The Role of System Dynamics Approaches in Aquatic Disease Management: An Application to Sea Lice Control in Norway

by

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Important Note

Funding for this work was provided from the Norwegian Research Council through the SALMODIS project (Sustainable disease control strategies in salmon farming; decision support integrating economic, environmental and social dimensions, NFR project 207570/S40). SALMODIS has different academic and industrial partners. The industrial partners are looking for a tool that assists them to improve decision quality in terms of disease management. Academic partners aim to publish papers and contribute to the knowledge in the field of aquaculture health economics. Therefore, to achieve SALMODIS strategic goals, we develop a thesis package that includes two main reports: (1) policy paper, and (2) scientific paper (journal article). The Policy paper consists of executive summary, model description, hypothesis and analysis, conclusion, and references. The scientific paper, in addition to the section addressed in policy paper (except executive summary), includes abstract, introduction, literature review, and background – sea lice in Norway. Thesis package starts with the policy paper as a main part of the document and the scientific paper is reported in appendix 1. Thus, the academic reviewers are referred to appendix 1. The industrial partners are referred to the policy paper. There are five other appendices to support both policy and scientific paper that report, model structure, equations, validation tests and analysis, and model interface description.

Policy Paper:

The role of system dynamics approaches in aquatic disease management: an application to sea lice control in Norway

Kanar Hamza, Karl Rich, and David Wheat

Executive Summary

Disease control is a key concern for the economic viability of aquaculture, particularly as bourgeoning environmental issues and food safety requirements increase production costs and complicate disease management. Different methodologies have been used to model the epidemiology and economics of aquaculture diseases, including input-output models, benefit-cost analysis, linear programming, simple spreadsheet-based models, compartment models based on differential equations, and spatial models. Despite the advantages that each of these different models provide, there is a need to develop a more integrated approach to the epidemiology and economics of disease that better represents and captures existing feedback mechanisms, interventions to control aquatic disease, and the economic consequences of these interventions on producer behavior.

System Dynamics (SD) modeling approaches have utility in this context. While SD has been used to model terrestrial animal diseases, its application in fisheries has been limited to questions of stock management. Here we report the application of system dynamics modeling in the context of sea lice control in Norwegian farmed salmon. Separate models of sea lice and salmon growth evolution were designed and integrated to capture the feedback between them.

The model includes four main sectors: (1) biology (fish growth), (2) epidemiology (sea lice population dynamics), (3) policy options (lice control treatments), and (4) economics. These sectors of the model are integrated in a way that allows decision makers to test strategic lice control disease management scenarios, in the meantime getting feedbacks regarding economic consequences of his/her decisions in monetary terms. The user interface is provided to facilitate the process of running and planning different lice control management scenarios and learning from simulation. The interface allows the user to run various simulations and test different lice control management scenarios and compare the results of these experiments in terms of lice population, fish growth, and cost-effectiveness of each scenario.

The major insights of the model are:

1- The treatments form past production cycle (data) did not break lice population cycle and therefore lice population arose shortly after each treatment.

2- In order to have an effective lice control management strategy, timing and type of treatments must be selected carefully to ensure breaking of the lice population cycle, which in turn results in significant decline of lice population.
3- Treatments should target to reduce adult lice population before reaching high levels as a way to minimize water contamination (i.e. lice eggs) which improves lice control effectiveness.
4- Not allowing preadult stage lice to grow to high levels is an effective way to improve lice control effectiveness because controlling preadult lice automatically leads to reducing adult lice population, which leads to reducing lice egg production and breaks lice population cycle.

The effectiveness of lice control treatments largely depends on the size of the lice population before implementing a treatment. In real system is hard to know lice population in advance, we prepared a simulation package that include four scenarios. Each scenario include a course of actions along with it economic consequences. In each scenario, we report and analyze the simulation outputs of different timing and type of treatments in terms of lice population condition, fish growth, and cost-effectiveness. The reported scenarios are examples to show what the model provides to decision makers to make strategic decisions to manage sea lice infection. The user can use the model interface to run as many scenarios as necessary to enhance learning and to improve decision quality in the future.

Contents

General structure of an SD model of aquatic disease

There is a need for an integrated model for aquatic health economics to bridge the gap work in the aquatic field that is done separately by epidemiologists or economists. This model provides a unique integrated platform that incorporates as sub-models the biological, epidemiological and economic aspect of aquatic diseases. The overall model (a) captures the dynamic interactions between sub-models over time, and (b) provides a tool that converts the consequences of epidemics to monetary values in real time. These two characteristics of the model assist in making better decisions for controlling aquatic epidemics.

Our model is divided into four major components or sub models: (1) fish aging, (2) epidemiology, (3) policy, and (4) economics. Figure 1 illustrates how each of these model components interacts with the others. In this section, we examine the general structure by using causal loop diagrams (CLD) of the model that focus on the interconnectedeness of the model components, as well as provide specific details on the components themselves.

