize the usefulness of our final product, and it is undeniable that the scope is much broader than the detail is fine. However, it is our hope that future enhancements of the model and the data therein can improve its comprehensiveness and reliability.

Cumulative effects over time: At present, the model only takes into account effects of one harvest cycle. The main implication here is that the model tends to suggest underestimated amounts of many environmental effects. For example, over multiple cycles the impacts of excess waste and chemicals are likely accumulate, although not necessarily in a simple additive fashion. The concentration of copper in surrounding sediments, for example, that accrues after one harvest cycle may be of little concern, but after several years of copper deposition, the sediments could become inhospitable to important benthic species.

Cumulative effects over space: Due to a lack of spatially explicit data in the concession proposal EIAs, we were unable to model cumulative effects over space. One of the most important pieces of missing data was the spatial arrangement of farms within concessions. To model cumulative effects of impacts including nutrient and chemical pollution, it would be necessary to know the amount of space between farms within a given concession (and between farms of different nearby concessions). Pollution impact areas resulting from farms that are closer together, or in areas of higher current speeds or water depth, are more likely to overlap and therefore cause cumulative effects on marine life.

Accuracy of EIA data: EIAs were used to establish default and range values for most inputs and some parameters. In basing values on these data, we assume that they correctly represent actual farming practices and environmental conditions. Some of the information given in the EIAs, however, could be considered suspect, such as the commonly reported FCRs in the range of 1 to 1.3. Much of our research indicates these values could be significantly higher, possibly in the range of 1.7. There is also a notable source of potential bias, as it is the aquaculturists themselves that complete these proposals. Aquaculture companies seeking approval of their concession clearly have an incentive to put forward favorable estimates.

Accuracy of the Model: Due to limited data availability, outcome values are not expected to be completely accurate; conclusions, therefore, serve to suggest the direction and magnitude of recommended change based on changes in inputs, but not necessarily the exact values that will be observed. Indications of the direction and magnitude of effects can still be used to confidently compare the potential impacts of multiple proposed concessions and rank them based on the outcomes that are of most interest.

Parameter and Default Input data: We used what we believed to be the best available values for the default inputs and parameters in our model and we believe that they lead to results that are of a level of reliability consistent with the scope and depth of the model. However, these values can be thought of as placeholders for better data as it becomes available. In particular, many of our parameter values are based on information from other parts of the world due to the distinct shortage of information specific to the Magallanes. Increased region-specific accuracy in these values will result in a more robust model. With our sensitivity analysis, we identify the parameter values to which the model is most sensitive. These are the parameters that would be most beneficial to have better information in in order to improve the model's accuracy. Future research efforts should be focused on these values first, if the goal is to improve the accuracy of predictive tools such as ours.

MATLAB: Due to its level of complexity and the need to run many thousands of scenarios to achieve broadly meaningful results, we housed our model in the computer software program MATLAB. It will therefore require someone familiar with the program, and with sufficient computing capacity, to run future simulations and analyses. It is our hope that this will not be a major obstacle in the model's implementation in aquaculture decision-making processes.

Recommendations to the Industry

Our model results lead to some recommendations for the salmon farming industry and policy makers in southern Chile. These recommendations are aimed mainly at regulatory agencies such as Subpesca and Sernapesca, but also at SalmonChile, as this industry group has significant influence in shaping industry standards. Another audience for these recommendations includes the salmon farming companies themselves, who have a clear stake in the success of their industry.

One of the main benefits of the model that we have created is that it highlights the industry practices that have the greatest effect on the outcomes of interest. Our elasticity matrix (Table 6) highlights the number of smolt at the start of the cycle as an input that has strong effects on many outcomes. If managers wish to increase Concession Profit, they would be advised to start with more smolt; however, this decision comes with a predicted increase in probability of ISA transmission and decreased tourism profit, fisheries profit, and ecosystem health. One way to diminish the risk of ISA transmission could be to reduce the length of the cycle. There are more relationships between inputs and outcomes that can lead to specific recommendations for salmon farming managers.

Since one of the primary stakeholders is the aquaculture companies operating in the Magallanes, a point of interest is the impacts that our inputs have on Concession Profit. Our analysis identifies the potential to increase industry profits with equipment upgrades. Moving to newer technology, such as copper cages, results in a 13% increase in profit, while simultaneously improving most other outcomes of interest, including a 25% increase in Ecosystem Health and a 111% increase in tourism profits. Therefore, equipment upgrades are a promising option for improving both environmental and industry outcomes.

Another major stakeholder group comprises those interested in the ecological integrity of the Magallanes coastal region, including our project client, WCS Chile. Our analyses show that Smolt at Start has the strongest influence on Ecosystem Health. Increasing this input results in a decrease in both Species Abundance and Species Health. These results highlight the opportunity to balance negative environmental impacts with industry profits by setting limits on the starting number of smolt.

Our model also helps illuminate industry practices that do not have great influence on the outcomes of interest. These inputs include Depth and Number of Slice Treatments. Implementing changes in these practices would lead to little effect on the outcomes of interest, so it is advisable to leave these practices at the status quo and focus attention on those inputs that have strong effects on important outcomes. This model primarily captures the direct effects of these inputs on our important outcomes. It's important to note, however, that some inputs that appear to have minimal influences on outcomes of interest could have indirect effects that are not accounted for in our model. For example, while regulatory costs of labor violations may not appear to have significant direct effects on Concession Profit, a history of repeated labor violations can negatively affect a company's reputation. If a company's reputation is compromised, distributors facing local and international pressure might stop purchasing from a company, resulting in negative effects on profits.

Another recommendation is for aquaculture managers (e.g. Subpesca) to utilize this model to assess future applications for salmon farming concession proposals. Many more concession proposals are expected as the industry grows in the Magallanes, and the ranking of proposals that we performed can be recreated by managers to help determine which future proposals should be accepted, and which should be denied. As demonstrated in this project, these rankings can be calculated to reflect various stakeholder interests, and can be especially useful in visualizing tradeoffs between outcomes. These rankings and the resultant efficiency frontiers can also be used to identify issues on which particular concessions should focus if they wish to improve their impacts in one or more outcome. For example, a proposed concession that ranks poorly in Ecological Health could be approved with contingency on extra monitoring or mitigation of potential ecological impacts.

Conclusions

The Model as a Framework

While our model offers an implementable tool for aquaculture managers in southern Chile, it is important to reiterate that this model is also meant to act as a framework that can be expanded upon and enriched to achieve more comprehensive and accurate results. In its current state, the model provides results that reflect the scope and level of detail that it contains, and we believe these results to be a reasonably reliable estimate of the influences of particular aquaculture practices on their associated outcomes. The model has the potential to be continually improved by adding data richness and extending its scope. Data richness can be achieved by obtaining more detailed and precise data (i.e. parameter values and mathematical relationships) that improve the accuracy of our sub-model results; the model's scope can be extended by incorporating new sub-models that capture additional impacts that salmon aquaculture can impart on its ecological and socioeconomic system, and by extending the reach of the current sub-models.

In addition to providing a base for increased depth and scope, another of the model's important functions as a framework is its potential to be applied to other regions of the world. Just as we collected data that was (to the extent possible) specific to the Magallanes region of Chile, the model could instead be populated with parameter values and equations that describe other geographical regions. For example, our sub-model describing the effects of farmed salmon escapes on native species focused on two species that are found in southern Chile. Parameters including the rates of population growth, intrinsic mortality, and energy conversion that describe these species currently fill out the sub-model, but these parameters could be replaced with those describing species in a different geographical region. Revising the relevant parameters and equations in each sub-model to reflect the conditions in a different region of interest would allow this model to be applied that part of the world.

Similarly, the model can be modified to focus on alternative sub-model subjects within the setting of the Magallanes. For example, if a manager is more concerned about the spread of an infection like IPN than of ISA, the sub-model predicting the risk of ISA infection can be modified to describe that other disease. This modification would require replacing parameters including the distance and biomass coefficients to reflect the characteristics of the alternate disease. In the same way, the escapes sub-model could be altered to focus on different wild prey species if, say, those species become more important to local artisanal fisheries.

As such, our model not only provides a relevant and immediately useful tool for aquaculture management in southern Chile, but also an important platform on which to build greater detail and breadth that can improve aquaculture management in that part of the world and beyond.

Suggestions for Further Research

As previously discussed, our model has limitations on its level of detail and scope. Suggestions for further research pertaining to the level of detail are discussed in the Sensitivity Analysis and Recommendations for the Industry sections; however, another important area of potential research lies in the breadth of topics that this model includes – the model's scope. At present, the scope is confined to the inputs, outcomes, and the sub-models that describe the relationships between them. Each of these sub-models in turn has defined boundaries beyond which it does not assess impacts. Therefore, the model could be expanded in two ways: 1) by building in new sub-models that address impacts that are not already incorporated in the model, and 2) by extending the reach of individual sub-models to assess impacts beyond its current conceptual boundary.

We believe that the inputs, outcomes, and sub-models included in the model represent the most important issues surrounding salmon aquaculture in southern Chile. However, new sub-model subject areas that could be added to the model to increase its comprehensiveness include: impacts of antibiotic use on farmed salmon, wild species, and humans; impacts on native predatory species like sea lions and birds; extent of wild fish harvest required to feed farmed salmon; and trade-offs between allocating space to large-scale salmon farming and other industries like tourism, artisanal fishing, and MPAs. If the model were to be applied to a part of the world where wild salmon fisheries exist, it would be important to add a sub-model predicting the impacts of farmed salmon on those wild populations. Sub-models describing subject areas like these would increase the scope of the model by addressing impacts that are it does not currently capture.

Extending the reach of each sub-model's conceptual boundary would also increase the scope of the model. For example, our sub-model describing Concession Profit could be extended to capture the total profits that a concession provides to the proprietary aquaculture company over one harvest cycle. This modification would require extending the measurement of financial costs and gains that are accrued to capture those along the length of the supply chain. Equally, the sub-models describing particular ecosystem effects (Species Richness, Health, and Abundance) could be extended to include ecosystem-wide impacts beyond the specific species or population characteristic that is their current focus. This modification would be of value in that it would assess cascading impacts and their effect on ecosystems as a whole.

Another important area for further research includes the cumulative effects of salmon aquaculture over time and space, which are not presently captured in the model. The model is currently limited to predicting the effects of a single harvest cycle, but impacts such as nutrient and chemical loading, ISA infection, and escapes are likely to accumulate over multiple harvest cycles in non-linear patterns. Similarly, the model does not presently capture the cumulative impacts over space, like converging impact areas of nutrient and chemical pollution and disease spread. Incorporating the cumulative patterns of these impacts would lead to more meaningful results for the aquaculture industry and other stakeholders.

Considerations for Industry Expansion in the Magallanes

As more salmon farming concessions are implemented in the Magallanes, spatial tradeoffs will have to be made that allocate coastal use rights between stakeholders including aquaculturists, fishers, tourism operators, conservationists, and other groups. The impacts predicted in our model can play into those tradeoff decisions. For example, the extent to which pollutants are expected to travel from a salmon farm due to currents could affect the best choice of placement of a MPA in order to avoid pollutants traveling into the MPA. Likewise, regional managers might want to consider the amount of revenue that different coastal industries could provide to the region; our model gives an idea of the amount of profit that can be gained from aquaculture operations.

Salmon farming is one of the most important economic activities in Chile (Buschmann et al 2009). However, its intensive production process coupled with its geographic expansion are likely to continue to impact coastal marine ecosystems, regardless of where or how it is practiced. This is continuing to cause concern among conservation groups like WCS, which has invested considerable resources into identifying areas of high conservation value in the Magallanes coastal region. One conservation solution that this group has proposed is the establishment of MPAs, which have the potential to offset some of the negative environmental impacts caused by salmon aquaculture. Given the many potential, and sometimes conflicting, uses of the Magallanes coast including aquaculture and MPAs, the regional government will have to determine its priorities for the region and evaluate the tradeoffs associated with allocation of spatial rights.

Towards Sustainable Salmon Aquaculture

Global demand for salmon is large and growing, especially as large consumer countries like China develop a taste for this fish. It is becoming increasingly the case that wild salmon populations fall short in meeting global demand, and this gap is continually widened as a result of the growing human population. Salmon farming is an obvious alternative to wild harvesting that has the potential to alleviate pressure on wild fish stocks while fulfilling global demand. However, salmon farming can have serious implications for ecological and socioeconomic systems on scales ranging from local to global. This practice should therefore be carried out with a high level of prudency in order to avoid compromising important ecological services and economic structures.

A crucial component of prudent management of salmon aquaculture is the ability to predict the effects of potential management decisions that represent differing farming techniques. This ability reduces reliance on "trial-and-error" management that can cause large and, in some cases, irreversible detriments to socioeconomic and ecological systems. The model that we present offers a tool to foresee the impacts that salmon farming could cause in a particular part of the world. With this tool, managers in southern Chile can base decisions regarding farming practices on their expected impacts on the local ecology and economy, leading to a more environmentally and economically sustainable industry. This model and other efforts to predict and manage the impacts of near-shore salmon aquaculture will be crucial as this industry increases in intensity and expands to new regions of the world.

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Appendices

Appendix A: Escaped Salmon

Predation Competition Equations
Beginning with basic Lotka-Volterra equations (amended to account for density dependent growth):

1. $\frac{dx}{dt} = x(\alpha - \beta y - \lambda x - \beta' E)$

and

2. $\frac{dy}{dt} = y(\delta x - \gamma - \mu y)$

where

- y = number of some predator species (e.g., hake)
- x = number of the predator's prey species (e.g., sardines)
- α = intrinsic growth rate of the prey species
- β = rate of predation on prey by native predators
- λ = density-dependent growth dampener for prey (negative growth rate)
- β' = rate of predation on prey by escaped salmon
- E = number of escaped salmon time zero
- t = time in months
- δ = conversion efficiency between prey and predators (i.e., how much the presence of prey "helps" predators)
- γ = intrinsic mortality rate of the predator species
- μ = density-dependent growth dampener for predators (negative growth rate)

we completed the following calculations.

System at equilibrium (no change in x or y):

3. $\alpha - \beta y - \lambda x - \beta' E = 0$

4. $y = (\alpha - \lambda x - \beta' E)/\beta$

and

5. $\delta x - \gamma - \mu y = 0$

6. $y = (\delta x - \gamma)/\mu$

set equal:

7. $\frac{\alpha - \lambda x - \beta' E}{\beta} = \frac{\delta x - \gamma}{\mu}$

8. $\alpha - \lambda x - \beta' E = \frac{\beta\delta x - \beta\gamma}{\mu}$

9. $\alpha - \lambda x - \beta' E + \left(\frac{\beta\gamma}{\mu}\right) = \frac{\beta\delta x}{\mu}$

10. $\alpha - \beta' E + \left(\frac{\beta\gamma}{\mu}\right) = x\left(\left(\frac{\beta\delta}{\mu}\right) + \lambda\right)$

11. $x = \frac{\alpha - \beta' E + \left(\frac{\beta\gamma}{\mu}\right)}{\left(\frac{\beta\delta}{\mu}\right) + \lambda}$

plug in for y:

12. $y = \frac{\delta\left(\frac{\left(\alpha - \beta' E + \left(\frac{\beta\gamma}{\mu}\right)\right)}{\left(\left(\frac{\beta\delta}{\mu}\right) + \lambda\right)}\right) - \gamma}{\mu}$

To solve for fractional change in number of prey individuals after addition of escapes (with system at steady state):

13. $\frac{x(with\ escapes)}{x(without\ escapes)} = \left(\frac{\alpha - \beta' E + \left(\frac{\beta\gamma}{\mu}\right)}{\left(\frac{\beta\delta}{\mu}\right) + \lambda}\right) * \left(\frac{\left(\frac{\beta\delta}{\mu}\right) + \lambda}{\alpha + \left(\frac{\beta\gamma}{\mu}\right)}\right)$

14. $\frac{x(with\ escapes)}{x(without\ escapes)} = \left(\frac{\alpha - \beta' E + \left(\frac{\beta\gamma}{\mu}\right)}{\alpha + \left(\frac{\beta\gamma}{\mu}\right)}\right)$

which simplifies to:

15. $\frac{x(with\ escapes)}{x(without\ escapes)} = 1 - \left(\frac{\beta' E}{\alpha + \left(\frac{\beta\gamma}{\mu}\right)}\right)$

which is linear.

To solve for fractional change in number of predator individuals after addition of escapes (with system at steady state):

16.

$$\frac{y(with\ escapes)}{y(without\ escapes)} = \left(\frac{\delta\left(\frac{\left(\alpha-\beta' E+\left(\frac{\beta\gamma}{\mu}\right)\right)}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)-\gamma}{\mu}\right) * \left(\frac{\mu}{\delta\left(\frac{\left(\alpha+\left(\frac{\beta\gamma}{\mu}\right)\right)}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)-\gamma}\right)$$

17.

$$\frac{y(with\ escapes)}{y(without\ escapes)} = \frac{\delta\left(\frac{\left(\alpha-\beta' E+\left(\frac{\beta\gamma}{\mu}\right)\right)}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)-\gamma}{\delta\left(\frac{\left(\alpha+\left(\frac{\beta\gamma}{\mu}\right)\right)}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)-\gamma}$$

which simplifies to:

18.

$$\frac{y(with\ escapes)}{y(without\ escapes)} = \frac{\left(\frac{\alpha\delta}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)-\left(\frac{\beta' E\delta}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)+\left(\frac{\frac{\beta\gamma\delta}{\mu}}{\left(\left(\frac{\beta\delta}{\square}\right)+\lambda\right)}\right)-\gamma}{\left(\frac{\alpha\delta}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)+\left(\frac{\frac{\beta\gamma\delta}{\mu}}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)-\gamma}$$

19.

$$\frac{y(with\ escapes)}{y(without\ escapes)} = 1 - E\,\frac{\frac{\beta'\delta}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}}{\left(\delta\left(\frac{\alpha+\left(\frac{\beta\gamma}{\mu}\right)}{\left(\left(\frac{\beta\delta}{\mu}\right)+\lambda\right)}\right)\right)-\gamma}$$

which is also linear.

Spread of Disease Equations:

Spread of disease or sea lice to native populations:

$$dh/dt = G - hm - \phi h(s + Z)$$ - Change in healthy animals,

$$ds/dt = \phi h(s + Z) - (s(m + v))$$ - Change in sick (or infested) animals,

Baseline values for native species are not known for southern Chile so placeholder values were used which would be sufficiently large to allow for the model to run throughout the length of a cycle. New healthy individuals in time 2 calculated as healthy individuals in time 1 plus change in healthy individuals. New sick/infested individuals in time 2 calculated as sick/infested individuals in time 1 plus change in sick/infested individuals. These calculations were done on a month to month basis for a number of months equal to the length of the cycle. Then fractional changes were calculated as follows:

$$FractionalChangeinHealthyIndividuals = h_{cycle} / h_{t=1}$$

where h_{cycle} = the number of healthy individuals in the month corresponding with the last month of the cycle, and $h_{t=1}$ = the number of healthy individuals at the start of the cycle. This process was repeated for the three trophic levels: predators, prey, and cetaceans.

