Bioeconomic Modeling of Salmon Farming Practices in Southern Chile

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Client: Wildlife Conservation Society of Chile
Additional Support Provided By: Goldman Sachs

Chile (South America) with major salmon farming regions highlighted

What is salmon farming?

Fish farming, or aquaculture, is a rapidly growing industry that has the potential to help meet increasing global demand for seafood (Pomeroy 2008). Salmon aquaculture in particular has increased drastically in the past three decades to meet high demand (Naylor & Burke, 2005).

Offshore salmon aquaculture consists of rearing salmon in farms composed of floating net pens. Although it can provide jobs and revenue to coastal communities, salmon farming can also cause significant adverse impacts on the coastal environment that can jeopardize other resources. Environmental impacts associated with offshore net-pen salmon aquaculture include nutrient and chemical pollution, competition and predation by escapes with wild fish, and the spread of disease and parasites to wild species.

Salmon Farming in Chile

Chile's salmon farming industry was established in the Los Lagos region in the late 1970s. The industry experienced explosive growth (Barton & Fløysand, 2010), and by 1992, Chile had risen to become the world's second largest exporter of farmed salmon (Bjørndal & Aarland, 1999). However, lack of scientific information on which to base regulations, coupled with weak on-the-ground enforcement, led to environmental degradation and exploitation of salmon farm employees. In 2007, an outbreak of the infectious salmon anemia (ISA) virus swept through the Los Lagos farms, driving the industry to virtual collapse and leaving heavy impacts on the regional environment and economy (Barton & Fløysand, 2010). To rebuild the tens of thousands of jobs and substantial national revenue lost, the industry has begun to expand to the 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 by Chile's National Fisheries Service.

Our client, the Wildlife Conservation Society 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).

Project Objectives

- Predict the effects of certain salmon farming practices on some of the industry's most important environmental and socioeconomic impacts.
- Identify the farming practices, or "inputs", that have the greatest effect on each impact, or "outcome of interest".
- Model the extent of impacts expected to occur from of each of the 21 currently approved Magallanes salmon farming concessions, as well as from potential future concessions, and identify the practices that lead to the best tradeoffs between outcomes of interest.

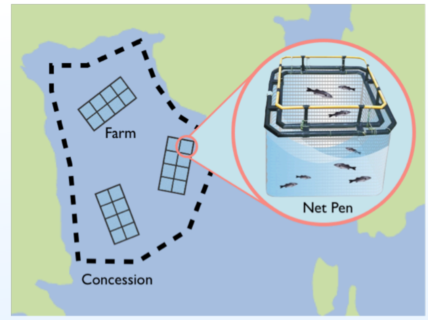

Diagram of salmon farming concession, farms, and net pens

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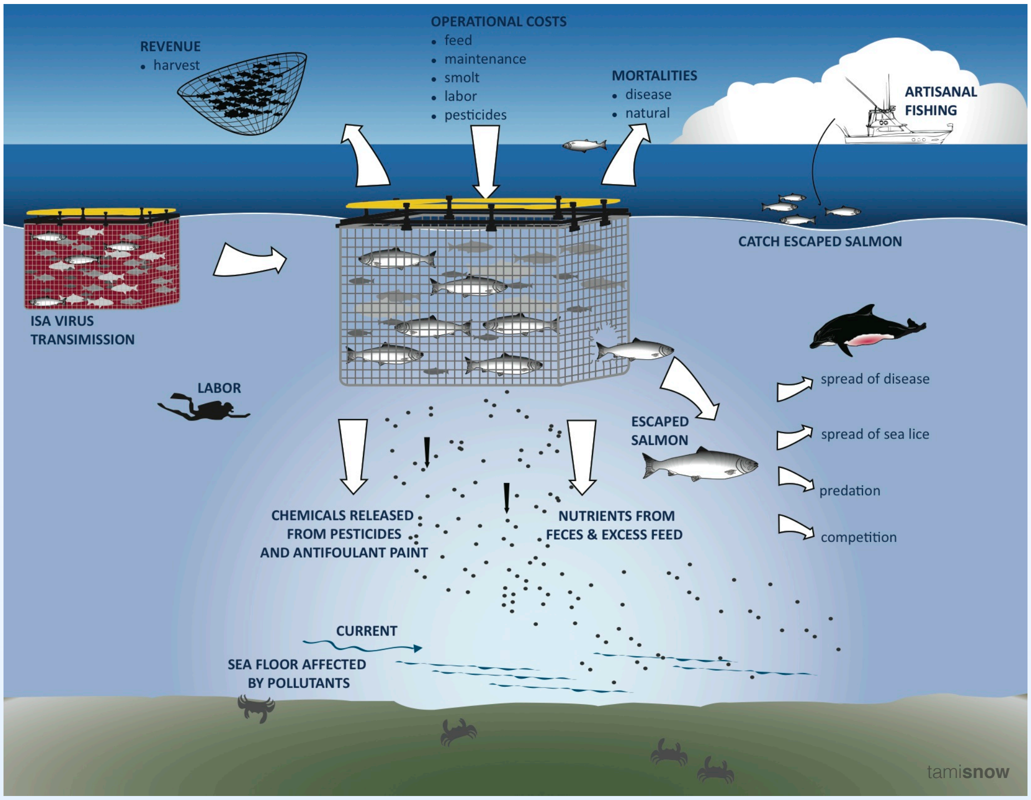

Impacts of Salmon Farming

Nutrient and chemical pollution flow out of salmon farms and onto the seafloor, impacting native sea life.