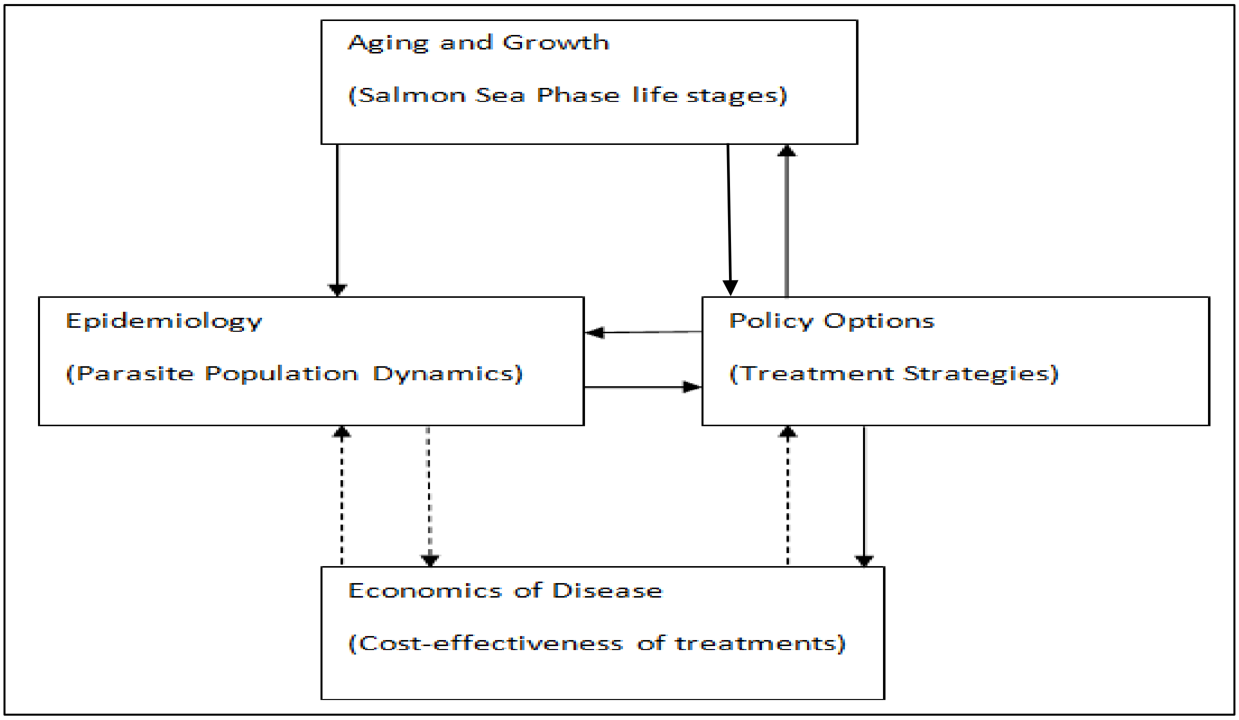

Figure 1: Model sector interactions

The model begins with a fish aging and growth sub model represent cages in the open sea. The aging model is connected to the epidemiological model of sea lice growth, since the population of sea lice begins to grow when there are fish in the cage. It is worth noting that there is no feedback from the parasite population to the growth and development of fish in cages. That is because parasite control strategies in salmon industries prevent the growth of the parasite population to the level that damages fish growth and development. The epidemiological model is linked to the policy model. Sea lice populations over the threshold level trigger control strategies that combat sea lice. Implemented treatments decrease parasite population, thus closing the feedback loop between the sectors.

The influences of the parasite population on fish growth and development is through treatment strategies (i.e. the policy options component of the model). Launching a treatment strategy to control parasite populations influences the growth and development of fish in two ways: (1) mechanical actions involved in treatments leads to the death of some fish, and (2) some treatment strategies require the starving of fish for five days prior to implementing a treatment which leads to decreased fish growth. Thus, the influence of the parasite population on fish growth and development happens indirectly through treatment actions and their consequences. The link from policy options to the aging and growth sub model represents the influence of control strategies (treatments) to the fish growth and development sub model and closes feedback loops among aging and growth, epidemiology, and policy sub models. Reduced fish growth and fish death due to treatments influence the amount of medicines used in in-feed treatments. This influence is represented by the link from aging and growth and policy options sub-models.

On the economic side of the model, the solid arrow represents a direct link from the policy sub model to economic sub model as a means of measuring the costs of implemented treatments. The other dashed arrows represent the insights that the user (decision maker) gets from looking at the cost-effectiveness of different treatment strategies that might influence his/her next decision which influences, and is influenced by, the parasite population and the previous set of decisions. Thus, the dashed arrows represent the insights that the user gets from running different decision and intervention scenarios, and which are considered open loops in the model to help the user to learn from different simulation results through model interface to identify the most cost effective course of actions to control lice in salmon farms. Appendix 6 presents details about the interface.

- ### Aging Sector

The aging sector of the model represents the life stages of farmed Atlantic salmon. Salmon life cycle goes through different stages till adulthood. Theses stages include fresh water and sea water phase. The fresh water phase of salmon life cycle includes eggs, fry, and parr. Smolts and adults are sea phase life stages of salmon. Adults return to fresh water to spawn and lay eggs[1]. However, in farmed salmon the return does not occur because adult salmon is harvested when reached adulthood. We only include the sea phase (i.e. smolt) life stages of farmed Atlantic salmon in the model because farmed fish is vulnerable to sea lice infection when it is in the

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[1] http://www.mesa.edu.au/aquaculture/aquaculture12.asp

open sea cages. Figure 2 shows the causal loop diagram (CLD) of the fish development and growth model.