Appendix B: Concession Profit

Harvestable Salmon by Month					
Month	Number of Salmon	Weight per Salmon in kg	Harvestable Salmon in kg	Value of Salmon in USD	Mortality Rate
at Start	1,400,000	-	-	-	-
1	1,362,120	0.039	48,794	214,947	2.17%
2	1,326,083	0.149	184,075	1,081,178	2.10%
3	1,294,050	0.325	391,127	2,297,310	1.86%
4	1,263,446	0.559	656,262	3,854,602	1.80%
5	1,240,523	0.843	972,088	5,709,628	1.24%
6	1,217,926	1.170	1,325,225	7,783,803	1.24%
7	1,199,789	1.534	1,711,106	10,050,306	0.90%
8	1,185,208	1.926	2,122,840	12,468,651	0.62%
9	1,170,981	2.340	2,548,288	14,967,552	0.60%
10	1,156,864	2.769	2,978,603	17,495,035	0.60%
11	1,143,319	3.204	3,407,047	20,011,536	0.56%
12	1,129,875	3.640	3,824,853	22,465,550	0.56%
13	1,119,355	4.069	4,235,328	24,876,502	0.31%
14	1,108,886	4.483	4,622,737	27,151,974	0.31%
15	1,098,468	4.875	4,980,181	29,251,449	0.31%
16	1,088,211	5.239	5,301,573	31,139,166	0.30%
17	1,078,004	5.566	5,580,082	32,775,009	0.30%
18	1,067,845	5.850	5,809,608	34,123,149	0.30%
19	1,057,734	6.084	5,984,313	35,149,291	0.30%
20	1,047,672	6.259	6,098,616	35,820,656	0.30%
21	1,037,658	6.370	6,147,191	36,105,968	0.30%
22	1,027,692	6.409	6,124,966	35,975,428	0.30%

Appendix C: Elasticity Matrix

`	Sp Rich	Sp Abund	Sp Health	Area Aff	Profit AQ	Profit AF	Profit T	Prob ISA	PotCost LV	ExpCost LV	Eco Health
#NetPens	0.2	0.0	0.0	0.0	-0.1	0.0	0.0	-1.7	0.0	0.0	0.1
Cycle	-0.2	0.0	0.0	0.0	1.2	0.0	0.0	5.1	0.0	0.0	-0.1
#SliceTx	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SalmonStart	-0.3	-0.4	-0.5	0.0	1.1	-0.1	-1.1	2.3	0.0	0.0	-0.4
Wage Violations	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.0
#HoursViolations	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0
CurrentSpeed	-0.8	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3
Depth	-0.7	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	-0.2
EQ Increased 3 to 4	0.01	-0.42	-0.35	0.00	-0.13	-0.12	-1.11	-0.06	0.00	0.00	-0.25
EQ Decreased 3 to 2	0.01	-0.10	0.04	0.00	-0.07	0.04	-0.33	-0.06	0.00	0.00	-0.02

Appendix D: Case Study Concession Data

<u>Concession Key</u>

Concession A: Península Morgan al Sur de Punta Lavapie
Concession B: Estero Poca Esperanza al Oeste de Punta Goddard
Concession C: Sector NorOeste Bahía Desilución, Isla Desolación
Concession D: Península Barros Arana al Este de Punta Obstrucción
Concession E: Canal Valdes al Norte de Caleta Fog
Concession F: Bahía Tranquila Sector 2
Concession G: Canal Cockburn, Isla Tierra del Fuego, Peninsula Brecknock
Concession H: Cultivo Canal Cockburn, Seno Chasco
Concession I: Canal Cockburn, Seno Brujo
Concession J: Isla Capitán Aracena-seno Lyell
Concession K: Canal Cockburn, Seno Chasco
Concession L: Sector Estancia María Olvido, Ensenada Ponsonby, Comuna de Rio Verde
Concession M: Sector Este Mina Elena, Ensenada Ponsonby, Comuna de Rio Verde
Concession N: Sector Río Los Palos, Ensenada Ponsonby, Comuna De Rio Verde
Concession O: Centro Piscicola Isla Riesco, Estuario Fanny, Este Penisula Fresia
Concession P: Bahía Easter, Canal Valdés, Comuna De Natales
Concession Q: Sector Weste Ex Isla Vergara, Comuna De Natales
Concession R: Sector Punta Vergara, Comuna De Natales
Concession S: Sector Paso Vattuone, Comuna De Natales
Concession T: Seno Skyring Surgidero Furia
Concession U: Seno Skyring Norte de Punta Laura

Ranking by Benefits to Species Richness											
Concession #	**Species Richness**	Species Abundance	Species Health	Affected Area	Concession Profit	Probability of ISA Outbreak	Percent of Profits to Artisanal Fisheries	Percent of Profits to Tourism	Potential Cost of Regulation for Labor	Expected Cost of Regulation For Labor	Ecosystem Health
F	0.94	0.82	0.73	4058	$1,813,961	0.00	0.87	0.69	$12,329	$1,479	2.24
E	0.92	0.67	0.48	3891	$4,740,505	0.00	0.76	0.42	$12,329	$1,479	1.72
D	0.89	0.71	0.52	6215	$4,029,660	0.00	0.82	0.50	$12,329	$1,479	1.66
N	0.87	0.66	0.48	3449	$4,708,033	0.00	0.77	0.41	$12,329	$1,479	1.39
T	0.81	0.78	0.74	14180	$1,332,890	0.00	0.91	0.63	$12,329	$1,479	1.63
S	0.77	0.55	0.43	11275	$7,300,427	0.01	0.80	0.20	$12,329	$1,479	0.90
Q	0.76	0.65	0.52	11548	$4,438,207	0.01	0.81	0.40	$12,329	$1,479	1.07
L	0.74	0.93	0.78	49814	$468,775	0.00	0.97	0.88	$12,329	$1,479	1.75
U	0.71	0.78	0.74	256916	$1,332,890	0.00	0.92	0.63	$12,329	$1,479	1.61
O	0.67	0.72	0.62	44868	$2,646,771	0.00	0.89	0.51	$12,329	$1,479	1.28
P	0.63	0.70	0.62	19210	$3,106,166	0.00	0.87	0.49	$12,329	$1,479	1.23
H	0.63	0.74	0.64	25540	$2,626,972	0.00	0.90	0.55	$12,329	$1,479	1.32
I	0.57	0.74	0.64	35751	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.32
M	0.52	0.65	0.48	31935	$4,708,033	0.00	0.86	0.41	$12,329	$1,479	1.03
G	0.49	0.74	0.64	84123	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
J	0.41	0.73	0.64	54819	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.31
K	0.34	0.74	0.64	260637	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
B	0.21	0.64	0.48	46131	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
C	0.15	0.64	0.48	51957	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
R	0.01	0.53	0.39	235033	$8,477,317	0.03	0.86	0.20	$12,329	$1,479	0.83
A	0.00	0.64	0.48	245183	$4,740,505	0.00	0.88	0.42	$12,329	$1,479	1.03

Ranking by Benefits to Species Abundance											
Concession #	Species Richness	**Species Abundance**	Species Health	Affected Area	Concession Profit	Probability of ISA Outbreak	Percent of Profits to Artisanal Fisheries	Percent of Profits to Tourism	Potential Cost of Regulation for Labor	Expected Cost of Regulation For Labor	Ecosystem Health
L	0.74	0.93	0.78	49814	$468,775	0.00	0.97	0.88	12329	1479	1.75
F	0.94	0.82	0.73	4058	$1,813,961	0.00	0.87	0.69	12329	1479	2.24
U	0.71	0.78	0.74	256916	$1,332,890	0.00	0.92	0.63	12329	1479	1.61
T	0.81	0.78	0.74	14180	$1,332,890	0.00	0.91	0.63	12329	1479	1.63
G	0.49	0.74	0.64	84123	$2,584,996	0.00	0.91	0.55	12329	1479	1.33
H	0.63	0.74	0.64	25540	$2,626,972	0.00	0.90	0.55	12329	1479	1.32
I	0.57	0.74	0.64	35751	$2,584,996	0.00	0.90	0.55	12329	1479	1.32
K	0.34	0.74	0.64	260637	$2,584,996	0.00	0.91	0.55	12329	1479	1.33
J	0.41	0.73	0.64	54819	$2,584,996	0.00	0.90	0.55	12329	1479	1.31
O	0.67	0.72	0.62	44868	$2,646,771	0.00	0.89	0.51	12329	1479	1.28
D	0.89	0.71	0.52	6215	$4,029,660	0.00	0.82	0.50	12329	1479	1.66
P	0.63	0.70	0.62	19210	$3,106,166	0.00	0.87	0.49	12329	1479	1.23
E	0.92	0.67	0.48	3891	$4,740,505	0.00	0.76	0.42	12329	1479	1.72
N	0.87	0.66	0.48	3449	$4,708,033	0.00	0.77	0.41	12329	1479	1.39
M	0.52	0.65	0.48	31935	$4,708,033	0.00	0.86	0.41	12329	1479	1.03
Q	0.76	0.65	0.52	11548	$4,438,207	0.01	0.81	0.40	12329	1479	1.07
B	0.21	0.64	0.48	46131	$4,740,505	0.00	0.87	0.42	12329	1479	1.01
C	0.15	0.64	0.48	51957	$4,740,505	0.00	0.87	0.42	12329	1479	1.01
A	0.00	0.64	0.48	245183	$4,740,505	0.00	0.88	0.42	12329	1479	1.03
S	0.77	0.55	0.43	11275	$7,300,427	0.01	0.80	0.20	12329	1479	0.90
R	0.01	0.53	0.39	235033	$8,477,317	0.03	0.86	0.20	12329	1479	0.83

Ranking by Benefits to Species Health											
Concession #	Species Richness	Species Abundance	**Species Health**	Affected Area	Concession Profit	Probability of ISA Outbreak	Percent of Profits to Artisanal Fisheries	Percent of Profits to Tourism	Potential Cost of Regulation for Labor	Expected Cost of Regulation For Labor	Ecosystem Health
L	0.74	0.93	0.78	49814	$468,775	0.00	0.97	0.88	$12,329	$1,479	1.75
T	0.81	0.78	0.74	14180	$1,332,890	0.00	0.91	0.63	$12,329	$1,479	1.63
U	0.71	0.78	0.74	256916	$1,332,890	0.00	0.92	0.63	$12,329	$1,479	1.61
F	0.94	0.82	0.73	4058	$1,813,961	0.00	0.87	0.69	$12,329	$1,479	2.24
G	0.49	0.74	0.64	84123	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
H	0.63	0.74	0.64	25540	$2,626,972	0.00	0.90	0.55	$12,329	$1,479	1.32
I	0.57	0.74	0.64	35751	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.32
J	0.41	0.73	0.64	54819	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.31
K	0.34	0.74	0.64	260637	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
O	0.67	0.72	0.62	44868	$2,646,771	0.00	0.89	0.51	$12,329	$1,479	1.28
P	0.63	0.70	0.62	19210	$3,106,166	0.00	0.87	0.49	$12,329	$1,479	1.23
D	0.89	0.71	0.52	6215	$4,029,660	0.00	0.82	0.50	$12,329	$1,479	1.66
Q	0.76	0.65	0.52	11548	$4,438,207	0.01	0.81	0.40	$12,329	$1,479	1.07
A	0.00	0.64	0.48	245183	$4,740,505	0.00	0.88	0.42	$12,329	$1,479	1.03
B	0.21	0.64	0.48	46131	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
C	0.15	0.64	0.48	51957	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
E	0.92	0.67	0.48	3891	$4,740,505	0.00	0.76	0.42	$12,329	$1,479	1.72
M	0.52	0.65	0.48	31935	$4,708,033	0.00	0.86	0.41	$12,329	$1,479	1.03
N	0.87	0.66	0.48	3449	$4,708,033	0.00	0.77	0.41	$12,329	$1,479	1.39
S	0.77	0.55	0.43	11275	$7,300,427	0.01	0.80	0.20	$12,329	$1,479	0.90
R	0.01	0.53	0.39	235033	$8,477,317	0.03	0.86	0.20	$12,329	$1,479	0.83

Ranking by Benefits to Profits to Aquaculture Industry											
Concession #	Species Richness	Species Abundance	Species Health	Affected Area	**Concession Profit**	Probability of ISA Outbreak	Percent of Profits to Artisanal Fisheries	Percent of Profits to Tourism	Potential Cost of Regulation for Labor	Expected Cost of Regulation For Labor	Ecosystem Health
R	0.01	0.53	0.39	235033	$8,477,317	0.03	0.86	0.20	$12,329	$1,479	0.83
S	0.77	0.55	0.43	11275	$7,300,427	0.01	0.80	0.20	$12,329	$1,479	0.90
A	0.00	0.64	0.48	245183	$4,740,505	0.00	0.88	0.42	$12,329	$1,479	1.03
B	0.21	0.64	0.48	46131	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
C	0.15	0.64	0.48	51957	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
E	0.92	0.67	0.48	3891	$4,740,505	0.00	0.76	0.42	$12,329	$1,479	1.72
M	0.52	0.65	0.48	31935	$4,708,033	0.00	0.86	0.41	$12,329	$1,479	1.03
N	0.87	0.66	0.48	3449	$4,708,033	0.00	0.77	0.41	$12,329	$1,479	1.39
Q	0.76	0.65	0.52	11548	$4,438,207	0.01	0.81	0.40	$12,329	$1,479	1.07
D	0.89	0.71	0.52	6215	$4,029,660	0.00	0.82	0.50	$12,329	$1,479	1.66
P	0.63	0.70	0.62	19210	$3,106,166	0.00	0.87	0.49	$12,329	$1,479	1.23
O	0.67	0.72	0.62	44868	$2,646,771	0.00	0.89	0.51	$12,329	$1,479	1.28
H	0.63	0.74	0.64	25540	$2,626,972	0.00	0.90	0.55	$12,329	$1,479	1.32
G	0.49	0.74	0.64	84123	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
I	0.57	0.74	0.64	35751	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.32
J	0.41	0.73	0.64	54819	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.31
K	0.34	0.74	0.64	260637	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
F	0.94	0.82	0.73	4058	$1,813,961	0.00	0.87	0.69	$12,329	$1,479	2.24
U	0.71	0.78	0.74	256916	$1,332,890	0.00	0.92	0.63	$12,329	$1,479	1.61
T	0.81	0.78	0.74	14180	$1,332,890	0.00	0.91	0.63	$12,329	$1,479	1.63
L	0.74	0.93	0.78	49814	$468,775	0.00	0.97	0.88	$12,329	$1,479	1.75

Ranking by Benefits to Probability of ISA Outbreak											
Concession #	Species Richness	Species Abundance	Species Health	Affected Area	Concession Profit	**Probability of ISA Outbreak**	Percent of Profits to Artisanal Fisheries	Percent of Profits to Tourism	Potential Cost of Regulation for Labor	Expected Cost of Regulation For Labor	Ecosystem Health
T	0.81	0.78	0.74	14180	$1,332,890	0.00	0.91	0.63	$12,329	$1,479	1.63
U	0.71	0.78	0.74	256916	$1,332,890	0.00	0.92	0.63	$12,329	$1,479	1.61
L	0.74	0.93	0.78	49814	$468,775	0.00	0.97	0.88	$12,329	$1,479	1.75
F	0.94	0.82	0.73	4058	$1,813,961	0.00	0.87	0.69	$12,329	$1,479	2.24
G	0.49	0.74	0.64	84123	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
H	0.63	0.74	0.64	25540	$2,626,972	0.00	0.90	0.55	$12,329	$1,479	1.32
I	0.57	0.74	0.64	35751	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.32
J	0.41	0.73	0.64	54819	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.31
K	0.34	0.74	0.64	260637	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
P	0.63	0.70	0.62	19210	$3,106,166	0.00	0.87	0.49	$12,329	$1,479	1.23
O	0.67	0.72	0.62	44868	$2,646,771	0.00	0.89	0.51	$12,329	$1,479	1.28
D	0.89	0.71	0.52	6215	$4,029,660	0.00	0.82	0.50	$12,329	$1,479	1.66
A	0.00	0.64	0.48	245183	$4,740,505	0.00	0.88	0.42	$12,329	$1,479	1.03
B	0.21	0.64	0.48	46131	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
C	0.15	0.64	0.48	51957	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
E	0.92	0.67	0.48	3891	$4,740,505	0.00	0.76	0.42	$12,329	$1,479	1.72
M	0.52	0.65	0.48	31935	$4,708,033	0.00	0.86	0.41	$12,329	$1,479	1.03
N	0.87	0.66	0.48	3449	$4,708,033	0.00	0.77	0.41	$12,329	$1,479	1.39
S	0.77	0.55	0.43	11275	$7,300,427	0.01	0.80	0.20	$12,329	$1,479	0.90
Q	0.76	0.65	0.52	11548	$4,438,207	0.01	0.81	0.40	$12,329	$1,479	1.07
R	0.01	0.53	0.39	235033	$8,477,317	0.03	0.86	0.20	$12,329	$1,479	0.83

Ranking by Benefits to Percent of Profits to Artisinal Fisheries											
Concession #	Species Richness	Species Abundance	Species Health	Affected Area	Concession Profit	Probability of ISA Outbreak	**Percent of Profits to Artisanal Fisheries**	Percent of Profits to Tourism	Potential Cost of Regulation for Labor	Expected Cost of Regulation For Labor	Ecosystem Health
L	0.74	0.93	0.78	49814	$468,775	0.00	0.97	0.88	$12,329	$1,479	1.75
U	0.71	0.78	0.74	256916	$1,332,890	0.00	0.92	0.63	$12,329	$1,479	1.61
K	0.34	0.74	0.64	260637	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
T	0.81	0.78	0.74	14180	$1,332,890	0.00	0.91	0.63	$12,329	$1,479	1.63
G	0.49	0.74	0.64	84123	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
J	0.41	0.73	0.64	54819	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.31
I	0.57	0.74	0.64	35751	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.32
H	0.63	0.74	0.64	25540	$2,626,972	0.00	0.90	0.55	$12,329	$1,479	1.32
O	0.67	0.72	0.62	44868	$2,646,771	0.00	0.89	0.51	$12,329	$1,479	1.28
A	0.00	0.64	0.48	245183	$4,740,505	0.00	0.88	0.42	$12,329	$1,479	1.03
P	0.63	0.70	0.62	19210	$3,106,166	0.00	0.87	0.49	$12,329	$1,479	1.23
C	0.15	0.64	0.48	51957	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
B	0.21	0.64	0.48	46131	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
F	0.94	0.82	0.73	4058	$1,813,961	0.00	0.87	0.69	$12,329	$1,479	2.24
R	0.01	0.53	0.39	235033	$8,477,317	0.03	0.86	0.20	$12,329	$1,479	0.83
M	0.52	0.65	0.48	31935	$4,708,033	0.00	0.86	0.41	$12,329	$1,479	1.03
D	0.89	0.71	0.52	6215	$4,029,660	0.00	0.82	0.50	$12,329	$1,479	1.66
Q	0.76	0.65	0.52	11548	$4,438,207	0.01	0.81	0.40	$12,329	$1,479	1.07
S	0.77	0.55	0.43	11275	$7,300,427	0.01	0.80	0.20	$12,329	$1,479	0.90
N	0.87	0.66	0.48	3449	$4,708,033	0.00	0.77	0.41	$12,329	$1,479	1.39
E	0.92	0.67	0.48	3891	$4,740,505	0.00	0.76	0.42	$12,329	$1,479	1.72

Ranking by Benefits to Percent of Profits to Tourism											
Concession #	Species Richness	Species Abundance	Species Health	Affected Area	Concession Profit	Probability of ISA Outbreak	Percent of Profits to Artisanal Fisheries	**Percent of Profits to Tourism**	Potential Cost of Regulation for Labor	Expected Cost of Regulation For Labor	Ecosystem Health
L	0.74	0.93	0.78	49814	$468,775	0.00	0.97	0.88	$12,329	$1,479	1.75
F	0.94	0.82	0.73	4058	$1,813,961	0.00	0.87	0.69	$12,329	$1,479	2.24
T	0.81	0.78	0.74	14180	$1,332,890	0.00	0.91	0.63	$12,329	$1,479	1.63
U	0.71	0.78	0.74	256916	$1,332,890	0.00	0.92	0.63	$12,329	$1,479	1.61
G	0.49	0.74	0.64	84123	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
H	0.63	0.74	0.64	25540	$2,626,972	0.00	0.90	0.55	$12,329	$1,479	1.32
I	0.57	0.74	0.64	35751	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.32
J	0.41	0.73	0.64	54819	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.31
K	0.34	0.74	0.64	260637	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
O	0.67	0.72	0.62	44868	$2,646,771	0.00	0.89	0.51	$12,329	$1,479	1.28
D	0.89	0.71	0.52	6215	$4,029,660	0.00	0.82	0.50	$12,329	$1,479	1.66
P	0.63	0.70	0.62	19210	$3,106,166	0.00	0.87	0.49	$12,329	$1,479	1.23
A	0.00	0.64	0.48	245183	$4,740,505	0.00	0.88	0.42	$12,329	$1,479	1.03
B	0.21	0.64	0.48	46131	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
C	0.15	0.64	0.48	51957	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
E	0.92	0.67	0.48	3891	$4,740,505	0.00	0.76	0.42	$12,329	$1,479	1.72
M	0.52	0.65	0.48	31935	$4,708,033	0.00	0.86	0.41	$12,329	$1,479	1.03
N	0.87	0.66	0.48	3449	$4,708,033	0.00	0.77	0.41	$12,329	$1,479	1.39
Q	0.76	0.65	0.52	11548	$4,438,207	0.01	0.81	0.40	$12,329	$1,479	1.07
R	0.01	0.53	0.39	235033	$8,477,317	0.03	0.86	0.20	$12,329	$1,479	0.83
S	0.77	0.55	0.43	11275	$7,300,427	0.01	0.80	0.20	$12,329	$1,479	0.90

Ranking by Benefits to Ecosystem Health											
Concession #	Species Richness	Species Abundance	Species Health	Affected Area	Concession Profit	Probability of ISA Outbreak	Percent of Profits to Artisanal Fisheries	Percent of Profits to Tourism	Potential Cost of Regulation for Labor	Expected Cost of Regulation For Labor	**Ecosystem Health**
F	0.94	0.82	0.73	4058	$1,813,961	0.00	0.87	0.69	$12,329	$1,479	2.24
L	0.74	0.93	0.78	49814	$468,775	0.00	0.97	0.88	$12,329	$1,479	1.75
E	0.92	0.67	0.48	3891	$4,740,505	0.00	0.76	0.42	$12,329	$1,479	1.72
D	0.89	0.71	0.52	6215	$4,029,660	0.00	0.82	0.50	$12,329	$1,479	1.66
T	0.81	0.78	0.74	14180	$1,332,890	0.00	0.91	0.63	$12,329	$1,479	1.63
U	0.71	0.78	0.74	256916	$1,332,890	0.00	0.92	0.63	$12,329	$1,479	1.61
N	0.87	0.66	0.48	3449	$4,708,033	0.00	0.77	0.41	$12,329	$1,479	1.39
K	0.34	0.74	0.64	260637	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
G	0.49	0.74	0.64	84123	$2,584,996	0.00	0.91	0.55	$12,329	$1,479	1.33
I	0.57	0.74	0.64	35751	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.32
H	0.63	0.74	0.64	25540	$2,626,972	0.00	0.90	0.55	$12,329	$1,479	1.32
J	0.41	0.73	0.64	54819	$2,584,996	0.00	0.90	0.55	$12,329	$1,479	1.31
O	0.67	0.72	0.62	44868	$2,646,771	0.00	0.89	0.51	$12,329	$1,479	1.28
P	0.63	0.70	0.62	19210	$3,106,166	0.00	0.87	0.49	$12,329	$1,479	1.23
Q	0.76	0.65	0.52	11548	$4,438,207	0.01	0.81	0.40	$12,329	$1,479	1.07
M	0.52	0.65	0.48	31935	$4,708,033	0.00	0.86	0.41	$12,329	$1,479	1.03
A	0.00	0.64	0.48	245183	$4,740,505	0.00	0.88	0.42	$12,329	$1,479	1.03
B	0.21	0.64	0.48	46131	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
C	0.15	0.64	0.48	51957	$4,740,505	0.00	0.87	0.42	$12,329	$1,479	1.01
S	0.77	0.55	0.43	11275	$7,300,427	0.01	0.80	0.20	$12,329	$1,479	0.90
R	0.01	0.53	0.39	235033	$8,477,317	0.03	0.86	0.20	$12,329	$1,479	0.83