Escaped salmon compete with and prey on native species, and spread sea lice and disease.

Spread of ISA from one farm to another can occur when farms hold too many fish or are too close to each other.

Artisanal fishing and tourism industries are impacted when important native species change in abundance due to escaped salmon and pollution.

Concession profit depends on operational costs and the value of harvested salmon.

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. We then created a model that takes nine "inputs" – practices or conditions over which aquaculturists have some degree of control – and calculates the extent of their effects on these outcomes of interest. The relationships between inputs and outputs are represented by sub-models that translate input values into outcome values. Each sub-model is comprised of parameter values and mathematical relationships obtained from the literature and other primary sources.

There are a number of salmon farming concessions that have already been approved for operation in the Magallanes, so we gathered data from those concessions' environmental impact assessments (EIAs) to use as inputs and parameters in our model. The average values 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 were assumed to represent the total possible range of values for salmon farming practices to be expected.

Each run of the model represents a possible management decision – a combination of input values that can be selected by an aquaculturist or required by the government. The corresponding outcome values represent the extent of impacts that our model predicts will occur after one cycle of aquaculture under those conditions.

Inputs

Stocking Density
Length of Cycle
Number of Net Pens
Equipment Quality
Number of Chemical Treatments
Current Speed
Water Depth
Hours Law Violations
Wage Law Violations

→ **The Model** (7 sub-models) →

Outcomes of Interest

Ecosystem Health
Concession Profit
Area Affected by Pollutants
Probability of ISA Infection
Artisanal Fisheries Profit
Tourism Profit
Expected Cost of Labor Violations

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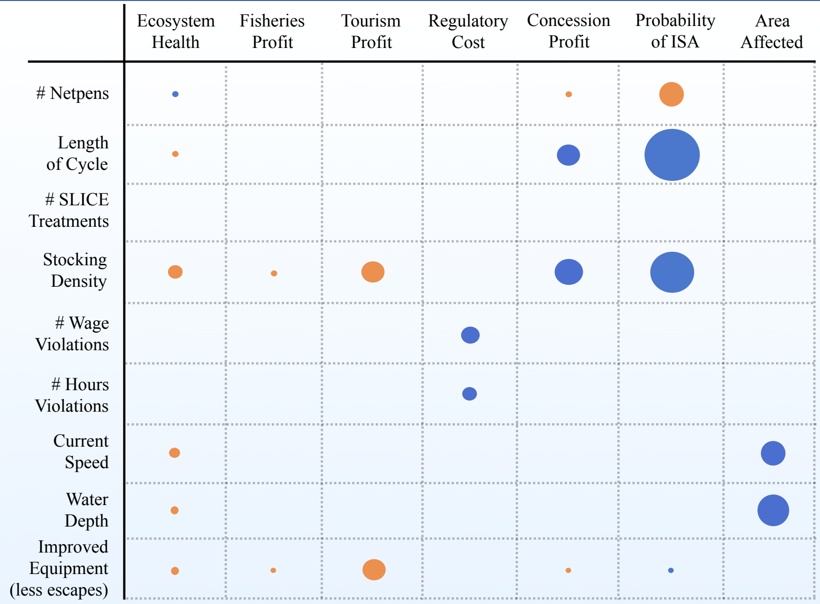
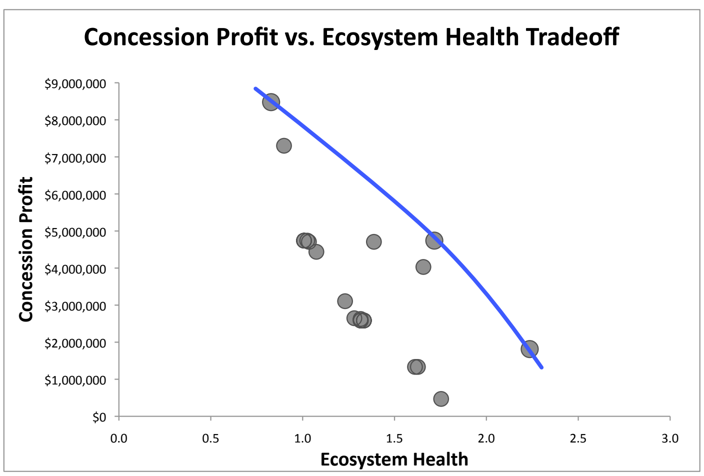
Which salmon farming practices have the strongest effects on the outcomes of interest?