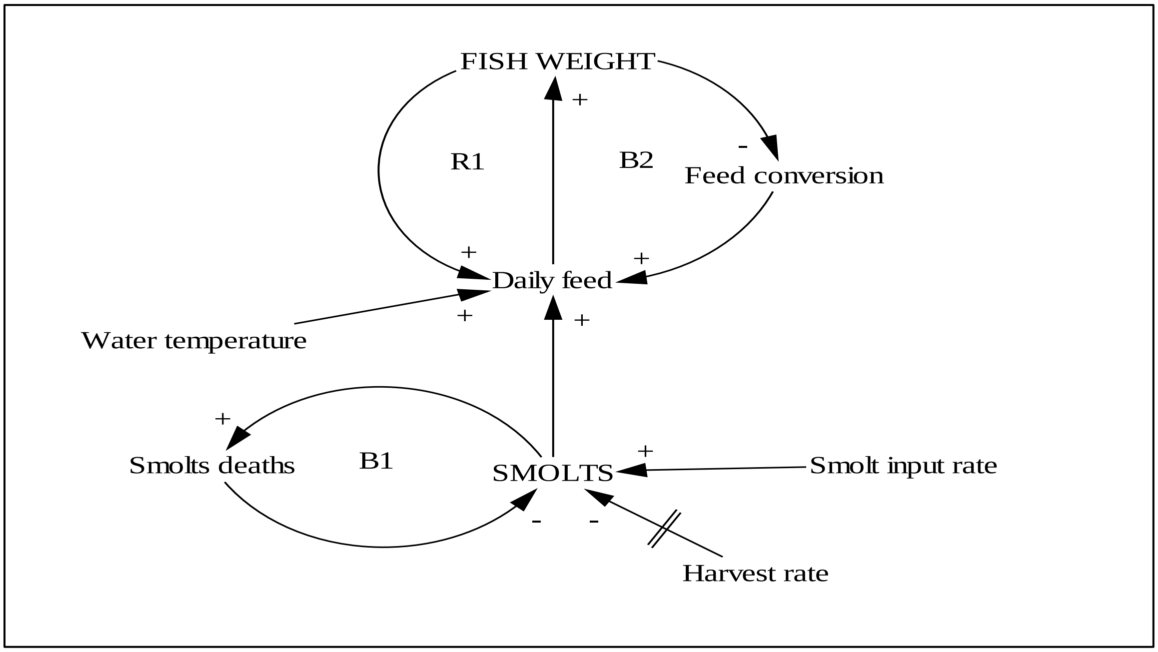

Figure 2: CLD of fish development and growth model

R is reinforcing feedback loop or positive feedback loop. “Positive loops are self-reinforcing.” The more feed given to fish, more fish growth, leading to still more feed given to fish, and so on. B is balancing feedback loop or negative feedback loop. “Negative loops are self-correcting.” The more fish growth, less feed conversion ratio, which leads to lower feed given to fish than what it would normally be, and less fish growth, and so on (Sterman, 2000).

The fish aging section of the model tracks the development of fish from one life stage to another (i.e. from smolts to mature). The growth section of the model represents the growth of fish weight from stocking time until slaughtering/harvesting time. The model starts through *smolt input rate*. That is, the process starts when smolts are introduced to the pen, after which the stock of fish remains at the smolt stage until it grows and reaches marketable size (i.e. *harvest rate*). Feedback loop B1 represents deaths occurring at the smolt stage.

As long as there are fish in the cage, the growth model is active. Two feedback loops govern fish growth, R1 and B1. R1 represents the effect of daily amount of feed that is given to existing fish stocks. The daily amount of feed is a function of fish weight and water temperature. The daily amount of feed increases when there is an increase in fish weight and/or water temperature. B1 represents the influence of fish weight on the feed conversion ratio, which is the ratio of fish meal that is converted to fish weight. As fish grow in size (weight), the feed conversion ratio declines. That means fish grow faster at early stages and then at a slower rate as the feed conversion ratio falls.

- **Epidemiology**

The epidemiological section of the model includes sea lice (*lepeophtheirus Salmonis*) population dynamics. The causal loop diagram shown in figure 3 represents a simplified version of the model that replicates sea lice population dynamics.