21 Concession EIA Inputs									
Concession	Number of Netpens	Number of Months in Cycle	Equiptment Quality	Number of Salmon at Start	Average Current Speed in cm/second	Feed Conversion Ratio	Percent of Feed Eaten	Number of Workers	Average Depth of Seafloor in meters
A	24	18	3	1,560,000	79.20	1.20	95	8	60
B	24	18	3	1,560,000	21.31	1.20	95	8	60
C	24	18	3	1,560,000	23.34	1.20	95	8	60
D	24	18	3	1,344,000	5.20	1.20	95	8	60
E	24	18	3	1,560,000	3.96	1.20	95	8	60
F	24	14	3	840,000	4.20	1.20	92	10	60
G	30	14	3	1,200,000	14.65	1.20	97	22	105
H	30	14	3	1,200,000	12.20	1.20	97	16	65
I	30	14	3	1,200,000	14.55	1.20	97	22	68
J	30	14	3	1,200,000	21.50	1.20	97	22	65
K	30	14	3	1,200,000	57.00	1.20	97	22	76
L	32	18	3	312,500	22.40	1.20	97	14	60
M	23	18	3	1,562,500	8.50	1.20	99	14	95
N	23	18	3	1,562,500	9.40	1.20	99	14	28
O	18	14	3	1,300,000	3.00	1.25	97	5	260
P	20	14	3	1,350,000	11.00	1.20	99.5	18	60
Q	16	16	3	1,600,000	8.27	1.20	99	14	58
R	20	16	3	2,400,000	25.50	1.10	99.5	36	120
S	20	14	3	2,400,000	5.47	1.10	99.5	36	77
T	40	12	3	1,000,000	10.43	1.25	97	15	55
U	40	12	3	1,000,000	24.17	1.25	96	15	130

* Due to missing data from the EIAs, gray values and all values not listed are pulled from the default values in the model

Appendix E: Labor Impacts

Record of Violations of Labor Laws for Salmon Aquaculture: Companies, taken from the Ministry of Trabajos Department of Inspection						
COMPANY	**FINE TRACK #**	**DATE OF ENFORCEMENT**	**N° UTM FINAL**	**UTM - $ USD**	**$ USD paid**	**STATEMENT**
CULTIVOS MARINOS CHILOÉ LTDA	3117/06/125-2	NA	40	79.9	3196	Do not give 2 Sundays rest in the calendar month.
CULTIVOS MARINOS CHILOÉ LTDA	7721/08/013-3	NA	40	79.9	3196	Exceed the normal working day (weekly)
CULTIVOS MARINOS CHILOÉ LTDA	7721/08/013-4	NA	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
CULTIVOS MARINOS CHILOÉ LTDA	7721/08/012-1	NA	40	79.9	3196	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
CULTIVOS MARINOS CHILOÉ LTDA	3941/11/025-1	NA	40	79.9	3196	Did not grant the excess rest days due accumulated in the week, according to the agreement.
CULTIVOS MARINOS CHILOÉ LTDA	3941/11/025-2	NA	40	79.9	3196	No overtime pay.
CULTIVOS MARINOS CHILOÉ LTDA	7793/07/081-1	NA	40	79.9	3196	Do not give 2nd Sunday rest in the calendar month.
CULTIVOS MARINOS CHILOÉ LTDA	7715/07/074-3	NA	40	79.9	3196	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
CULTIVOS MARINOS CHILOÉ LTDA	3941/07/016-2	NA	15	79.9	1198.5	Failing to grant rest during the day
CULTIVOS MARINOS CHILOÉ LTDA	7721/07/020-1	NA	40	79.9	3196	Exceeded maximum of 2 extra working hours per day
CULTIVOS MARINOS CHILOÉ LTDA	7818/06/071-1	NA	41	79.9	3275.9	No overtime pay
CULTIVOS MARINOS CHILOÉ LTDA	3135/07/030-1	NA	60	79.9	4794	No overtime pay.
CULTIVOS MARINOS CHILOÉ LTDA	7715/06/086-1	NA	40	79.9	3196	Exceeded maximum of 2 extra working hours per day
CULTIVOS MARINOS CHILOÉ LTDA	7715/06/086-2	NA	40	79.9	3196	Exceeding maximum normal working day of 10 hours.
CULTIVOS MARINOS CHILOÉ LTDA	7818/06/078-1	NA	21	79.9	1677.9	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)

CULTIVOS MARINOS CHILOÉ LTDA	3481/05/023-3	NA	8	79.9	639.2	Failed to grant rest during the working day.
CULTIVOS MARINOS CHILOÉ LTDA	3481/05/023-5	NA	8	79.9	639.2	Failure to pay wages
AQUACHILE S.A.	3117/09/080-1	NA	8.4	79.9	671.16	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
AGUAS CLARAS S.A.	3358/06/090-2	24-10-2011	40	79.9	3196	Excluded from the limitation of the ordinary working day without meeting the legal requirements
AGUAS CLARAS S.A.	3117/10/025-1	NA	2	79.9	159.8	Altered the distribution of agreed working hours without meeting the legal requirements.
AGUAS CLARAS S.A.	7717/09/174-2	NA	40	79.9	3196	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	4433/07/080-1	NA	18	79.9	1438.2	Made deductions from wages without agreement of the parties
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	6235/07/082-1	NA	10.5	79.9	838.95	Do not give 2nd Sunday rest in the calendar month.
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	6235/07/081-1	NA	10.5	79.9	838.95	Do not give 2nd Sunday rest in the calendar month.
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	8073/09/134-1	NA	3	79.9	239.7	No pay for full week;
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	8073/09/135-1	NA	3	79.9	239.7	No pay for full week;
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	8073/09/136-1	NA	3	79.9	239.7	No pay for full week;
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	8073/09/137-1	NA	3	79.9	239.7	No pay for full week;
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	7905/09/081-1	NA	3	79.9	239.7	No pay for full week;
MAINSTREAM/ SALMONES MULTIEXPORT LTDA	7905/09/082-1	NA	3	79.9	239.7	No pay for full week;

MAINSTREAM/ SALMONES MULTIEXPORT LTDA	7719/08/047-1	22-12-2008	40	79.9	3196	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
SALMONES ANTARCTICA S.A	6234/08/006-1	18-06-2011	40	79.9	3196	Exceeding the legal ordinary working day.
SALMONES ANTARCTICA S.A	6234/08/006-3	18-06-2011	60	79.9	4794	Make deductions from wages without agreement of the parties
SALMONES ANTARCTICA S.A	7719/07/069-1	NA	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
SALMONES ANTARCTICA S.A	7719/07/069-2	NA	20	79.9	1598	Exceeding maximum normal working day of 10 hours.
SALMONES ANTARCTICA S.A	7719/07/069-3	NA	20	79.9	1598	Do not give 2nd Sunday rest in the calendar month.
SALMONES ANTARCTICA S.A	3620/07/063-1	28-11-2007	40	79.9	3196	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
SALMONES ANTARCTICA S.A	3620/07/063-2	28-11-2007	30	79.9	2397	No overtime pay.
SALMONES ANTARCTICA S.A	3620/07/063-6	28-11-2007	40	79.9	3196	Do not give 2nd Sunday rest in the calendar month.
SALMONES ANTARCTICA S.A	7719/07/067-2	28-11-2007	20	79.9	1598	Exceeding maximum normal working day of 10 hours.
SALMONES ANTARCTICA S.A	7719/07/067-3	28-11-2007	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
SALMONES ANTARCTICA S.A	7719/05/115-2	25-04-2007	22	79.9	1757.8	Exceeded maximum of 2 extra working hours per day
SALMONES ANTARCTICA S.A	8001/06/001-1	NA	4	79.9	319.6	Exceeding maximum normal working day of 10 hours.
SALMONES ANTARCTICA S.A	7840/06/009-1	16-02-2007	5.7	79.9	455.43	Exceded the ordinary working day
PRODUCTOS DEL MAR VENTISQUEROS S.A	3117/10/026-2	NA	4	79.9	319.6	Do not give 2nd Sunday rest in the calendar month.
PRODUCTOS DEL MAR VENTISQUEROS S.A	8034/07/090-1	30-04-2009	18	79.9	1438.2	Making illegal deductions and offsets of wages (unfair wages)
PRODUCTOS DEL MAR VENTISQUEROS S.A	8034/07/124-1	25-09-2008	30	79.9	2397	Failure to pay wages.
PRODUCTOS DEL MAR VENTISQUEROS S.A	8034/06/062-1	17-06-2008	40	79.9	3196	Exceeded maximum of 2 extra working hours per day

PRODUCTOS DEL MAR VENTISQUEROS S.A	6245/08/002-1	13-04-2008	60	79.9	4794	Failure to pay wages.
PRODUCTOS DEL MAR VENTISQUEROS S.A	7717/07/034-1	18-01-2008	60	79.9	4794	Failure to pay wages.
PRODUCTOS DEL MAR VENTISQUEROS S.A	4433/07/093-1	18-01-2008	60	79.9	4794	Failure to pay wages.
PRODUCTOS DEL MAR VENTISQUEROS S.A	8034/07/127-1	NA	60	79.9	4794	Failure to pay wages.
PRODUCTOS DEL MAR VENTISQUEROS S.A	6234/07/056-2	NA	60	79.9	4794	No overtime pay.
PRODUCTOS DEL MAR VENTISQUEROS S.A	3941/07/020-1	NA	41	79.9	3275.9	Failure to pay wages.
PRODUCTOS DEL MAR VENTISQUEROS S.A	4433/07/015-3	17-06-2007	60	79.9	4794	No overtime pay.
PRODUCTOS DEL MAR VENTISQUEROS S.A	4433/07/015-4	17-06-2007	40	79.9	3196	Exceeded maximum of 2 extra working hours per day
PRODUCTOS DEL MAR VENTISQUEROS S.A	4433/07/015-5	17-06-2007	60	79.9	4794	Exceding maximum stay of 12 hours
PESCA CHILE S.A.	8001/11/002-4	NA	40	79.9	3196	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
PESCA CHILE S.A.	3735/08/033-2	NA	10	79.9	799	Failure to pay wages.
PESCA CHILE S.A.	3067/09/009-1	13-02-2010	40	79.9	3196	Failure to pay balance of pay the worker's death to the spouse (the children) (the parents).
PESCA CHILE S.A.	7967/06/085-2	NA	40	79.9	3196	Failure to pay wages.
PESCA CHILE S.A.	3064/07/073-1	NA	4	79.9	319.6	Exceeded maximum of 2 extra working hours per day
NOVA AUSTRAL S.A	3010/10/015-1	28-02-2011	6	79.9	479.4	Failure to pay wages.
NOVA AUSTRAL S.A	4438/08/057-4	NA	4	79.9	319.6	non-compliance with resolution authorizing exceptional system based distribution of work and rest days
NOVA AUSTRAL S.A	7739/08/017-3	30-01-2009	3	79.9	239.7	non-compliance with resolution authorizing exceptional system based distribution of work and rest days

NOVA AUSTRAL S.A	7739/08/017-4	30-01-2009	3	79.9	239.7	non-compliance with resolution authorizing exceptional system based distribution of work and rest days
NOVA AUSTRAL S.A	8068/06/008-3	NA	40	79.9	3196	Exceeded maximum of 2 extra working hours per day
PESQUERA LOS FIORDOS LIMITADA	3160/09/061-2	25-07-2009	41	79.9	3275.9	No overtime pay.
PESQUERA LOS FIORDOS LIMITADA	7984/11/025-1	14-09-2011	10	79.9	799	Make deductions from wages without agreement of the parties
PESQUERA LOS FIORDOS LIMITADA	3342/11/001-1	14-05-2011	40	79.9	3196	Exceeded maximum of 2 extra working hours per day
PESQUERA LOS FIORDOS LIMITADA	3175/09/010-1	13-04-2011	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
PESQUERA LOS FIORDOS LIMITADA	3175/09/014-1	18-03-2011	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
PESQUERA LOS FIORDOS LIMITADA	3175/09/013-1	16-03-2011	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
PESQUERA LOS FIORDOS LIMITADA	3175/09/012-1	NA	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
PESQUERA LOS FIORDOS LIMITADA	3175/09/011-1	NA	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
PESQUERA LOS FIORDOS LIMITADA	3620/09/101-1	28-10-2009	40	79.9	3196	Failure to grant rest for the 2nd Sunday in the calendar month
MARINE HARVEST	4433/07/080-1	NA	18	79.9	1438.2	Make deductions from wages without agreement of the parties
MARINE HARVEST	6235/07/082-1	NA	10.5	79.9	838.95	Failure to grant rest for the 2nd Sunday in the calendar month
MARINE HARVEST	6235/07/081-1	NA	10.5	79.9	838.95	Failure to grant rest for the 2nd Sunday in the calendar month
MARINE HARVEST	8034/07/023-1	NA	10	79.9	799	Failure to pay wages.
MARINE HARVEST	4433/07/048-4	NA	40	79.9	3196	Exceeded maximum of 2 extra working hours per day
MARINE HARVEST	4433/07/048-5	NA	40	79.9	3196	Excluded from the limitation of the ordinary working day without meeting the legal requirements
MARINE HARVEST	7721/07/087-1	27-06-2008	20	79.9	1598	Failure to grant rest for the 2nd Sunday in the calendar month
MARINE HARVEST	7719/07/094-1	29-05-2008	40	79.9	3196	Failure to grant rest for the 2nd Sunday in the calendar month
MARINE HARVEST	7719/08/015-1	22-05-2008	20	79.9	1598	Exceeded maximum of 2 extra working hours per day

MARINE HARVEST	3358/06/016-2	NA	40	79.9	3196	Exceeded maximum of 2 extra working hours per day
MARINE HARVEST	7714/06/033-1	15-08-2007	20	79.9	1598	Failure to grant rest for the 2nd Sunday in the calendar month
MARINE HARVEST	7717/05/376-1	27-07-2007	40	79.9	3196	Failure to pay wages.
MARINE HARVEST	7717/05/388-1	27-07-2007	40	79.9	3196	Failure to pay wages.
MARINE HARVEST	3794/06/007-1	NA	60	79.9	4794	Failure to pay wages.
MARINE HARVEST	3358/06/012-2	28-06-2007	20	79.9	1598	Exceeded maximum of 2 extra working hours per day
MARINE HARVEST	3358/06/012-3	28-06-2007	30	79.9	2397	No overtime pay.
MARINE HARVEST	4433/06/116-1	23-04-2007	40	79.9	3196	Exceeding maximum normal working day of 10 hours.
MARINE HARVEST	4433/06/116-2	23-04-2007	40	79.9	3196	Exceeded maximum of 2 extra working hours per day
MARINE HARVEST	4433/06/116-4	23-04-2007	60	79.9	4794	No overtime pay.
MARINE HARVEST	3509/05/134-1	23-04-2007	40	79.9	3196	a) Exceeding the legal normal hours of work;
FJORD SEAFOOD CHILE LTDA (LINAO)	7717/08/144-1	NA	60	79.9	4794	b) Exceeding the conventional working day;
FJORD SEAFOOD CHILE LTDA (LINAO)	3117/06/112-1	39662	20	79.9	1598	c) Excluded from the limitation of the ordinary working day without meeting the legal requirements
FJORD SEAFOOD CHILE LTDA (LINAO)	3117/06/112-2	NA	40	79.9	3196	Failure to grant rest on Sundays and or festivals
FJORD SEAFOOD CHILE LTDA (LINAO)	7715/06/041-1	25-04-2007	21	79.9	1677.9	Improperly compensated for permitted overtime.
FJORD SEAFOOD CHILE LTDA (LINAO)	3117/06/115-3	NA	40	79.9	3196	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
FJORD SEAFOOD CHILE LTDA (LINAO)	7715/06/041-1	25-04-2007	21	79.9	1677.9	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)
FJORD SEAFOOD CHILE LTDA (LINAO)	3117/06/115-3	NA	40	79.9	3196	Distributed the regular workweek of 45 hours in more than 6 days (less than 5)

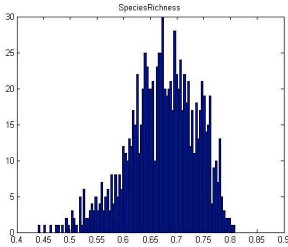
Average fine for wage violation	2573.189744
Average fine for hours violation	2304.833662

Appendix F: Sensitivity Analysis

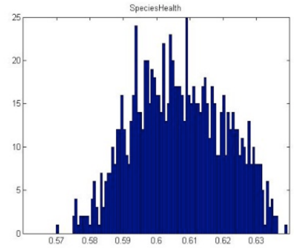
Monte Carlo Base Run

(all parameters varied)

a



b



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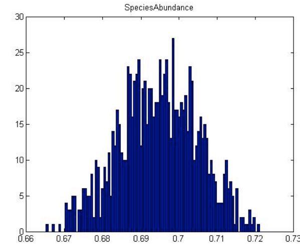

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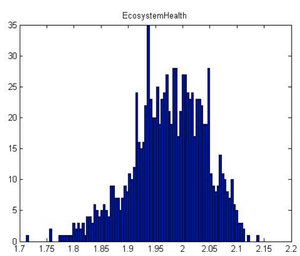
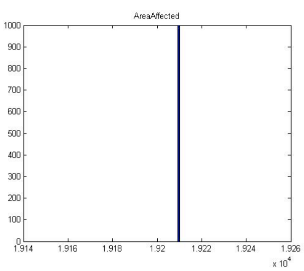


e



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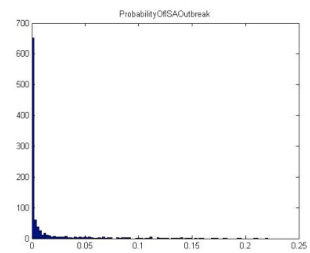

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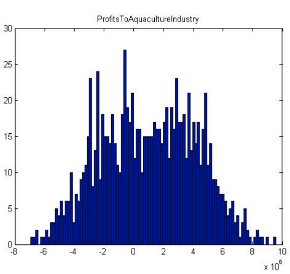

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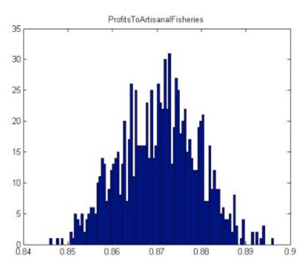
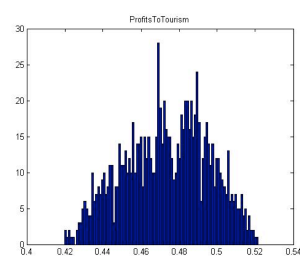
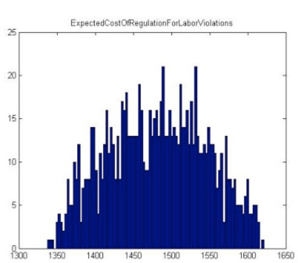


i



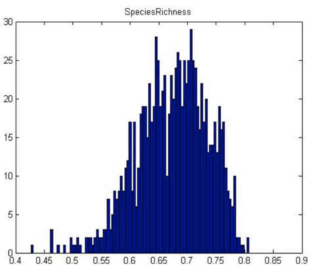
j



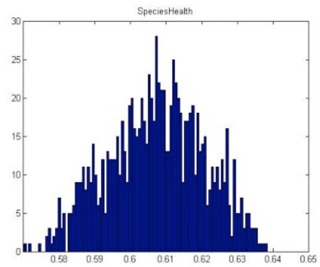
a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Average Fine Hours held constant

a.



b.



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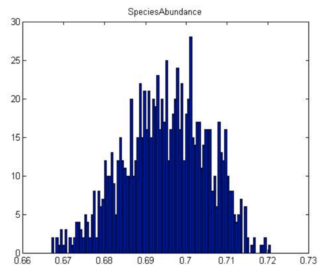
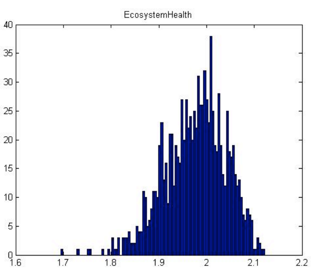


d.