We created an elasticity matrix to identify "leverage points", or inputs that, when adjusted, have the largest effect on a given outcome value. We performed this analysis by systematically adjusting each input value by a given percent and calculating the resulting percent change in each outcome. The elasticity matrix identifies inputs that managers can alter that will result in the greatest improvements on certain outcomes. Stocking Density was found to be the input with the greatest impact on the most outcomes. Length of Cycle and Equipment Quality are also important leverage points for some outcomes.



Elasticity matrix of inputs' effects on outcomes. Blue indicates positive correlation, and orange indicates negative correlation; circle size indicates the magnitude of effect.



Scatterplot illustrating the predicted performance of each approved Magallanes concession on the outcomes Ecosystem Health and Concession Profit. Each dot represents one concession. Dots that fall on the efficiency frontier (blue line) represent concessions that make the most efficient tradeoffs between these two outcomes. However, tradeoffs may be possible that are even more efficient than those than these.

Which of the approved Magallanes concessions are expected to perform the best?

We used our model to predict the performance of 21 approved Magallanes concessions on each outcome. We ran our model once for each concession, using the input and parameter values stated in the concession's EIA. Our results show that different concessions perform well on different outcomes, and that no concession performs the best on every outcome. Instead, there are tradeoffs between outcomes. Here, we highlight the tradeoff between the outcomes Ecosystem Health and Concession Profit.

The concessions that make the most efficient tradeoffs between these two outcomes fall along the outer bound of the plotted points, or the "efficiency frontier". Most of the 21 concessions fall inside the efficiency frontier, implying that their inputs result in sub-optimal outcome values for Ecosystem Health and Concession Profit. Our model can help managers determine how to adjust salmon farming practices at individual concessions to make them more efficient, moving them closer to the efficiency frontier.

Importantly, according to our research, none of the 21 approved concessions do, in fact, propose farming practices that lead to the most efficient possible values for these two outcomes. We found that there are combinations of input values that result in even higher scores for both Concession Profit and Ecosystem Health than are represented by the efficiency frontier of the approved concessions. For example, specific combinations of stocking density, equipment quality, current speed, and and depth lead to some of the most efficient tradeoffs. Therefore, there is room for improvement in Magallanes salmon farms.

Which parameters are most important to research?

We performed a sensitivity analysis to identify the parameters that have the greatest effect on each outcome. We found that the parameter describing feed conversion ratio has a large impact on Ecosystem Health, and mortality rate due to disease has a strong effect on Concession Profit. Increased certainty about these two parameters will lead to more reliable model results.

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Model Caveats

At present, our model predicts the impacts of one harvest cycle at one concession. It does not capture cumulative effects over time or space, although salmon farming takes place over many harvest cycles in succession, and there can be many salmon farms within relatively small areas. Therefore, it is possible that the model underestimates the magnitude of impacts on some outcomes. For example, chemical pollution could accumulate in the sediments over multiple harvest cycles, causing more acute impacts than our model predicts after only one cycle; equally, the areas affected by chemical pollution from multiple farms could overlap, leading to more concentrated chemicals than expected from only one farm.

Our model provides reasonable estimates of the direction and magnitude of change based on in input values, but the outcomes are not expected to be completely accurate. Many inaccuracies can be attributed to lack of data from this remote part of the world, and reliance on data that was supplied by EIAs, which are composed by aquaculture companies. Nevertheless, the model can be a useful tool for comparing the performance of many concessions and identifying ways to improve concessions' performance.

Atlantic salmon in a fish farm

Recommendations for the Industry

- Use our model to identify farming practices where improved regulation can lead to the greatest benefit for particular outcomes of interest.
- Use our model to assess applications for future salmon farming concessions. Predicting the extent of impacts and ranking applications based on particular outcomes can help determine which concessions to approve and how to improve those that are expected to perform sub-optimally.
- Our model serves as a framework. Adding more sub-models and incorporating more detailed information into the existing sub-models would expand the model's scope and increase the reliability of its results.

Towards Sustainable Salmon Farming in the Magallanes and Beyond

As the salmon aquaculture industry grows to meet rising demand, it will need to be carefully managed if the goal is to achieve favorable tradeoffs between environmental and socioeconomic impacts. Managing the environmental impacts of salmon farming could be particularly important for the Magallanes region, which supports tourisms and artisanal fishing industries that rely on the rich and abundant environmental services that the region currently provides (Iriarte et al, 2010). Our model offers a tool that can be used to predict impacts and make more informed decisions regarding use of the coastal ocean. Models like ours can reduce reliance on "trial-and-error" management that can cause large, and in some cases, irreversible detriments to socioeconomic and ecological systems. Models such as ours will be crucial as this industry grows both in the Magallanes and worldwide.

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