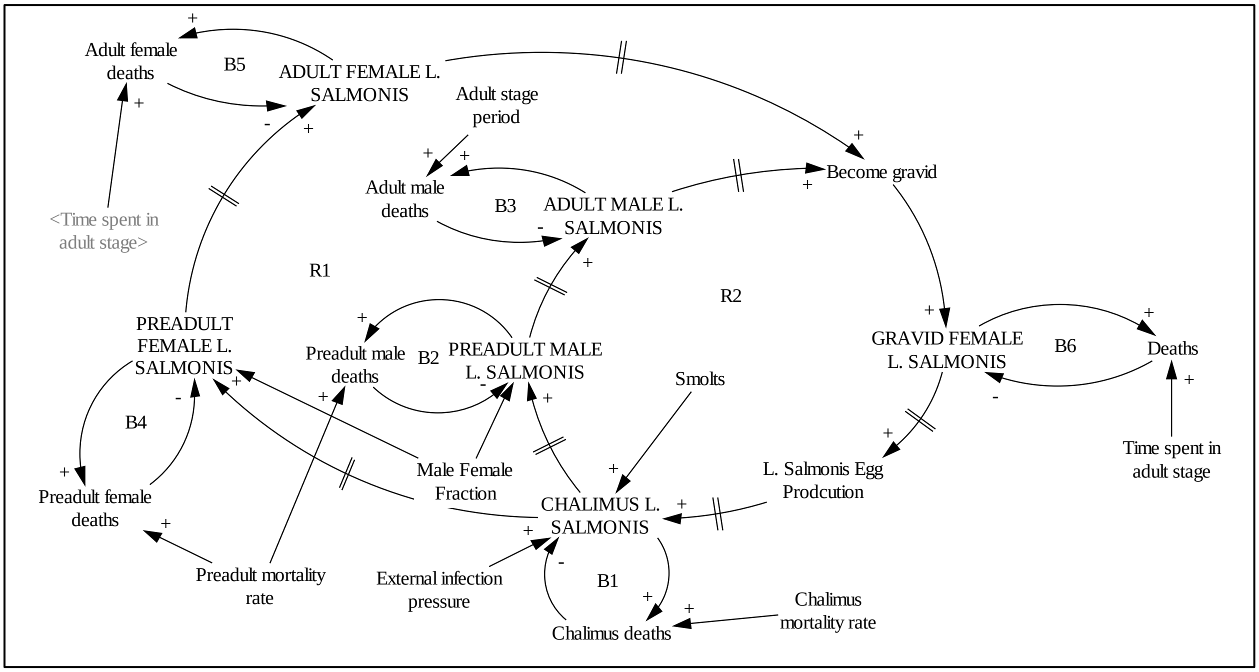

Figure 3: Sea lice population model

The CLD in figure 3 starts at *Chalimus L. Salmonis. Chalimus L. Salmonis* get attached to fish (i.e. smolts) via *External infection pressure* (i.e. free living chalimus around fish cage). From this point, R1 loop represent the development of chalimus L. Salmonis to preadult and adult male and R2 loop represent the same process for female lice. Then male lice fertilize female lice to produce eggs and the lice population cycle repeats in a reinforcing feedback loop.

The epidemiological model is active as long as there are fish in the cage (i.e. the stock "*smolts*"). When the cage is initially smoltified, fish are louse free. Sea lice are introduced to the cage through wild salmonids and nearby cages, *external infection pressure* represents free living chalimus. When chalimus is attached to the body of the fish, after some time the chalimus develop to either preadult male or preadult female stages. The parameter "*male female fraction*" identifies the fraction of chalimus that become male or female; an even distribution of males and females is assumed.

The development of sea lice from one life stage to the next is temperature dependent. As temperatures rise, the sea lice life cycle becomes shorter and vice versa. The life cycle of male lice is relatively shorter than that of female lice. The CLD in figure 3 is a simplified representation of a larger quantitative stock and flow model. Thus, for simplicity purposes, variables that represent time delays are not shown in the CLD, and are instead indicated by the delay marks (//) between sea lice life stages.

Sea lice population model, as shown in figure 3, start when a free living chalimus (see variable "*external infection pressure*") finds a host (i.e. a fish) to be attached to in order to survive. Sea lice life stages, after the chalimus stage, are separated into male and female lice. After some time, 50 % of *chalimus L. Salmonis* become pre-adult males and then adult males. Male lice will fertilize female lice, creating gravid females, which will lay eggs and start a new life cycle. This is represented by R1. The other 50% of *L. Salmonis chalimus male* go through a similar feedback loop represented by R2.

During each life stage of sea lice, only a fraction of lice survive. Feedback loops B1 to B6 represent deaths at each life stage of sea lice growth. The death rate varies among different stages of sea lice life. During the chalimus and earlier stages, the death rate is much higher than the death rate in pre-adult and later life stages due to the fact that the chalimus must find a host (i.e. a fish) in which to attach; in other stages, by contrast, the surviving lice are already attached to a fish. The evolution of the lice population initially starts exogenously through external infection pressure and then the internal reproduction process. R1 and R2 feedback loops dominate the growth of lice population in the farmed salmon cage.

- **Policy Options**

The policy option section of the model represents the decision making process to control sea lice population in fish cages. The CLD[2] in Figure 4 shows a simplified generic structure of the policy options model. This section of the model takes inputs from the epidemiological model (figure 3) and its output correspondingly influences the epidemiological model. The connection points are through the stocks "preadult male L. Salmonis", "preadult female L. Salmonis", "adult male L. Salmonis", "adult female L. Salmonis", and "gravid Female L. Salmonis". The dynamic changes of these stocks occur in the epidemiological model as shown in figure 3. In this section, we only take these stocks as an input to the policy option model because decisions to control the sea lice population in fish cages are made based on the level of adult and mobile[3] lice per fish. The overall model (with different sub-models) includes more feedback loops but here we

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[2] In the CLD, both "*treatments*" and "*implemented treatment effectiveness per each stage*" are aggregated versions of different treatments in the model. We aggregated them for communication purposes. The polarities at the head of arrows that link thresholds to treatments are active only when one and/or both of the thresholds are on.

[3] By adult female lice we mean L. Salmonis Adult Female (gravid and non-gravid). By mobile lice we mean all male lice and L. Salmonis Preadult Female lice.

only describe how the policy option model works and show the important loops that describe the sea lice control strategy decision process.