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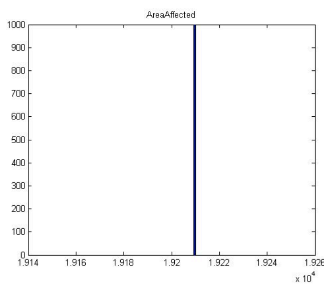

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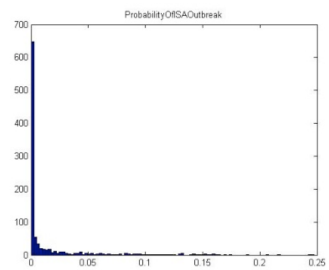

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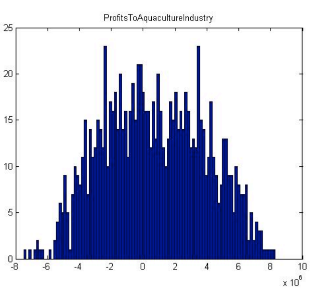

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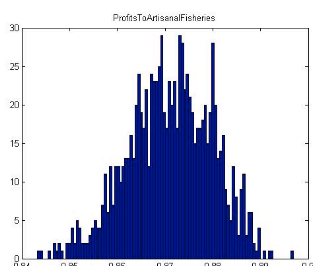

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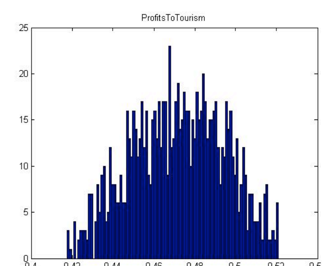

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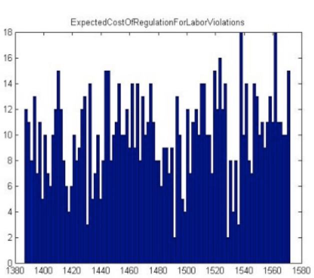
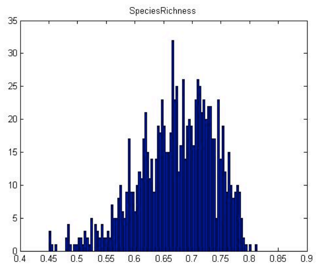


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Average Fine for a Wage Violation held constant

a.



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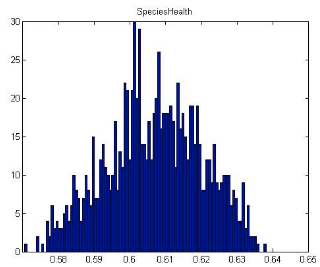

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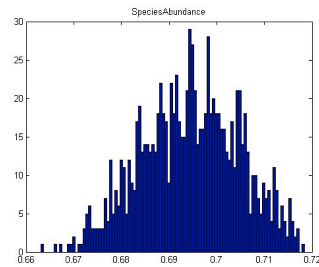

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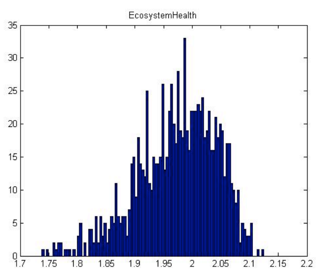

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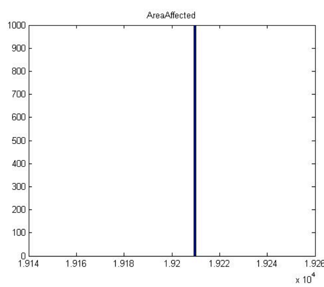

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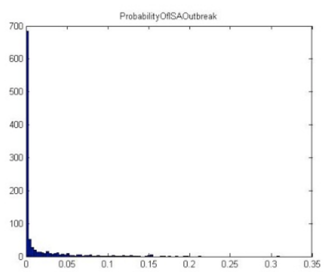

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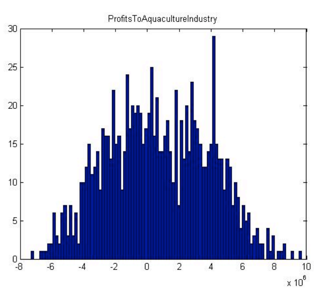

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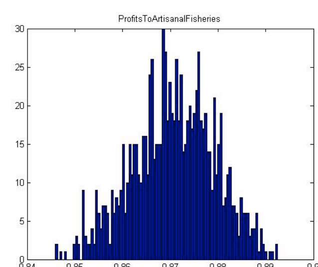

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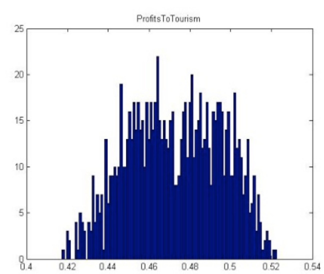

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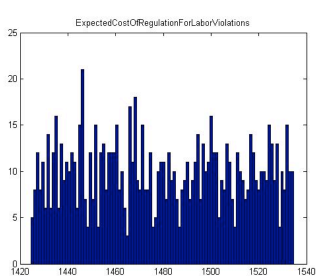

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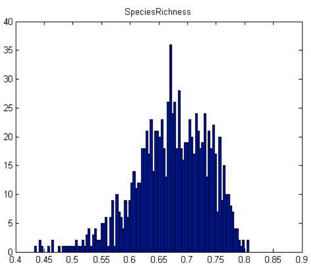
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Biomass Farm B held constant

a.



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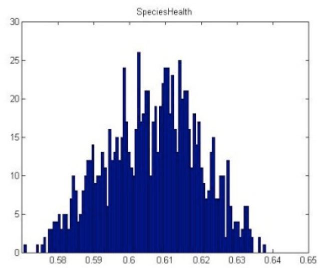

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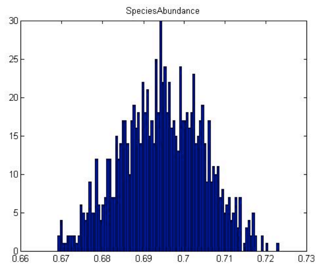

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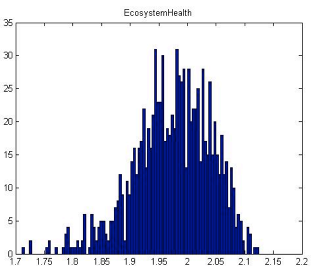

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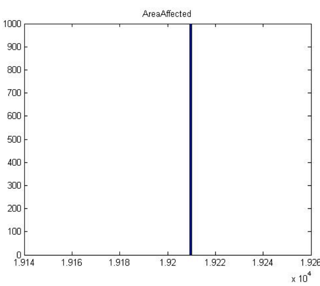

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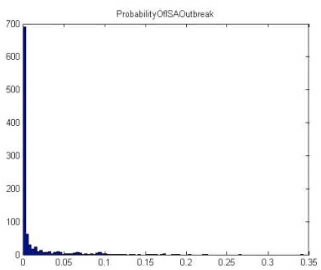

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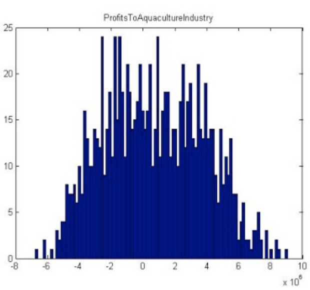

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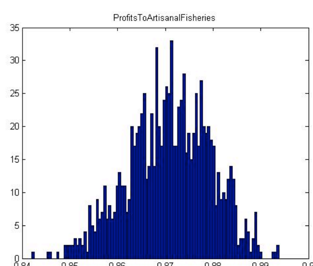

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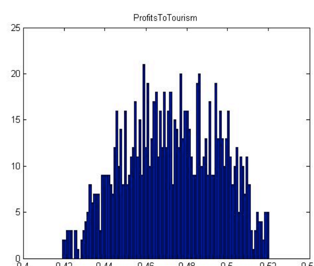

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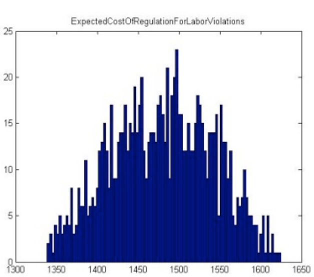

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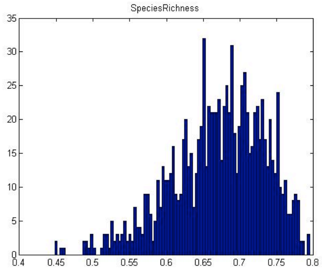
j. Expected Costs of Regulation for Labor Violations (USD)

Cages per Farm held constant

a.



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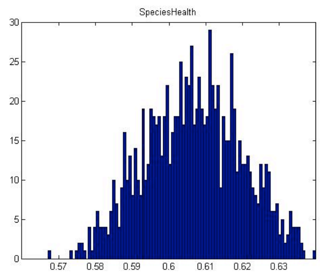

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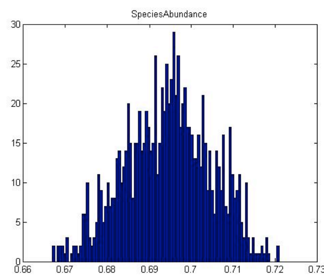

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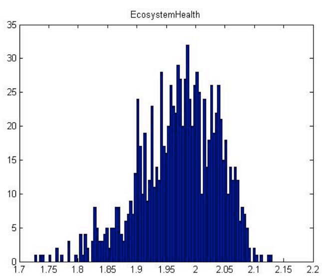

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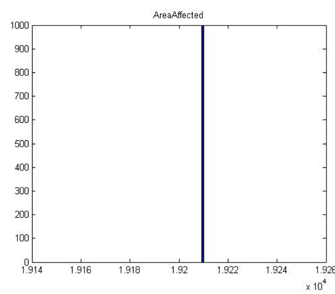

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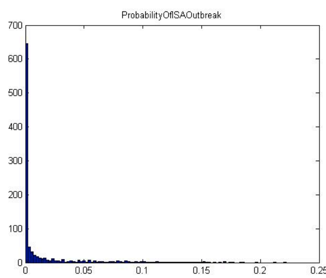

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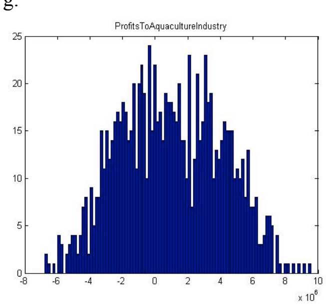

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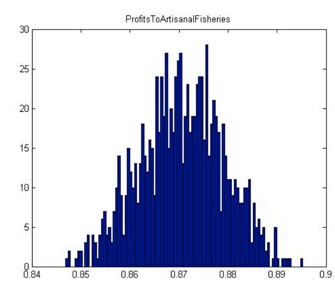

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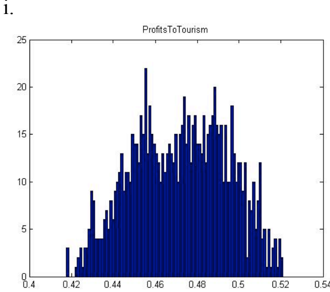

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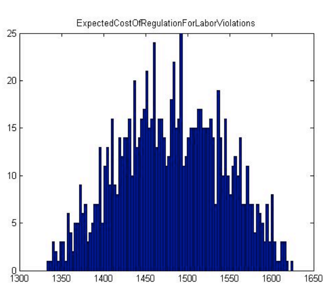

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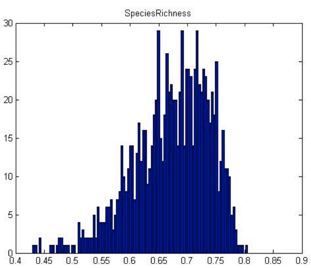
Concession Size held constant

a.



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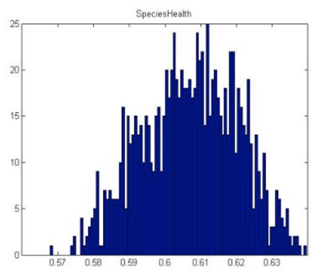

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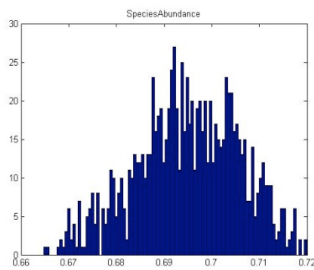

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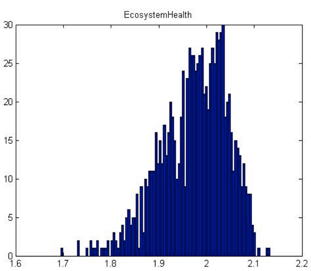

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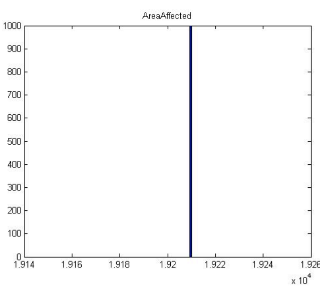

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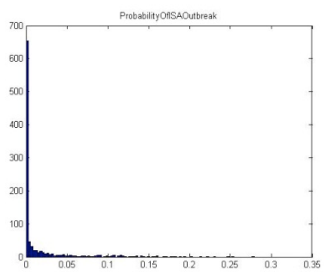

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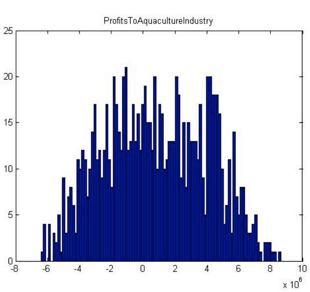

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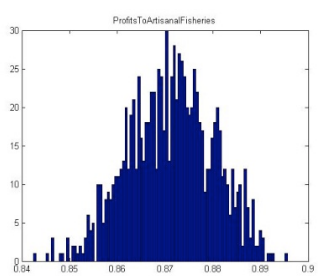

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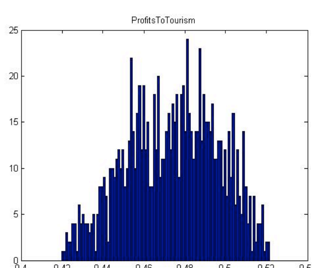

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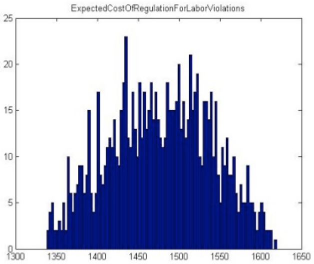

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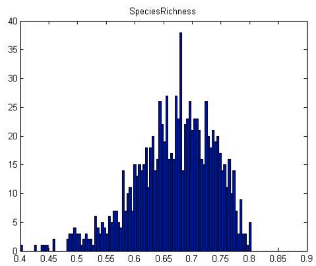
Distance Between Farms held constant

a.



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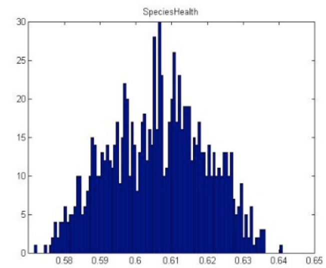

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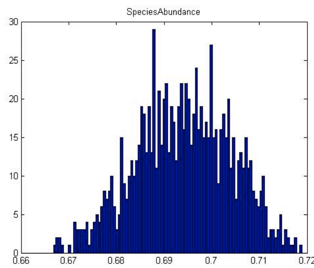

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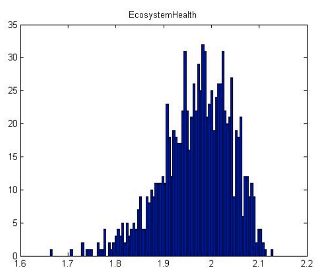

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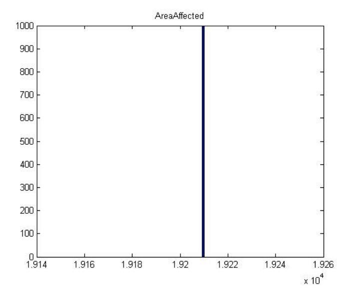

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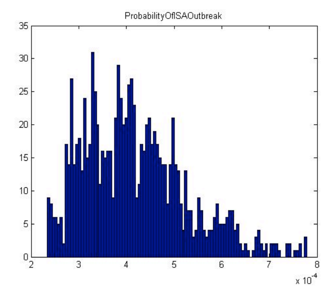

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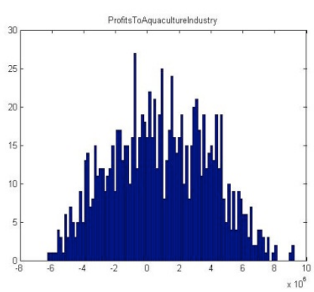

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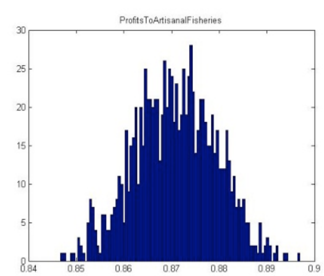

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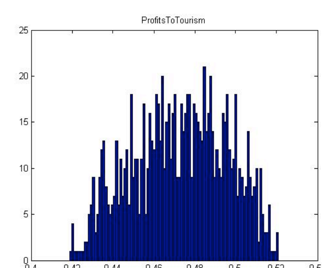

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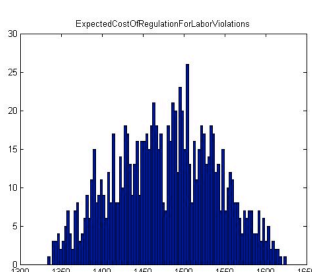

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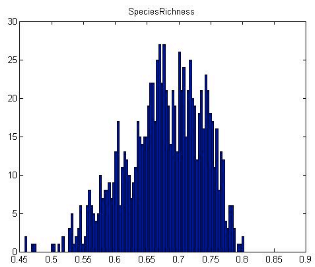
Economic FCR held constant

a.



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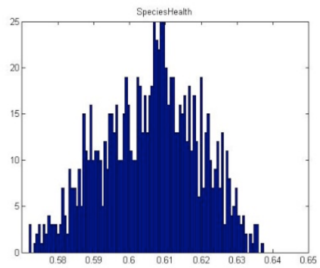

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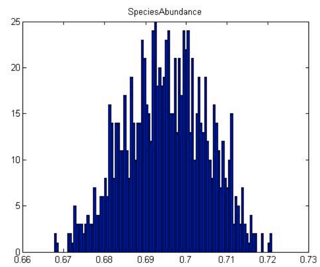

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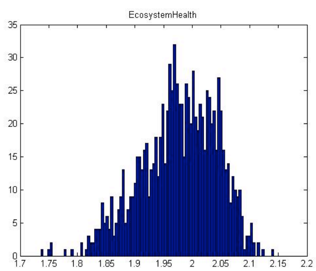

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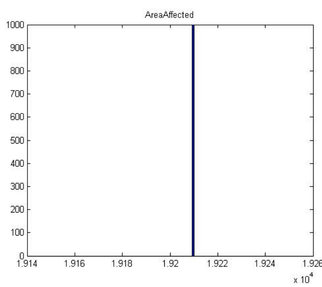

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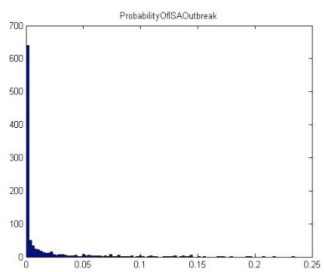

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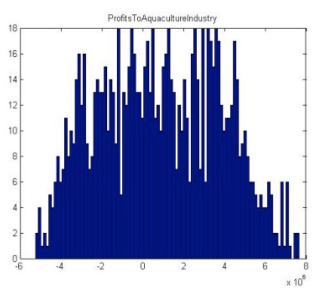

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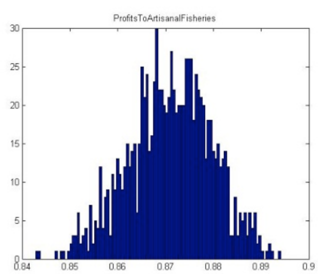

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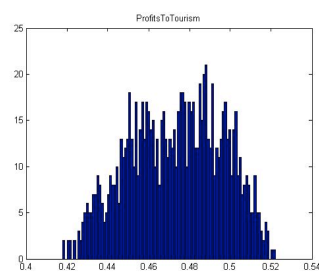

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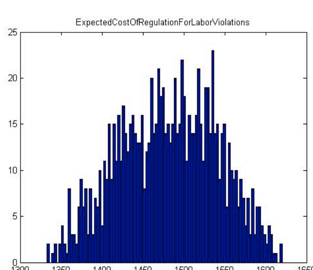

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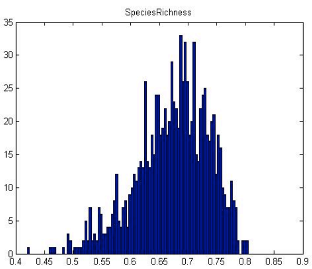
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Escape Decay held constant

a.