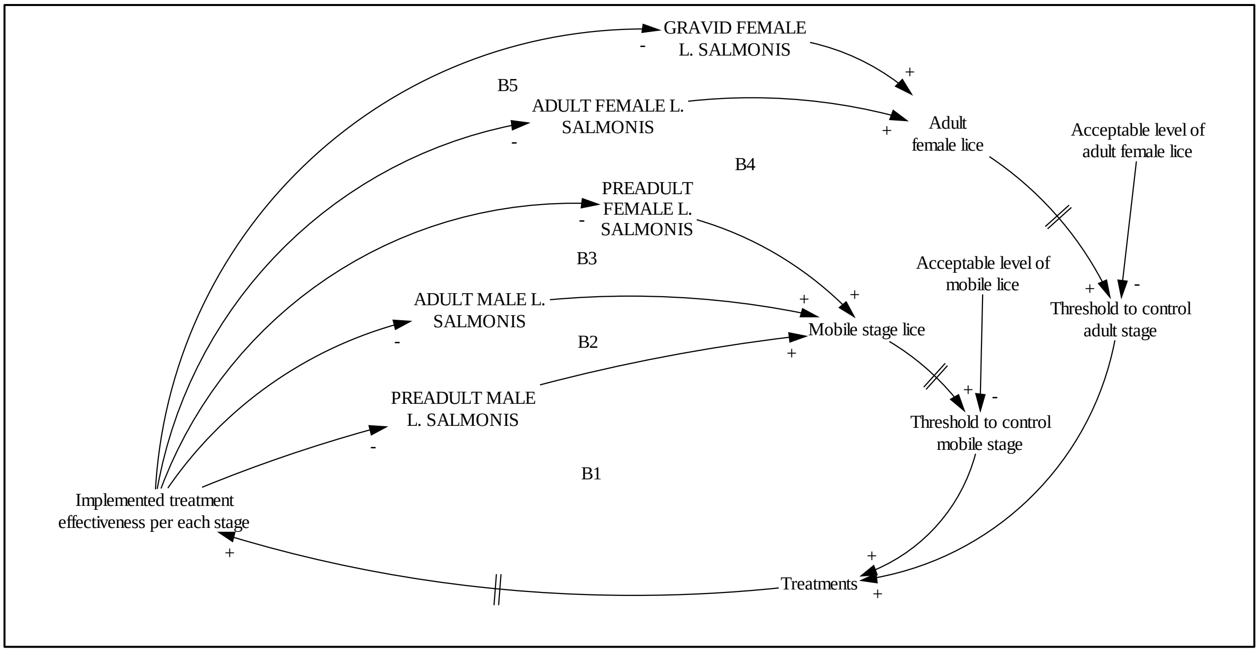

Figure 4: Policy option section of the model

In figure 4, the decision to launch a treatment strategy depends on the level of adult female lice and mobile stage lice per fish. The model launches a treatment as soon as adult female lice and/or mobile stage lice exceed their acceptable level (i.e. 0.5 or 1 adult female and 3 or 5 mobile stage lice per fish). At this point, the model selects a treatment to reduce the level of sea lice per fish. After a short time delay (i.e. 5 days, only for chemical treatments) due to treatment preparation, a treatment is implemented which reduces the sea lice population at each life stage (at different levels of effectiveness depending on the treatment chosen). This has a feedback effect on the lice populations. After a treatment is implemented, the model identifies whether there is a need for another treatment or not based on the level of sea lice per fish. Feedback loops B1 to B5 in figure 4 represent the process of controlling sea lice population at each stage in fish cages.

- ## Economic Model

The economic section of the model measures the costs of treatment to control sea lice level in a cage. A simplified structure of the model is shown in figure 5. The economic model takes inputs from the policy option sub model and its output provides an overview of the costs of different types of treatment strategies. The economic model becomes active whenever a treatment is implemented. There are four types of costs associated with the model: (1) operational costs, (2) material costs, (3) cumulative losses of fish weight due to treatments, and

(4) net present value of costs. Some treatments require starving fish for five days prior to implementation, the amount of money saved through not feeding fish is subtracted from treatment costs.

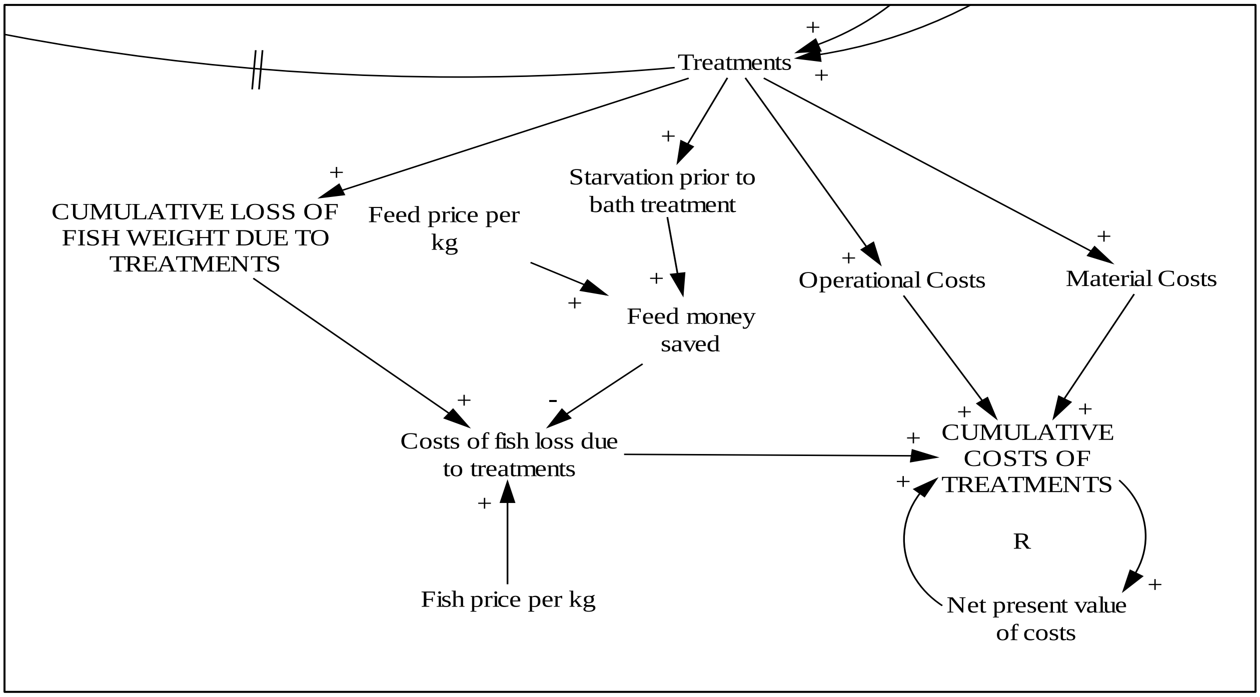

Figure 5: Economic section of the model

Operational costs are denoted as the cost of labor and equipment uses in preparing and implementing a treatment. Material costs are expenditures incurred when buying treatment materials such as medicines. The cumulative loss of fish weight due to treatments represents the loss of fish production, as some treatments require starving fish for five days prior to implementation which leads to reduced fish growth, and loss of fish due to direct deaths through mechanical actions involved in treatment implementation. The cumulative loss of fish weight due to treatments is converted into monetary terms by the variable “costs of fish loss due to treatments”; these are then added together in a stock “cumulative cost of treatments”. To this stock, net present value of costs is added, which represents the net present value of funds that are spent on treatments over time. Feedback loop R represents the process of accumulating net present value of costs, as the cumulative cost increases net present value of costs in a reinforcing feedback loop. In this manner, direct and indirect costs of treatments are accumulated in the economic model from stocking to harvesting time.

Hypothesis

We conduct simulation experiments to different treatment strategies to test different hypothesis. Our hypothesis is that early control of sea lice population results in a more effective control of sea lice population because of breaking sea lice population cycle and avoiding high peaks. The identified threshold to launch sea lice control treatments is 0.5 adult female lice and 3 mobile stage lice per fish from January 1st to August 31st of each year and 1 adult female lice and 5 mobile stage lice per fish from September 1st to December 31st of each year. We hypothesize that launching early treatment events before allowing lice population to reach these thresholds especially before approaching summer times were water temperature gets high will highly improve control effectiveness of sea lice population and keeps the magnitude of infection low. On the other hand, a late launch of treatment reduces the effectiveness of treatments especially when water temperature is high because lice grow extremely rapid under high water temperature case. Thus, by the time treatment is implemented; gravid female lice already lay enough eggs to contaminate surrounding water.

On the fish growth side of the model, early control of lice population leads to a healthier growth of fish and reduces treatment costs because early control may prevent the lice population peaks which results in decreased frequency of treatment events. We also hypothesize that increased number of chemical treatment events negatively influence fish growth because chemical treatments require starving fish for five days prior implementation which leads to decrease fish growth. Thus, as number of treatments (i.e. chemical treatments) increase, the lice population decline, costs increase, and fish get slower growth rate because of starvation prior to treatment implementation. But switching chemical treatments to in-feed treatments (if feasible) leads to better fish growth comparing to the case of using chemical treatments.

On the economic part of the model, our hypothesis is that increased number of treatments lead to a greater cost because (i) increases material and operational costs, (ii) greater loss of fish weight (in case of chemical treatments) because of increased starvation period and fish deaths, and (iii) increases in the net present value of costs . Thus, early treatments to control sea lice population should decrease fish health related costs through controlling sea lice population before reaching high peaks which leads to decreasing number of treatments. Thus, in order to choose the most cost effectiveness course of actions to control lice population, the goal is reducing lice population along with having acceptable level of fish growth.

Simulation Results and Analysis

The model is run in daily time increments over a simulated time horizon of 561 (i.e. one production cycle time) days with DT set to 1. The DT is set to 1 because the shortest time delay in the model is 2.5 days.

Epidemiology (Sea Lice Population Dynamics) and Policy Options

As long as there are fish in the cage, the epidemiological sector of the model is active, and parasites (i.e. sea lice) will begin to attach to fish and reproduce in the fish cage. This section shows three simulation outputs from the epidemiological sector of the model. The time horizon of all simulation outputs shown in figures 6 to 15 is similar. That is, from September 2008 to April 2010 (i.e. duration of past production cycle). We conduct different experiments over the same time horizon to test what would have happened if actions done differently. These experiments assists to learn from past and improve decision making in the future through learning from simulations.

The first one illustrates simulation results of sea lice population dynamics over time through inputting treatment events from past production cycle into the model. That is, the same type and timing of treatments over the same time horizon as in data (figure 6 and 7). The purposes of this run are to evaluate the replication of sea lice population data (from past production cycle) by the model and to provide a benchmark to evaluate different treatment options (that is, different timing of implementation over the same time horizon as in data) in the next simulation. The second result shows simulation of sea lice population dynamics through implementing treatments at different times. In this case, the user can pause the model (or the model automatically pause when sea lice population exceeds thresholds) whenever necessary to decide whether to launch a treatment to control sea lice. Two runs (figures 8, 9, 10, and 11) are reported to evaluate whether different timing of treatment event influence the efficiency of sea lice controls. The third result show the influence of experimenting different timing along with switching treatment types on sea lice population (figures 12 and 13).

Simulation 1: reference mode replication

Figures 6 and 7 show data and simulation[4] results of adult female and mobile stage sea lice per fish, respectively. The model generates results shown in figures 6 and 7 by introducing treatment events from past production cycle to the model to control sea lice level per fish.

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[4] Five treatment events are implemented in this simulation at days 78 (in-feed treatment), 126 (in-feed treatment), 377 (chemical treatment), 397 (in-feed treatment) and 464 (chemical treatment).