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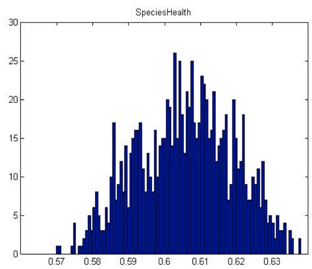

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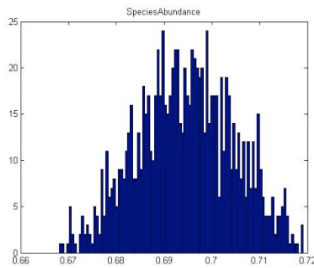

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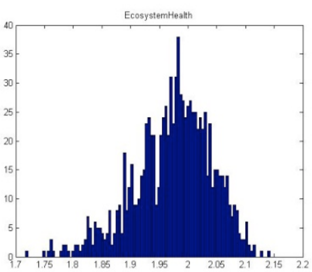

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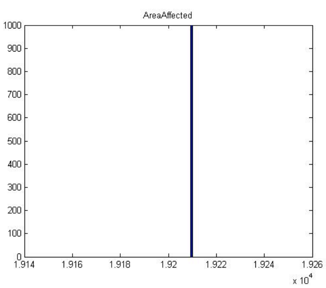

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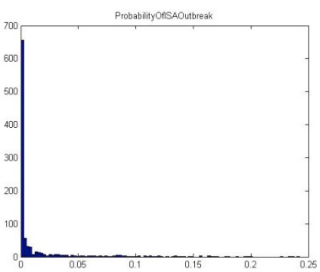

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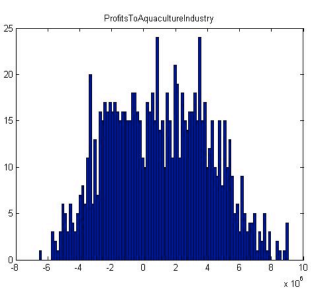

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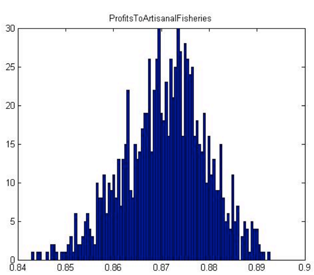

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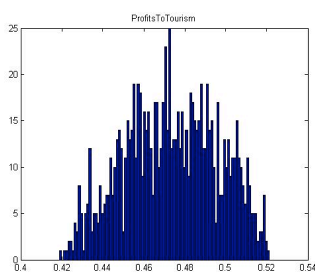

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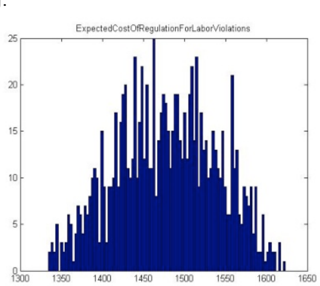
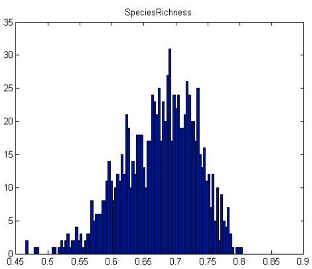


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Fecal Settling Speed held constant

a.



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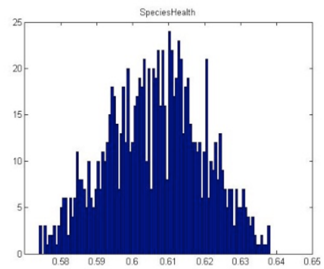

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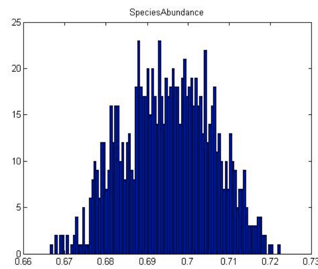

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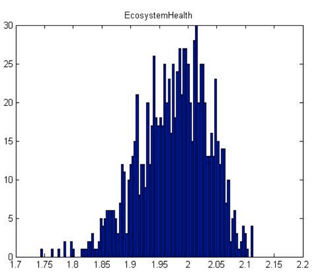

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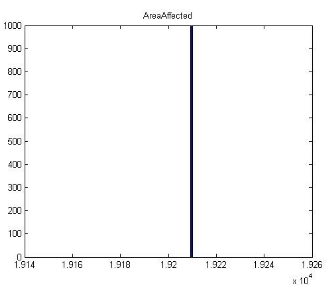

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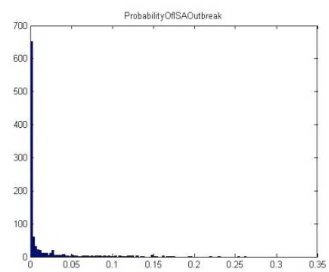

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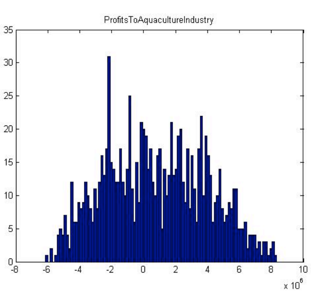

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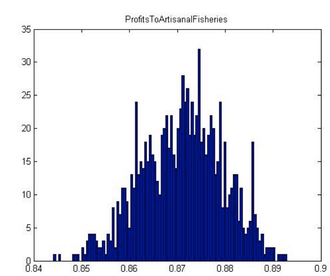

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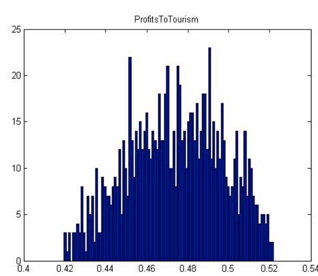

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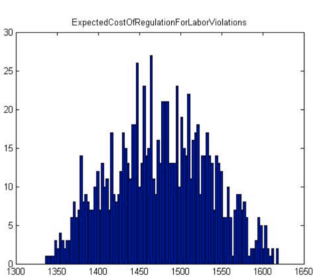
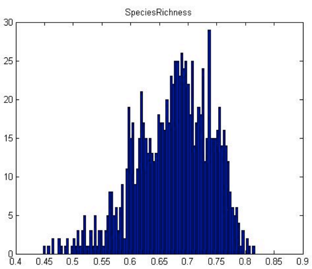


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Feed Eaten held constant

a.



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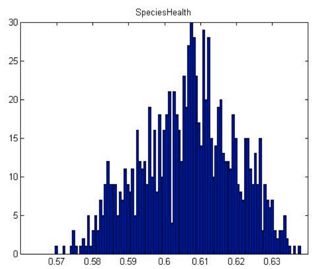

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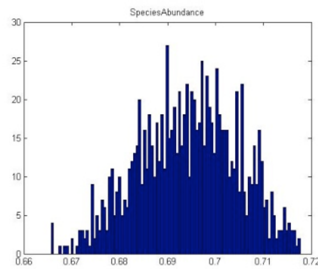

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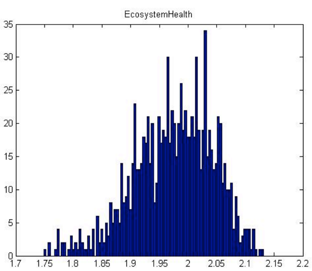

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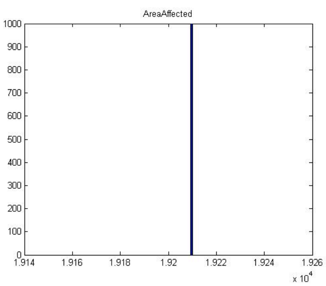

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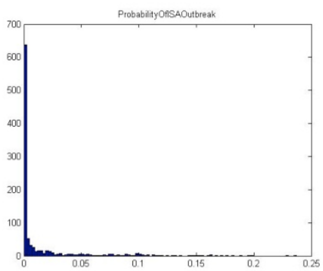

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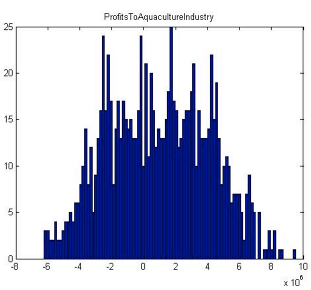

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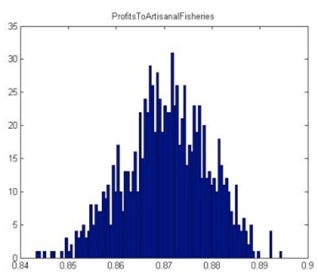

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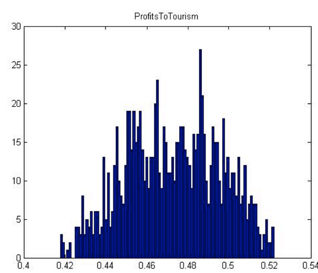

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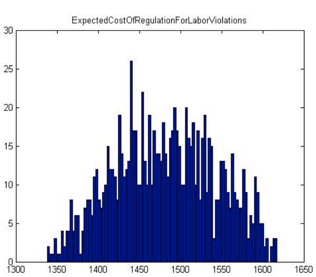

a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
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e. Area Affected (km^2)
f. Probability of ISA Outbreak
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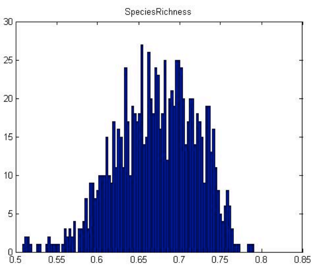
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Feed Settling Speed held constant

a.



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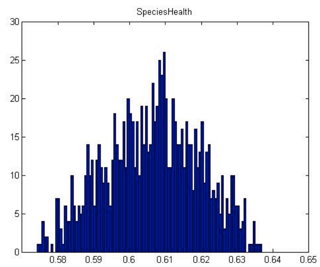

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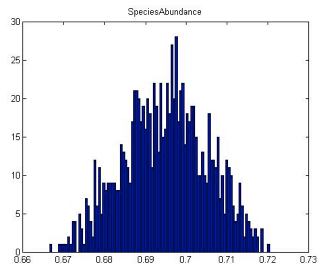

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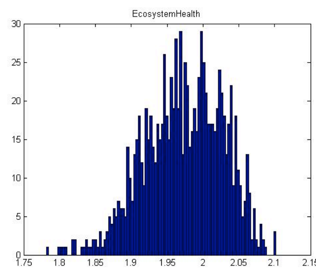

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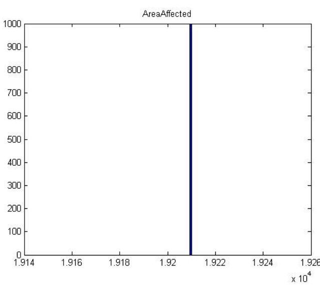

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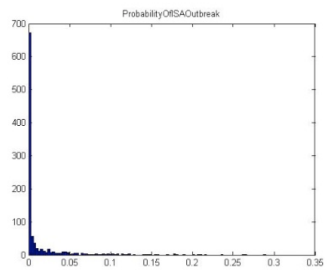

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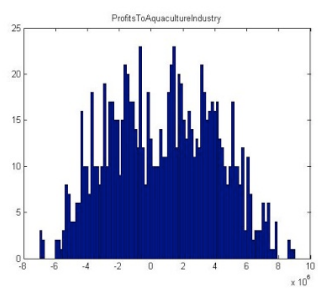

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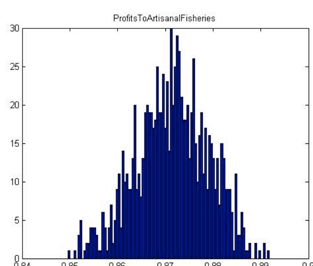

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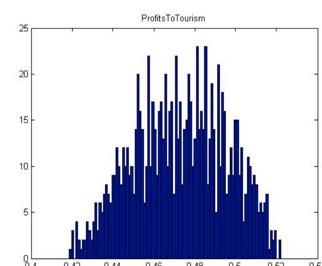

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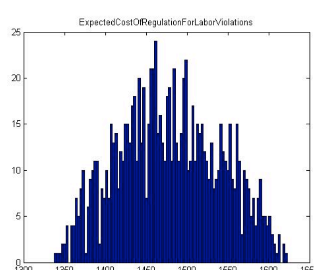

a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
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e. Area Affected (km^2)
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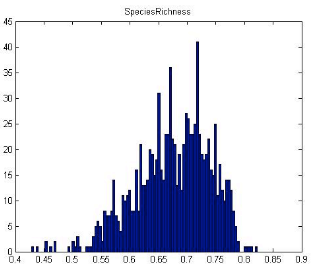
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Interest Depreciation held constant

a.



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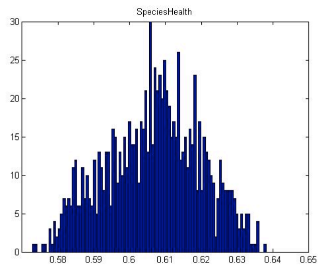

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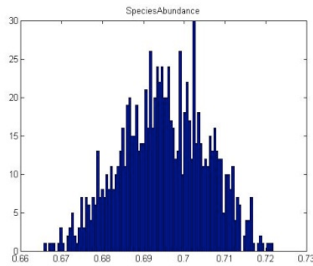

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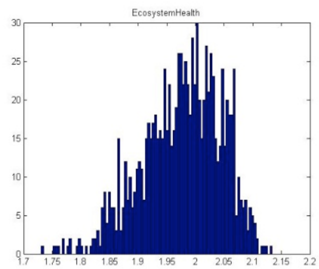

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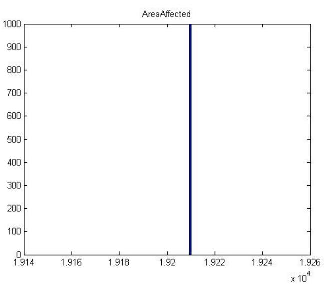

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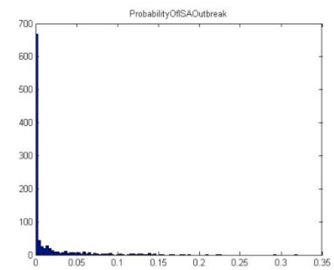

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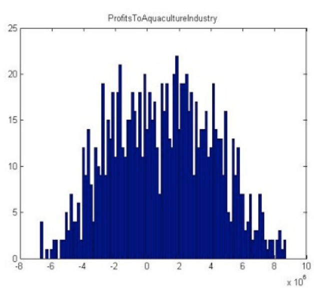

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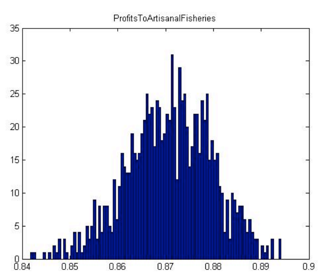
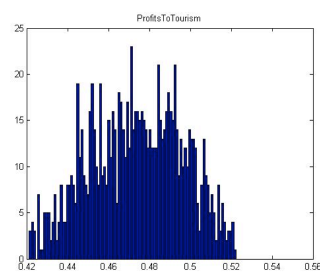


i.



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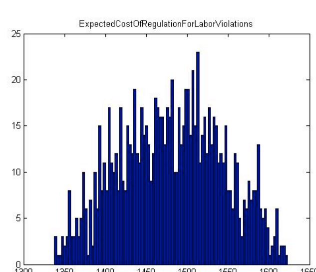

a. Species Richness (fractional change)
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f. Probability of ISA Outbreak
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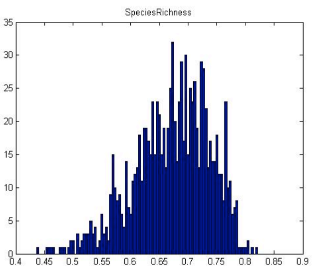
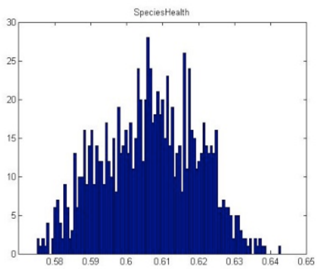
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Leaching Rate held constant

a.



b.



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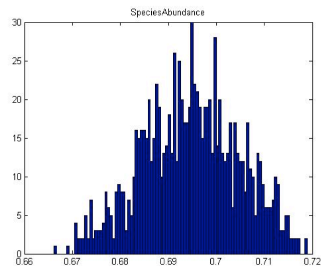

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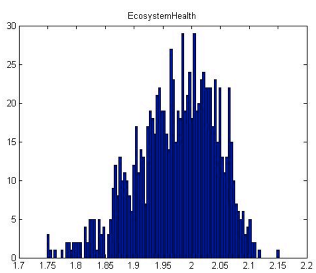

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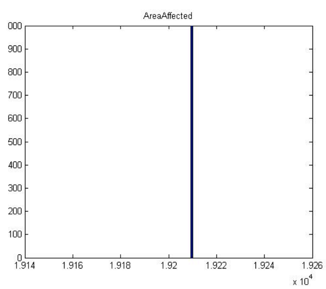

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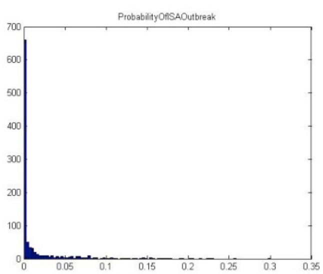

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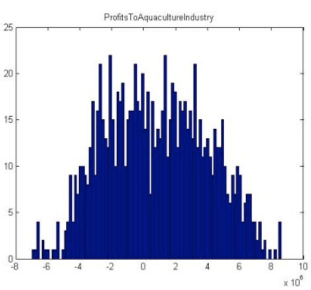

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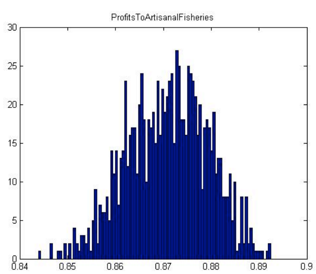

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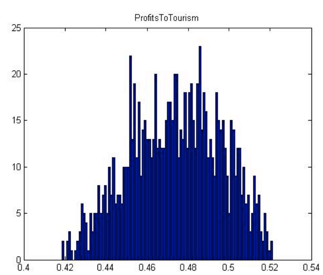

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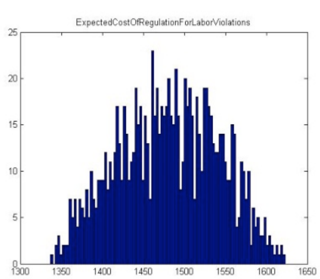

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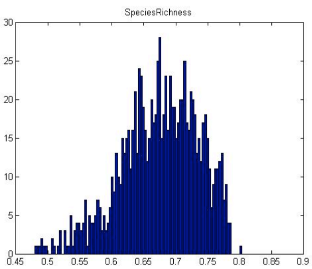
j. Expected Costs of Regulation for Labor Violations (USD)

Mortality Due to Disease held constant

a.



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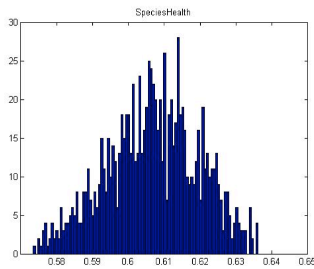

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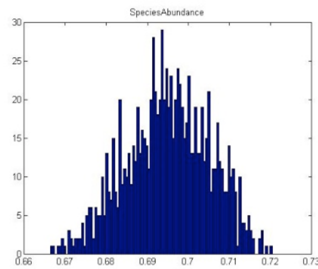

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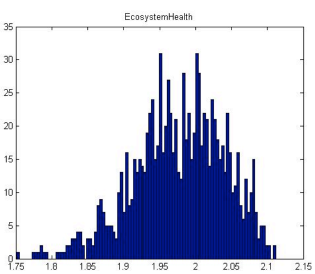

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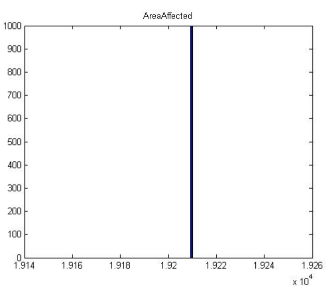

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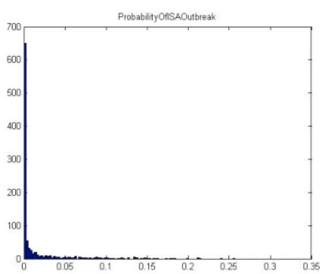

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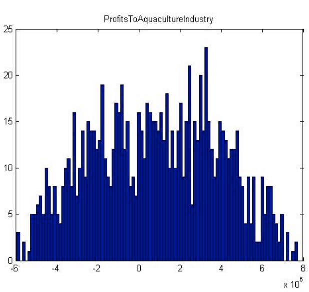
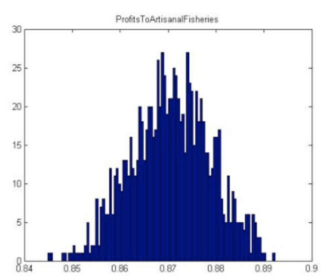


h.



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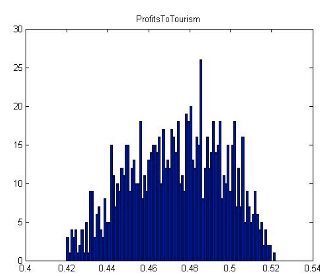

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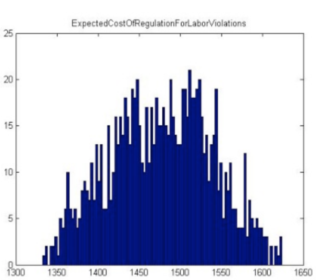
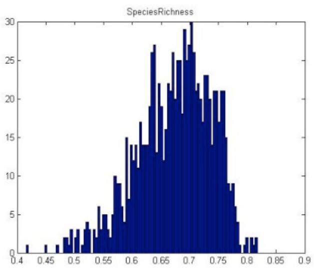


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Mortality Due to Sea Lice held constant

a.



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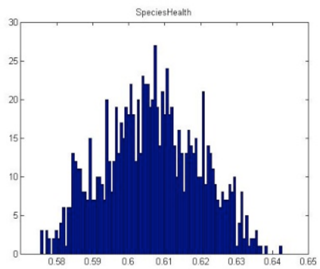

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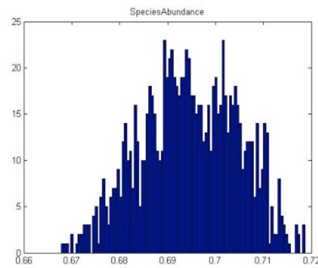

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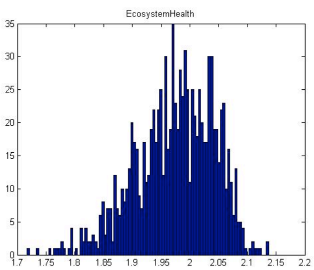

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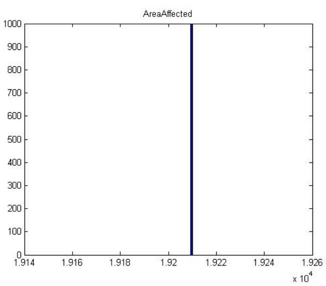

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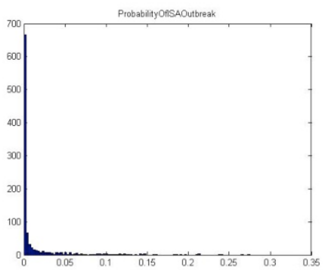

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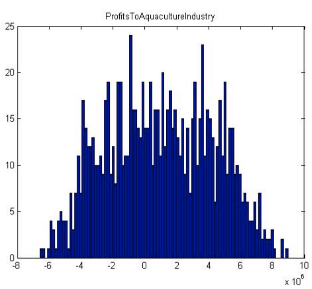

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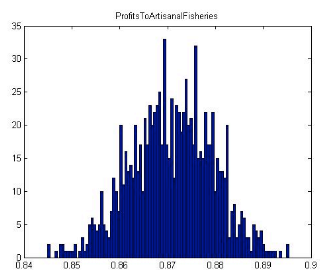

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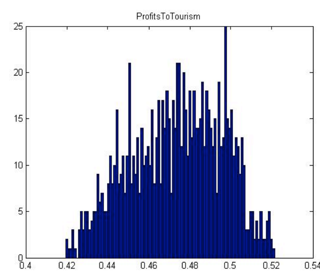

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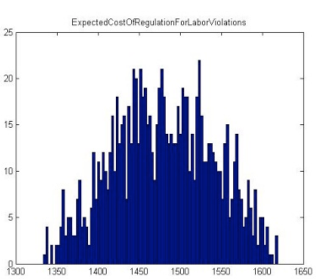
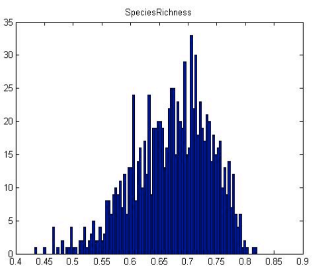


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Mortality Rate held constant

a.



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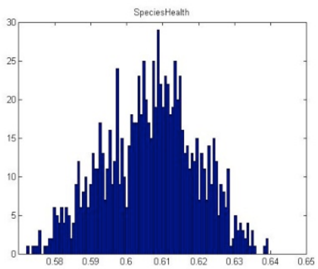

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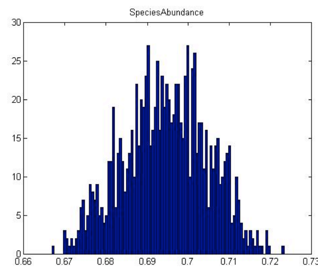

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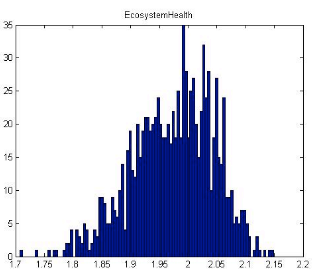

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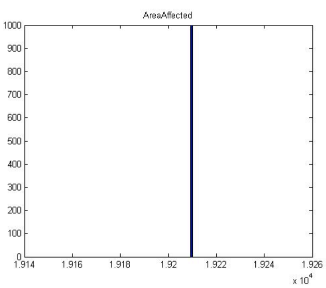

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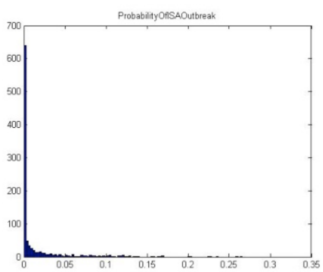

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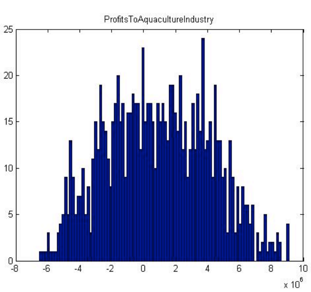

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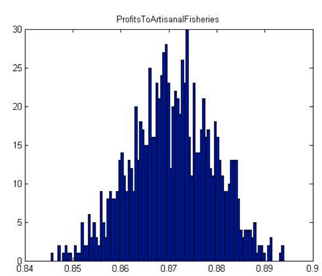

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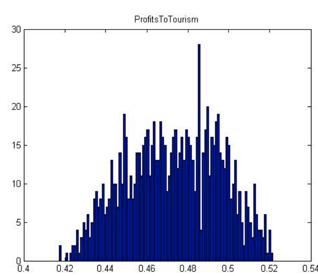

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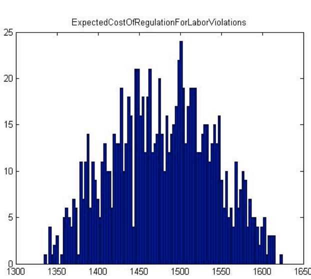

a. Species Richness (fractional change)
b. Species Health (fractional change)
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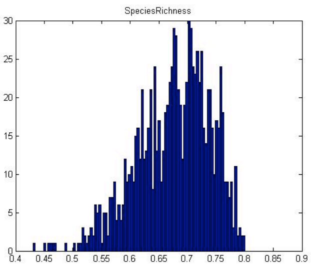
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Natural Mortality held constant

a.



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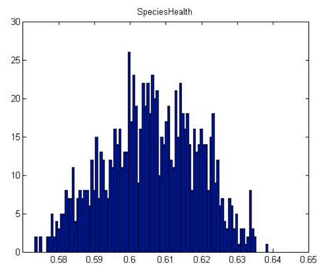

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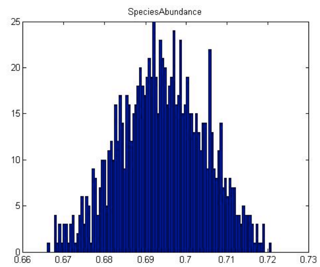

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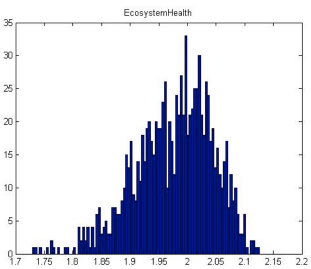

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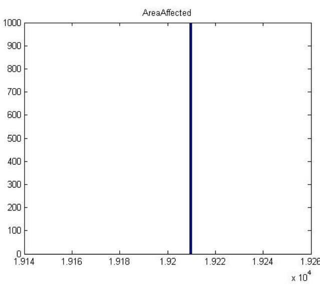

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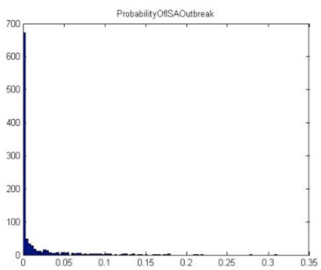

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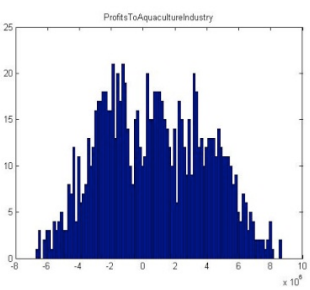

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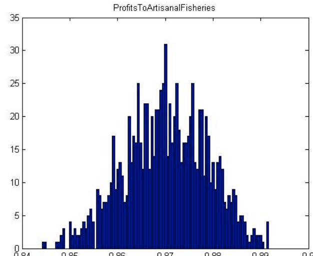

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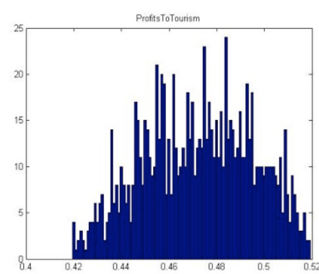

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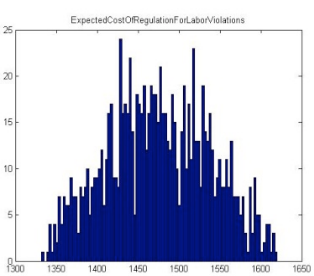

a. Species Richness (fractional change)
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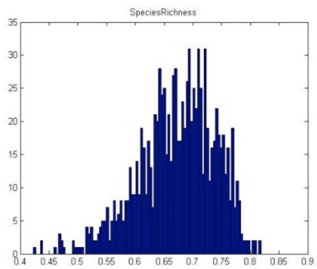
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

N Content in Feces held constant

a.



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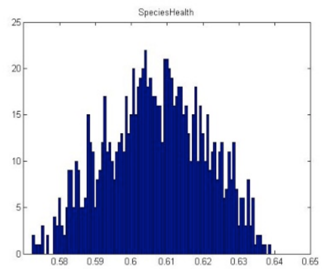

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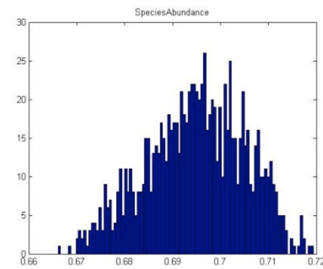

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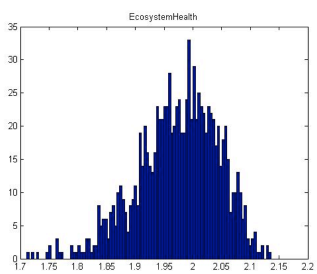

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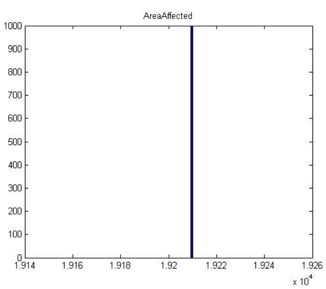

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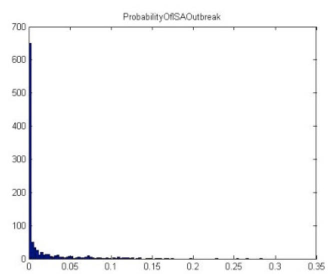

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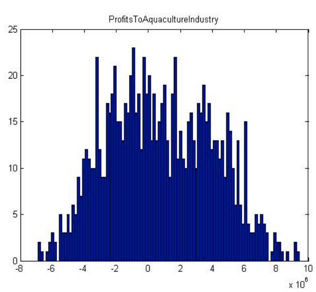

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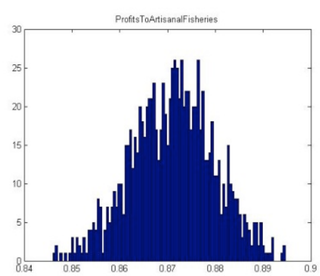
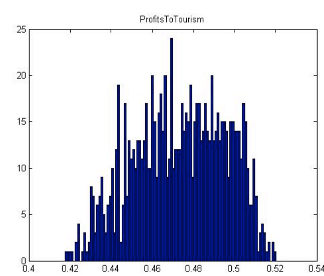


i.



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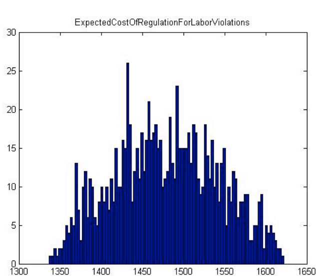

a. Species Richness (fractional change)
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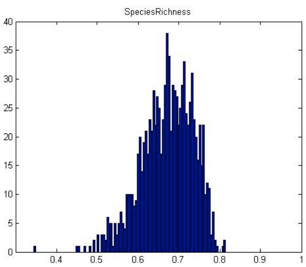
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

N Content in Feed held constant

a.



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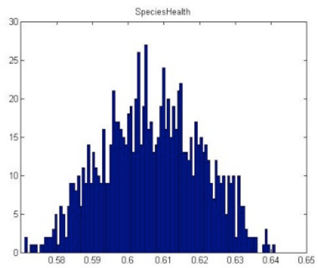

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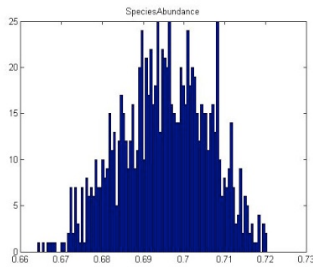

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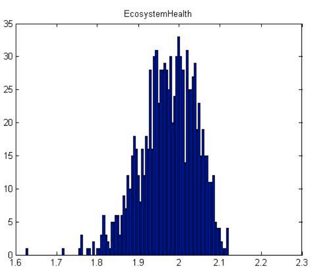

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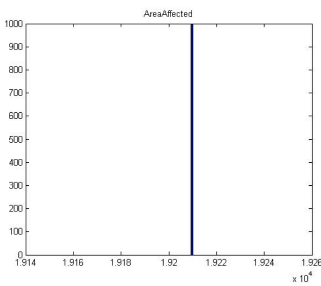

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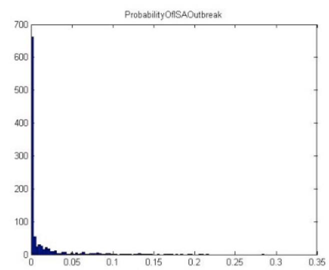

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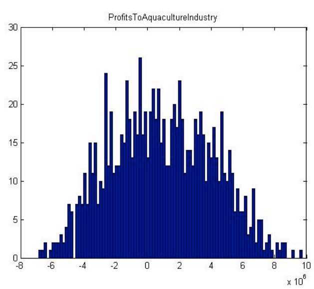

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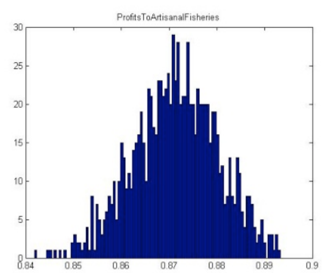

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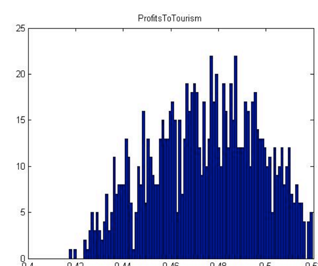
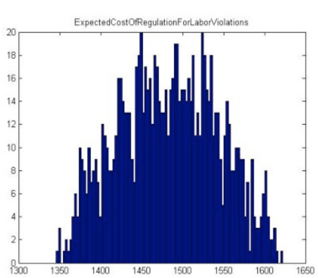


j.



a. Species Richness (fractional change)
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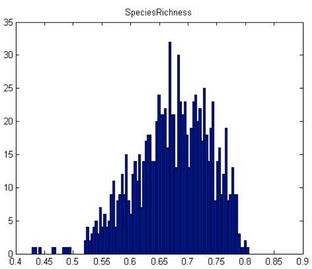
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

N Richness Elasticity held constant

a.



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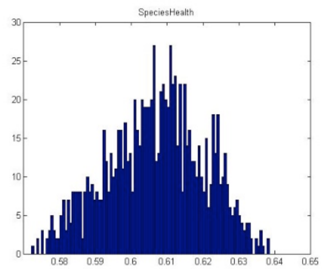

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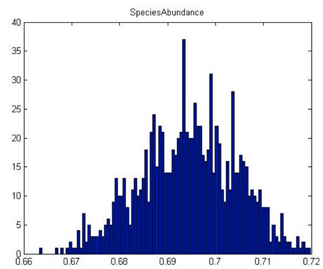

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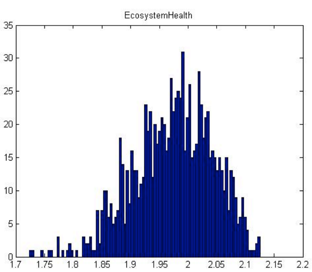
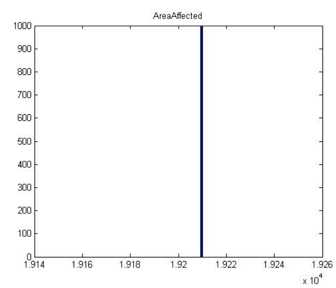


e.



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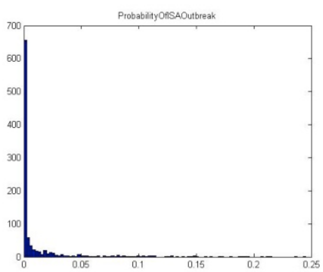
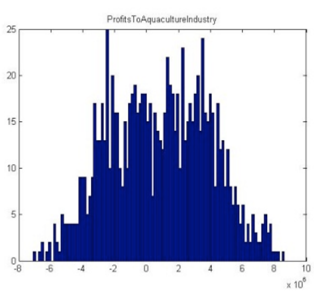


g.



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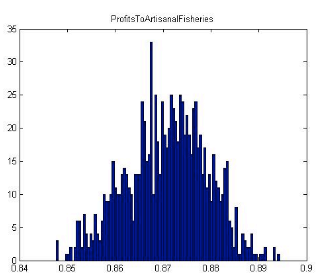
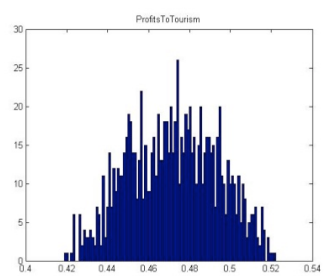
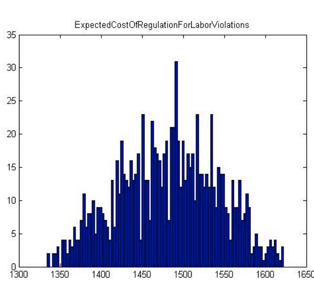


i.



j.



a. Species Richness (fractional change)
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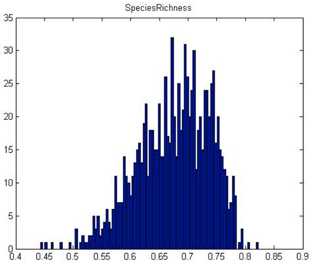
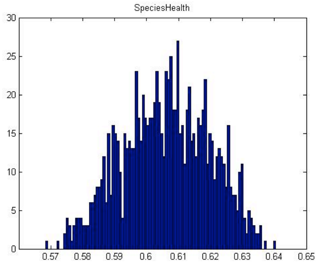
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Number to Halve Native Cetaceans held constant

a.



b.



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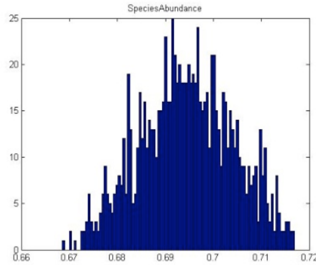

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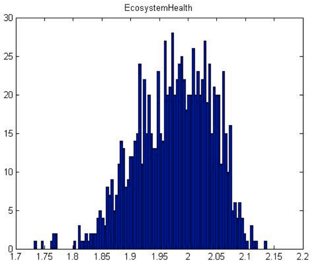

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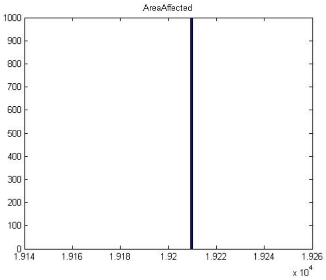

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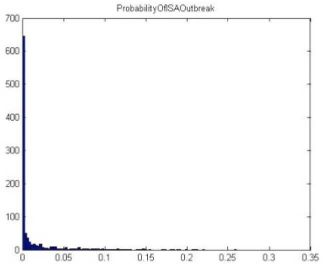

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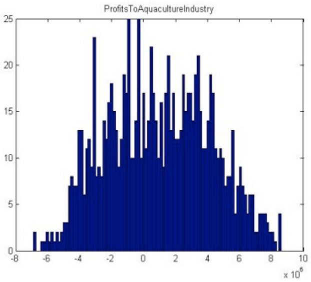

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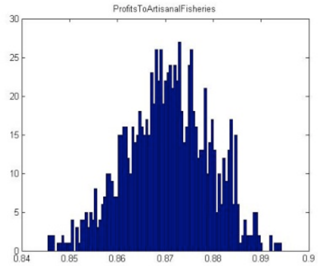
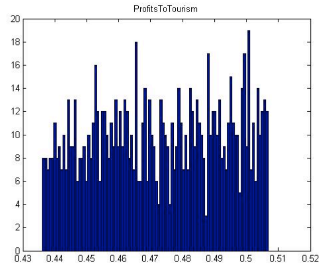


i.