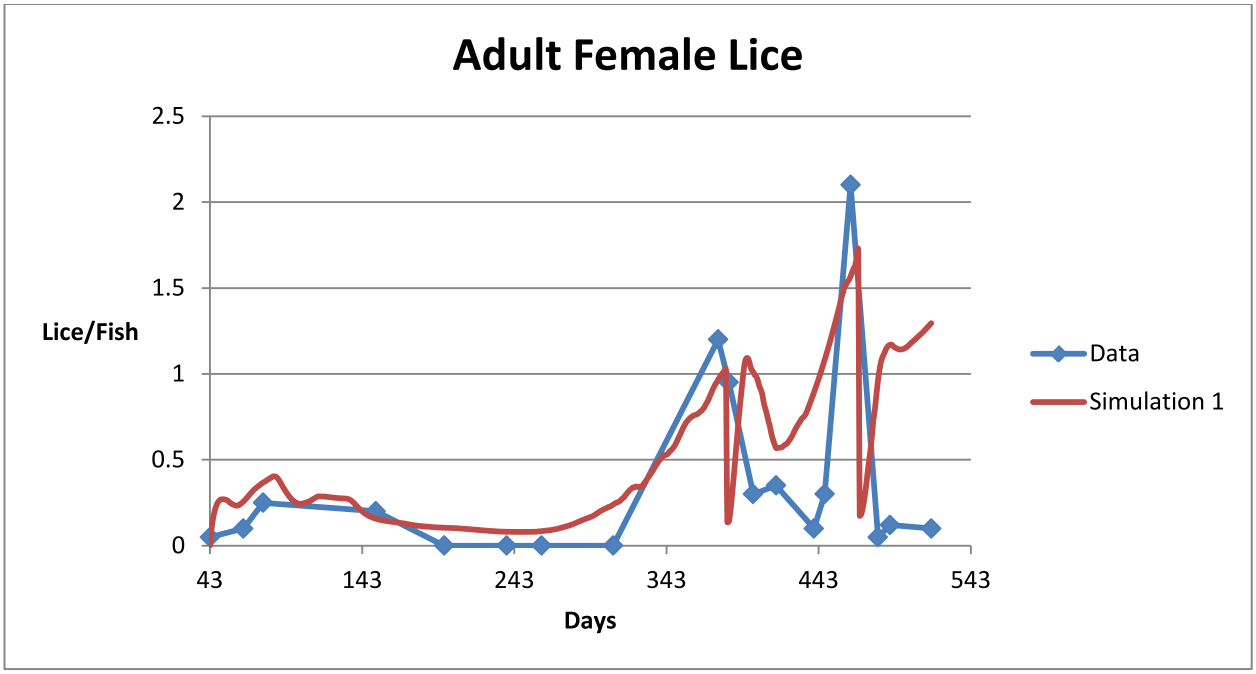

Figure 6: reference mode comparison (adult female lice)

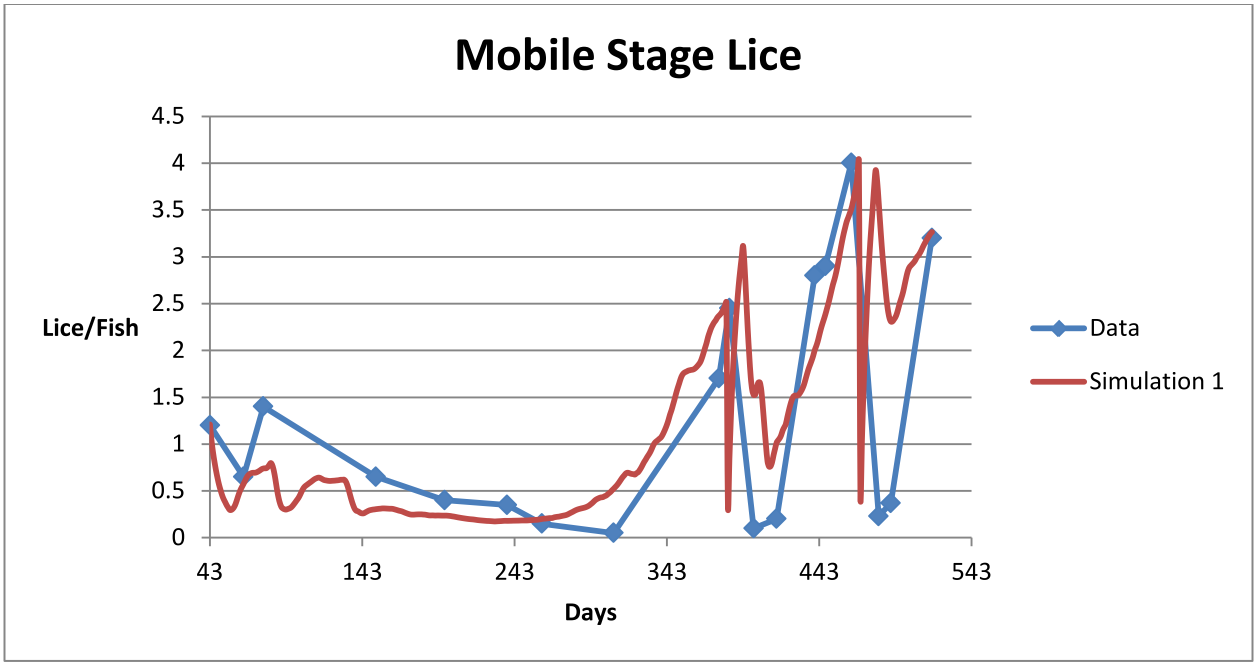

Figure 7: reference mode comparison (mobile stage lice)

The behavior patterns of simulation results[5] shown in figures 6 and 7 are described as follows:

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[5] Note: the data trend in the figures 8 to 13 are based on samples (that is, the dots in the trend) while simulation results are continuous from day 43 to the end of simulation.