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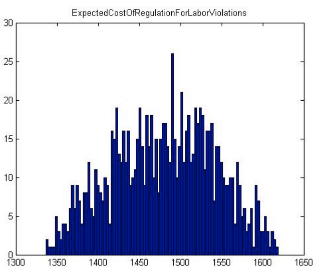
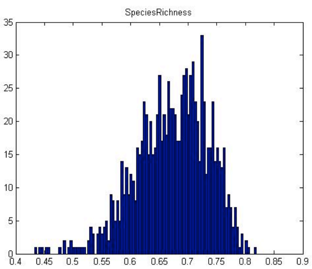


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Number to Halve Native Predators held constant

a.



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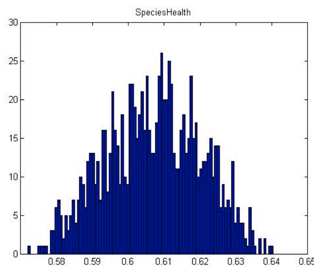

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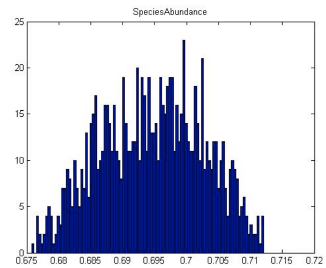

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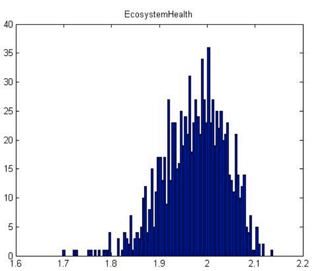

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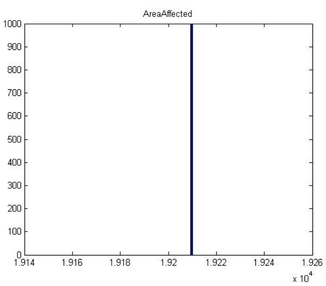

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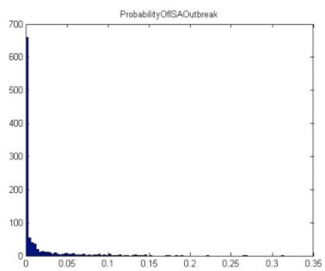

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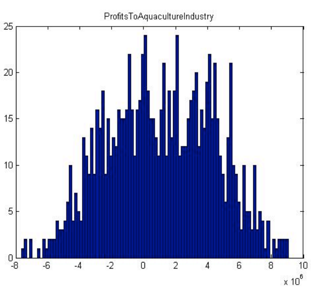

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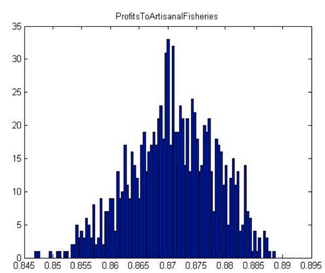

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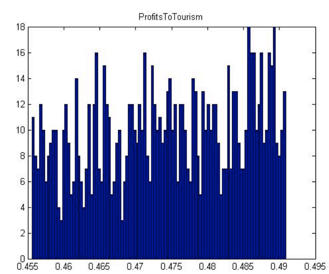

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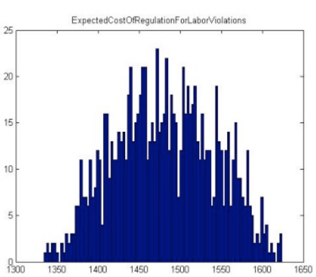
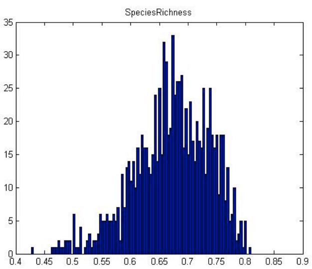


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Number to Halve Native Prey held constant

a.



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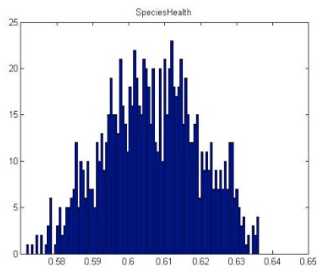

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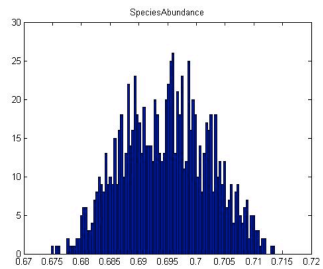

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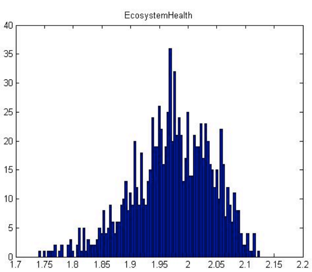

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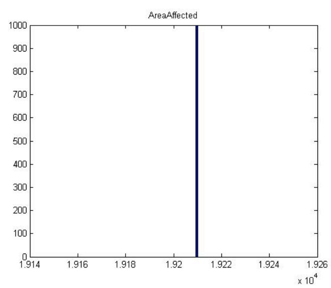

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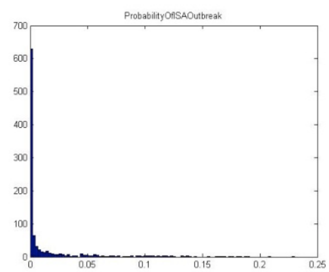

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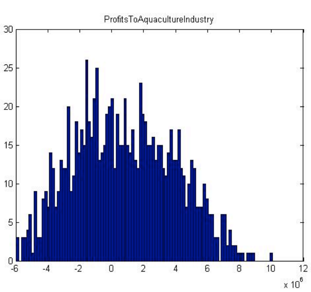

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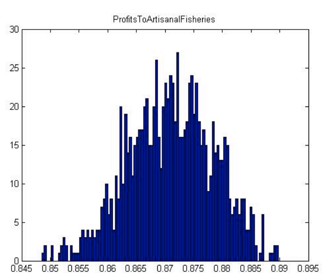

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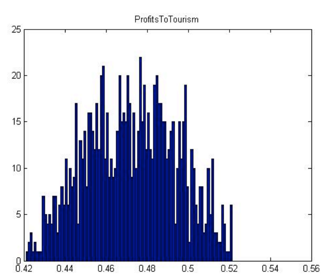

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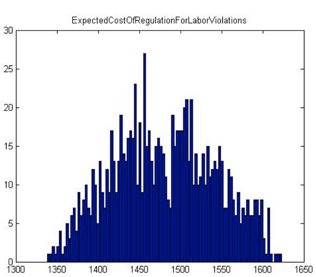
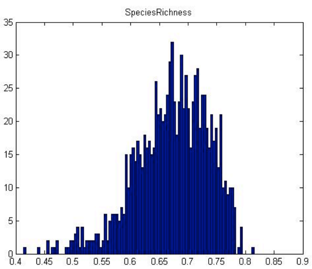


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Number Workers held constant

a.



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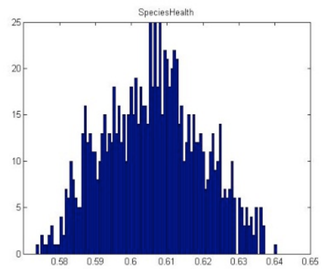

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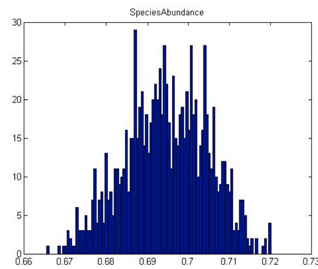

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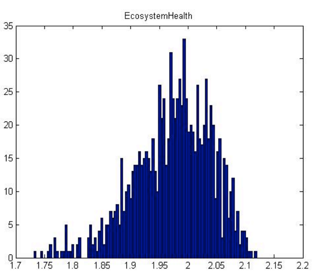

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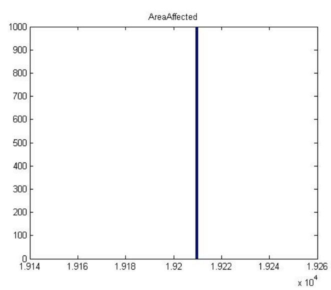

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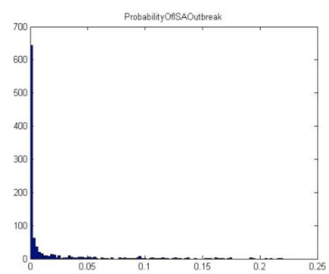

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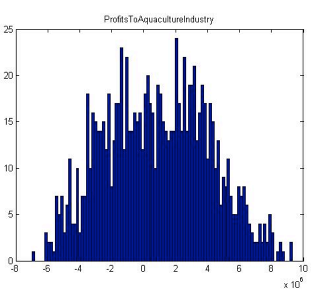

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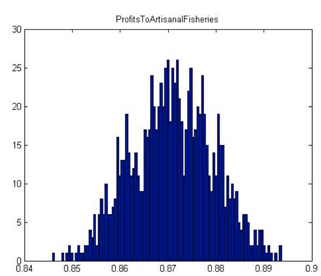

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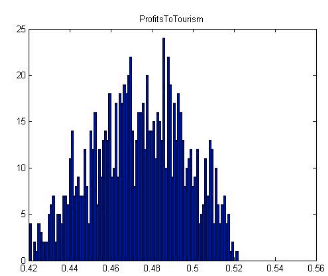

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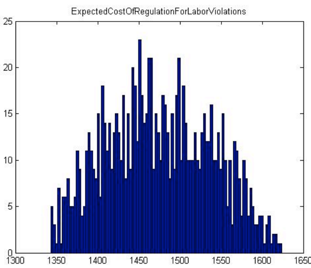

a. Species Richness (fractional change)
b. Species Health (fractional change)
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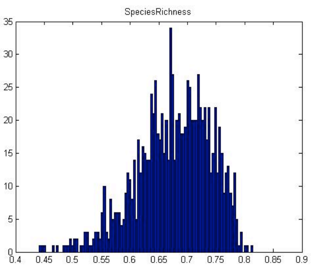
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Original N Density held constant

a.



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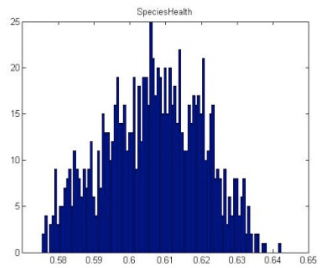

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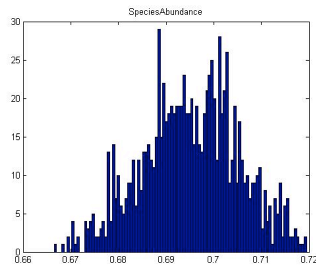

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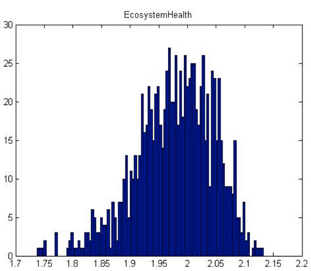

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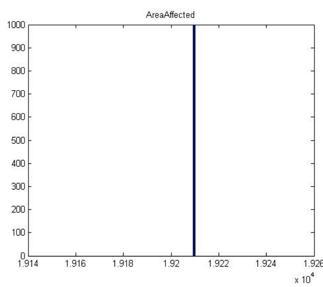

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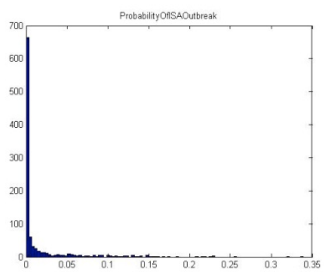

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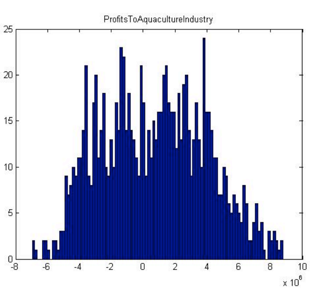

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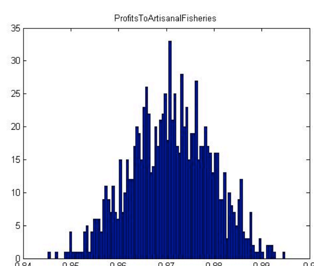

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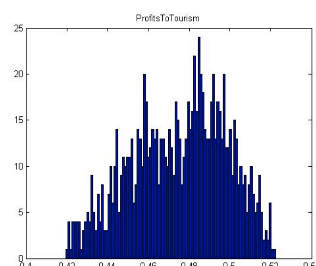

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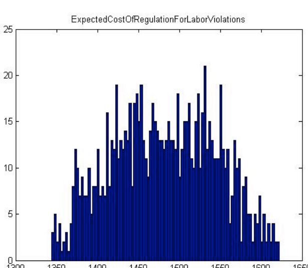

a. Species Richness (fractional change)
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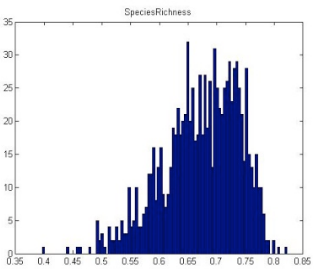
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Other Operation Costs held constant

a.



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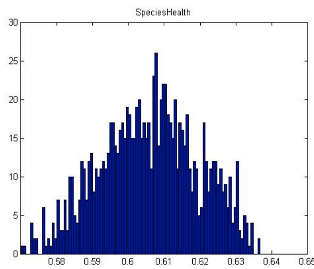

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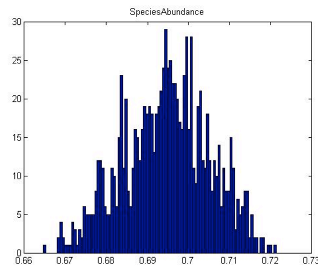

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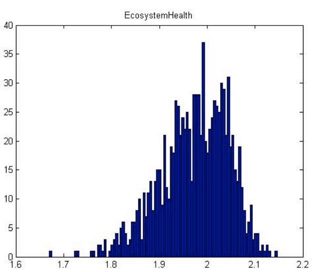

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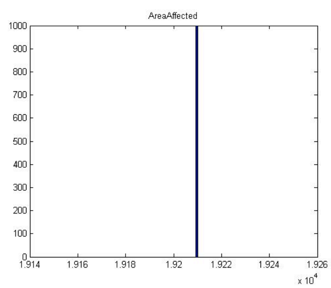

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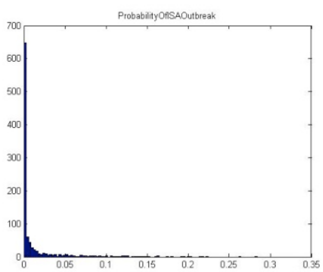

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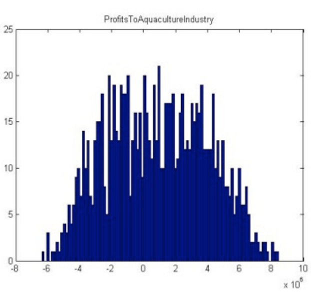

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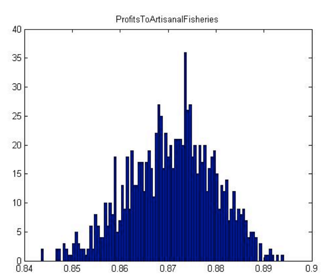

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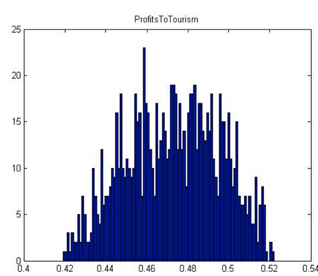

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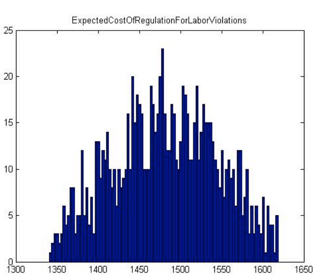

a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
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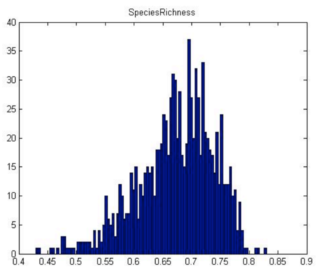
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Prices per Kilo held constant

a.



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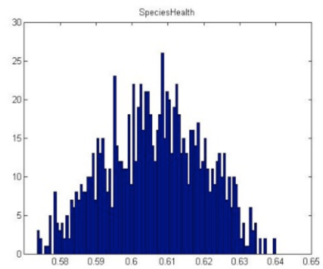

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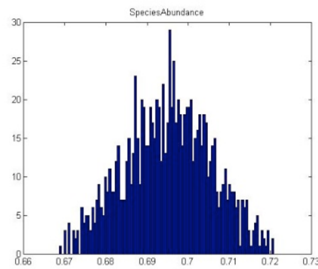

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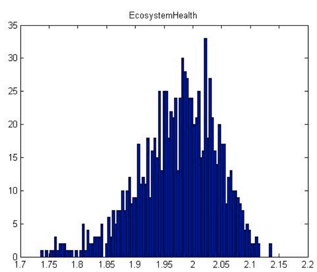

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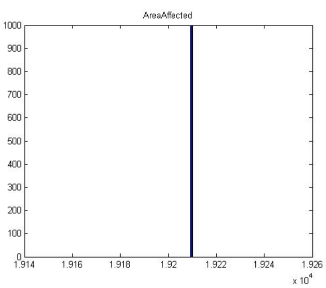

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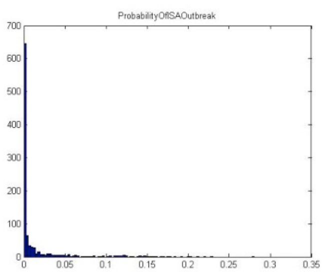

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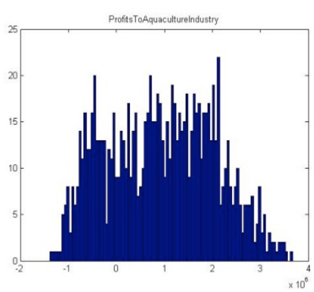

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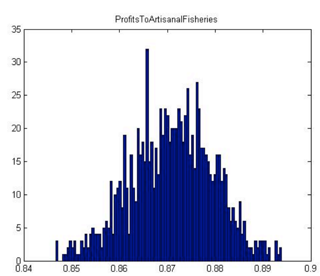

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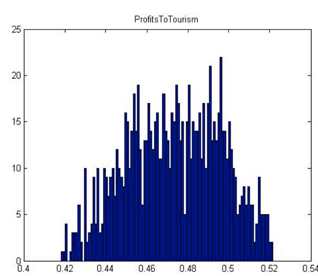
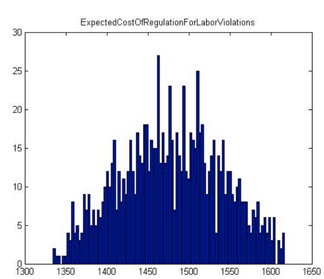


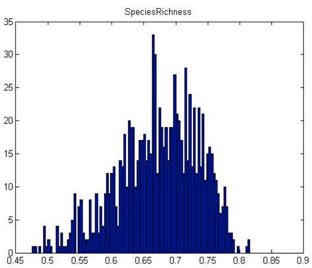
j.



a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Probability of Disease Inside Pens held constant

a.



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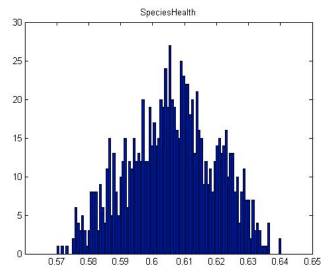

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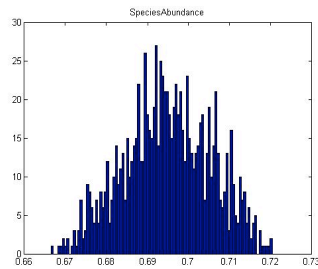

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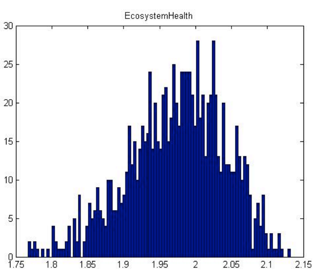

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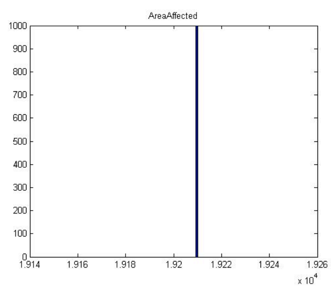

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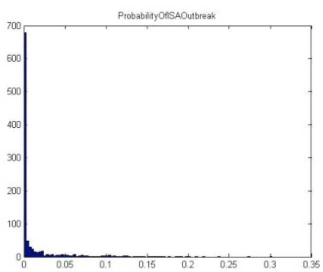

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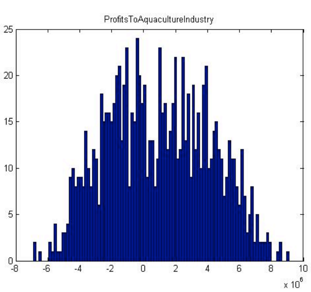

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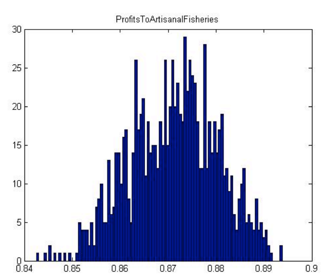
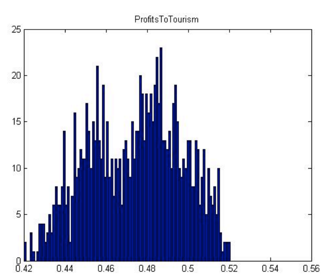


i.



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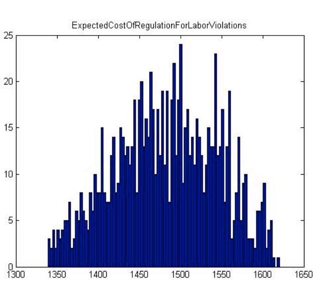
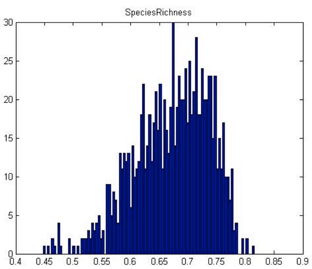


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Probability of Disease Outside Pens held constant

a.



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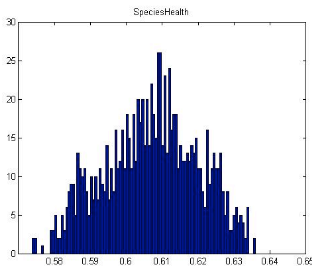

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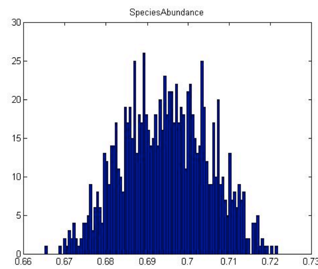

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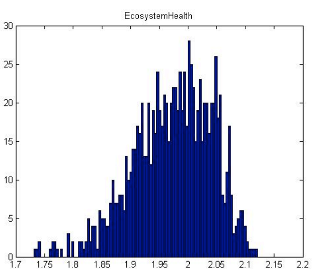

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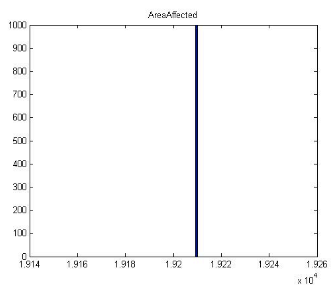

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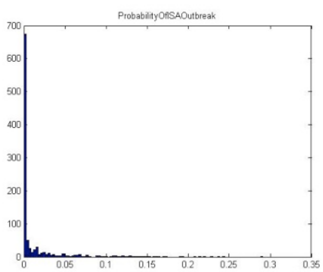

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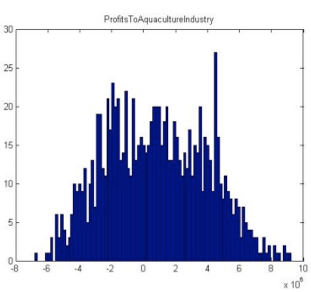

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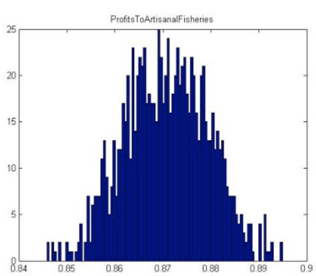
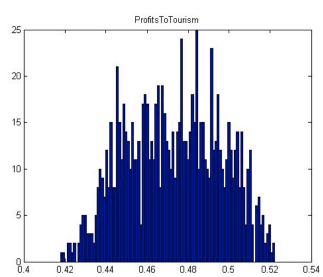


i.



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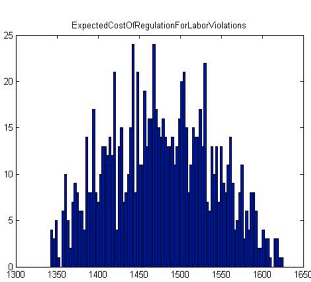
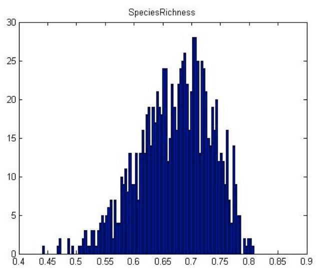


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Probability of Sea Lice Inside Pens held constant

a.



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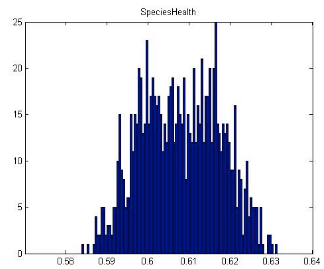

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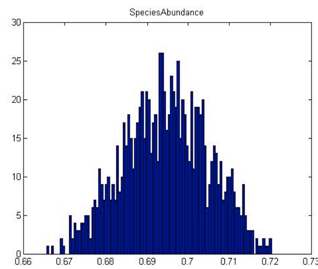

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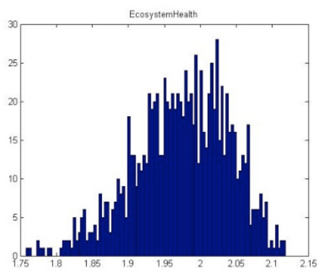
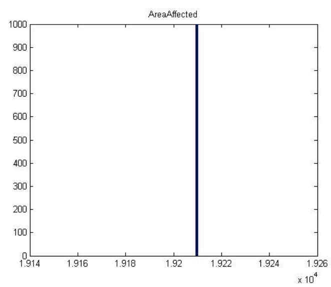


e.



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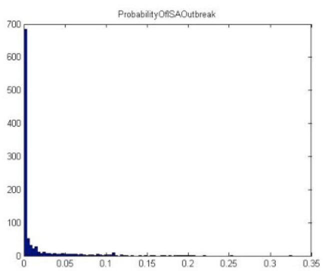

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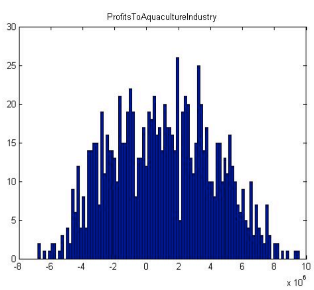

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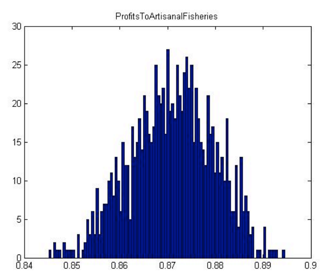

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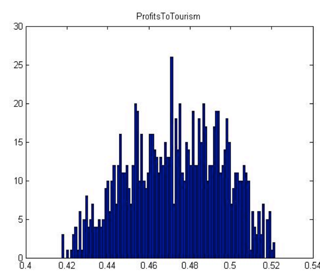

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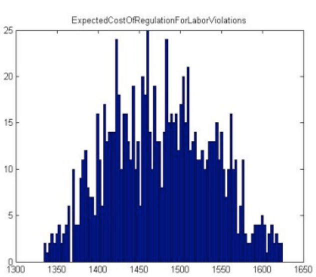
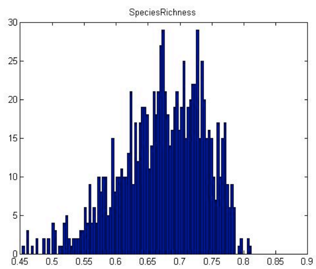


a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Probability of Sea Lice Outside Pens held constant

a.



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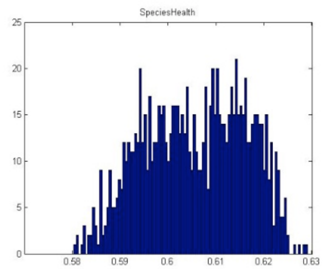

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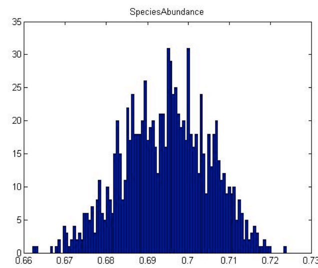

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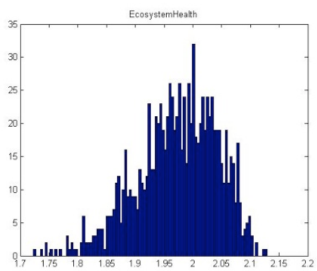

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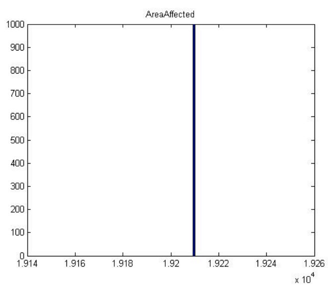

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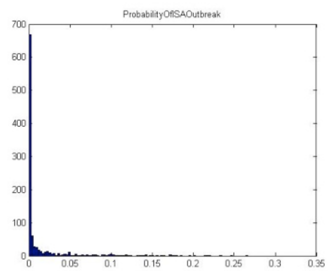

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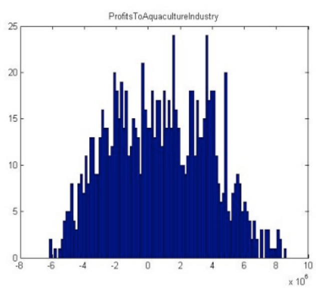

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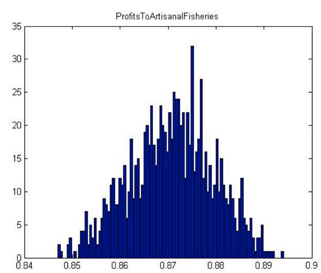

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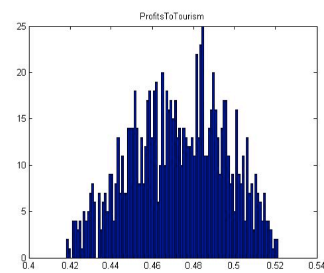

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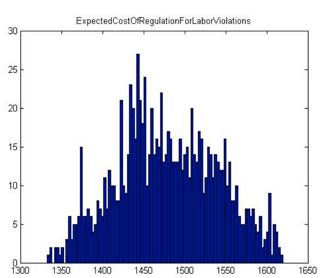
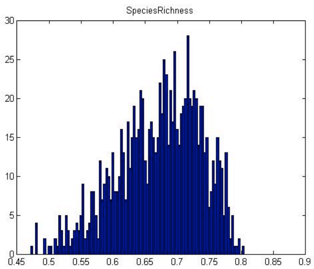


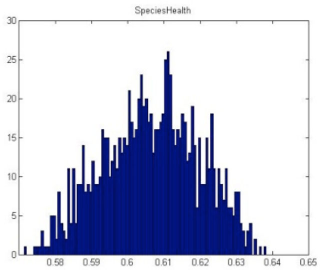
a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Sediment Density held constant

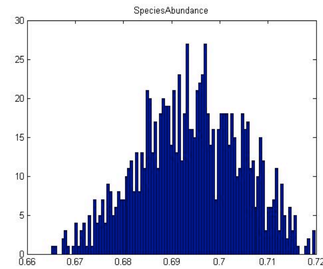
a.



b.



c.



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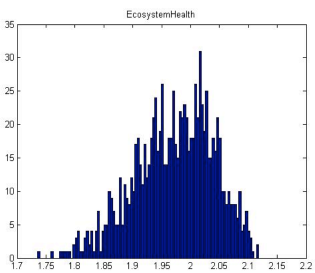

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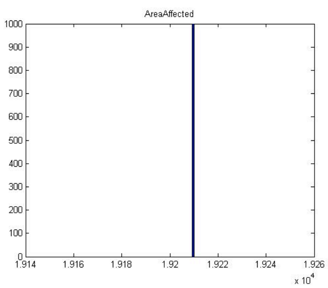

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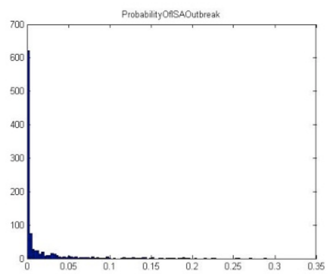

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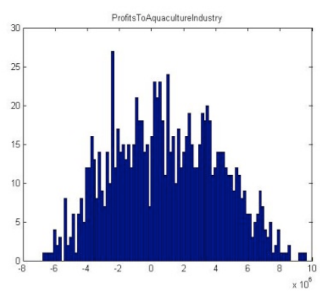

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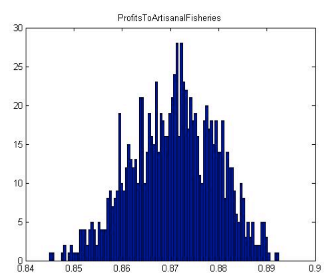

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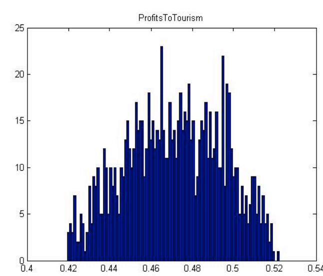
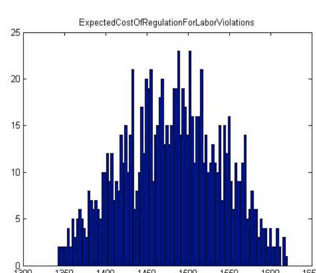


j.



a. Species Richness (fractional change)
b. Species Health (fractional change)
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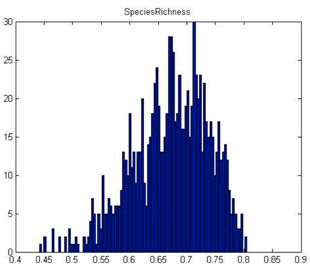
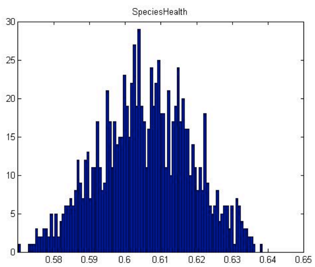
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Slice Days held constant

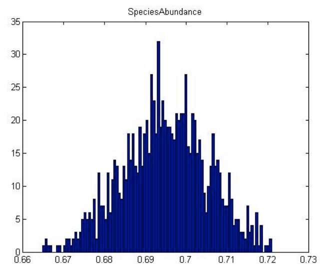
a.



b.



c.



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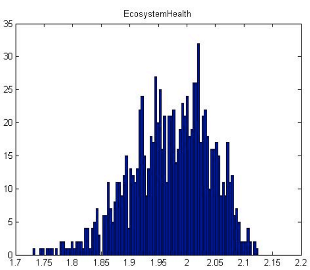

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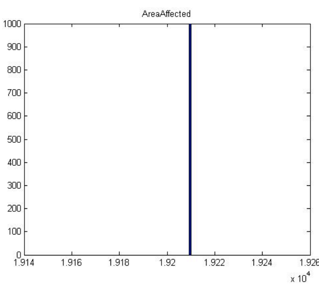
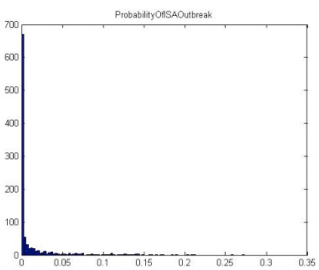


f.



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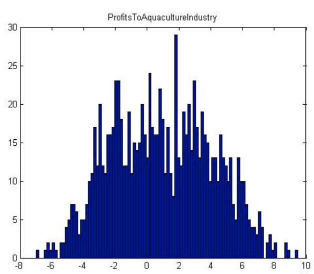

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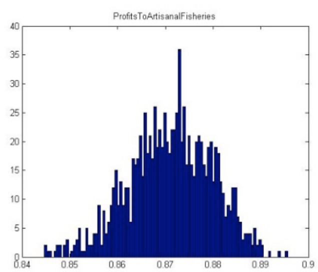
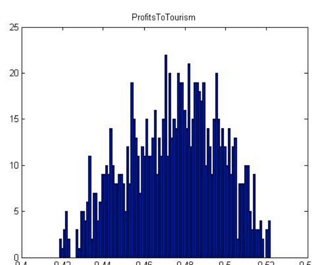


i.



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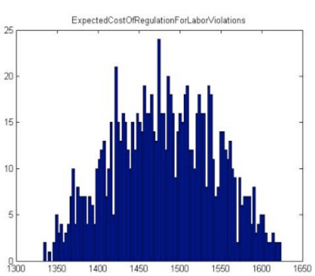

a. Species Richness (fractional change)
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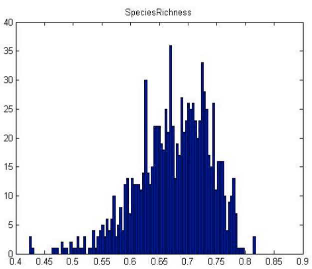
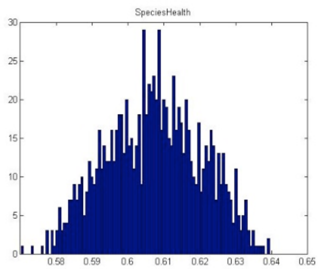
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Smolt held constant

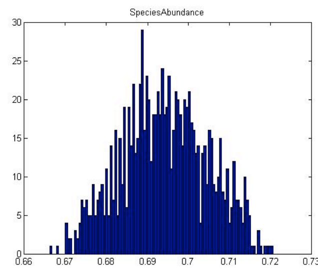
a.



b.



c.



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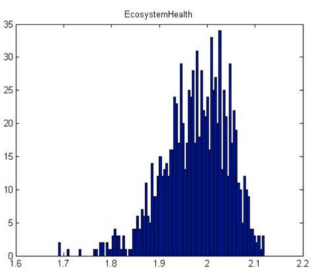
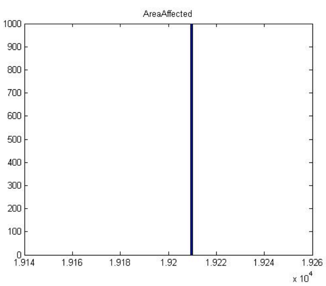


e.



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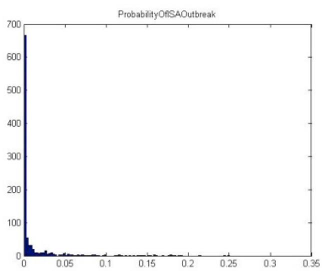

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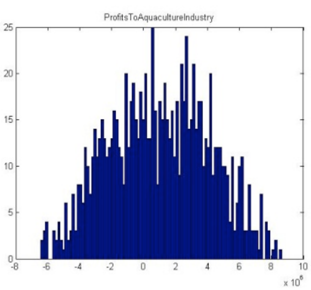

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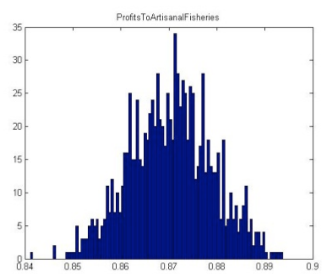
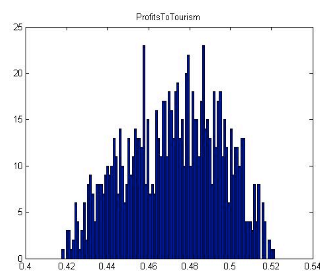


i.



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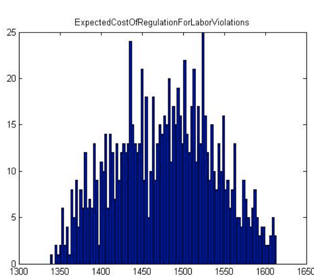

a. Species Richness (fractional change)
b. Species Health (fractional change)
c. Species Abundance (fractional change)
d. Ecosystem Health (fractional change)
e. Area Affected (km^2)
f. Probability of ISA Outbreak
g. Concession Profit (USD)
h. Profits to Artisanal Fisheries (fractional change)
i. Profits to Tourism (fractional change)
j. Expected Costs of Regulation for Labor Violations (USD)

Glossary

Concession: Area designated for aquaculture that holds one or more farm.

Farm: Structure comprised of multiple net pens.

Feed Conversion Ratio (FCR): calculated from the amount of kilograms of feed used to produce one kilogram of fish. When FCR is used in the context of this paper, it is defined as the economic feed conversion ratio, which takes into account total amount of feed applied including the affects from feed loss, escapes, and mortalities.

Infectious Pancreatic Necrosis (IPN): Infectious Pancreatic Necrosis (IPN) is a highly contagious systemic birnavirus disease of young fish of salmonid species. IPN mostly occurs under intensive rearing conditions in salmonid hatcheries or in post-smolt Atlantic salmon in sea-cages. Outbreaks can occur all year round, at water temperatures as low as 4 °C and as high as 18 °C. Atlantic salmon smolt normally develop the disease within weeks of transfer from freshwater to seawater.

Infectious Salmon Anemia (ISA): Infectious Salmon Anemia is a disease that affects Atlantic and is caused by a highly contagious orthomyxo-like-virus, resulting in severe anemia in infected fish. Increased fish mortality in combination with intentional culling to control spread of the virus is a major threat to the aquaculture industry.

Net pen: Individual net enclosures within a farm that contain farmed salmon.

SLICE®: A pharmaceutical drug developed by Schering-Plough to control sea lice in aquaculture fish. The active ingredient is emamectic benzoate and the drug is primarily administered in the fish feed.

Sernapesca: National Fisheries Service of Chile.

Subpesca: Under-Secretary of Fisheries of Chile.