1- The level (i.e. both adult female and mobile stage lice) of sea lice per fish is low at the beginning of the simulation because fish are lice-free when first stocked in the cage[6];

2- Sea lice are initially introduced to a cage from outside sources, after which lice begin to reproduce internally in the cage. The growth rate is temperature dependent; as temperature increases, their growth increases, and vice versa.

3- The level of sea lice until day 240 (day 300 for data) is relatively lower compared to later days of the production cycle. This is because fish are stocked in September and the water temperature starts to decline until late April (day 240) and therefore the magnitude of background infection pressure is low. In addition, the reproduction of sea lice in low water temperatures is much lower than the reproduction of sea lice in high water temperatures.

4- The level of sea lice per fish starts to grow from day 240 due to the fact that the water temperature begins to increase and so too does the magnitude of background infection pressure. In addition, sea lice reproduce at a faster rate internally and therefore the level of sea lice per fish increases extremely rapidly.

5- The continuous sharp growth and then decline in both data and simulation results occur as a result of implementing treatments to control sea lice levels per fish. Thus, each time sea lice reach or exceed a threshold level, the model launches a treatment strategy, and therefore the sea lice levels per fish decline sharply. But due to high water temperatures at this time, which leads to high lice reproduction rate, sea lice again grow at a faster rate. It should be noted that even at high levels of lice per fish, lice reproduction rates are high because even during treatment periods, the gravid female lice will have already laid enough eggs before the treatment to contaminate water around the cage.

As stated in hypothesis section, the purpose of this simulation 1 is to compare model behavior with data. The results in figure 6 and 7 show a reasonable fit of model behavior to data.

- **Simulation 2: alternative control strategies**

A) Option A:

Figures 8 and 9 show the same type of simulation as in figures 6 and 7 but here treatment events are launched at different times than the previous simulation. That is, the user decides when to launch a treatment. The purpose of this option is to test how early control of sea lice influences sea lice population dynamics. Thus, we use the same treatments as in simulation 1 but at different times[7].

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[6] Cages are located in the open sea.

[7] Treatment events are implemented at days 78 (in-feed treatment), 126 (in-feed treatment), 350 (chemical treatment), 370 (in-feed treatment) and 444 (chemical treatment).

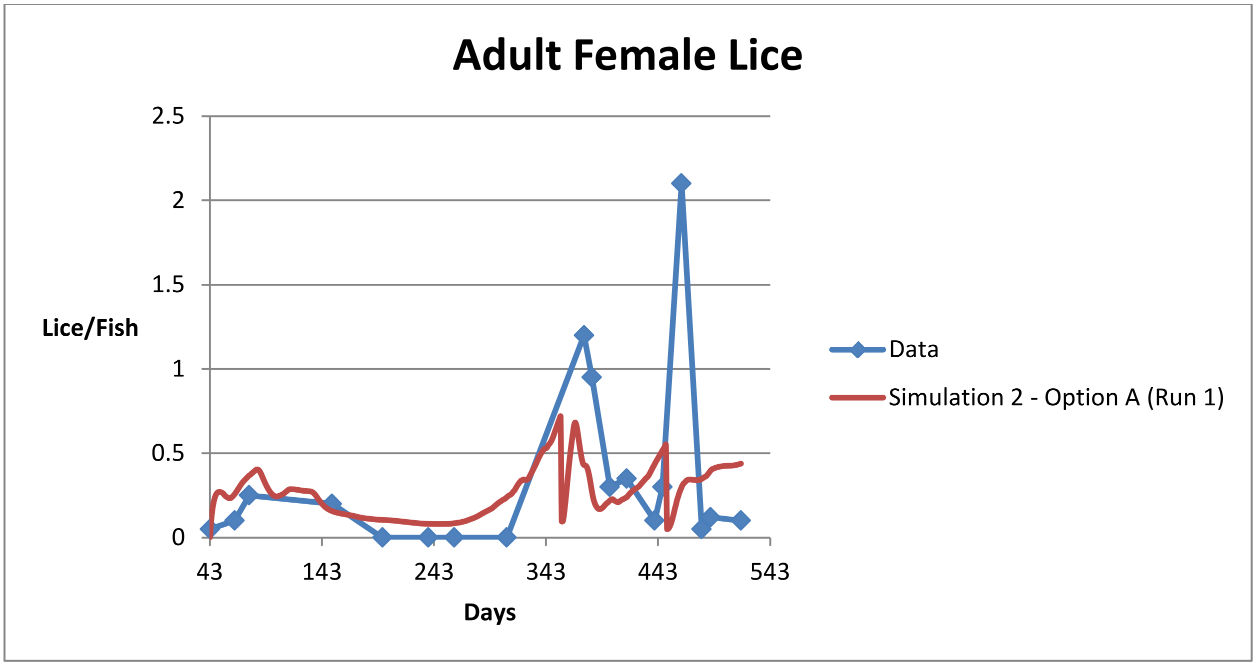

Figure 8: adult female lice population dynamics (option A – run 1 control strategy) comparing to data

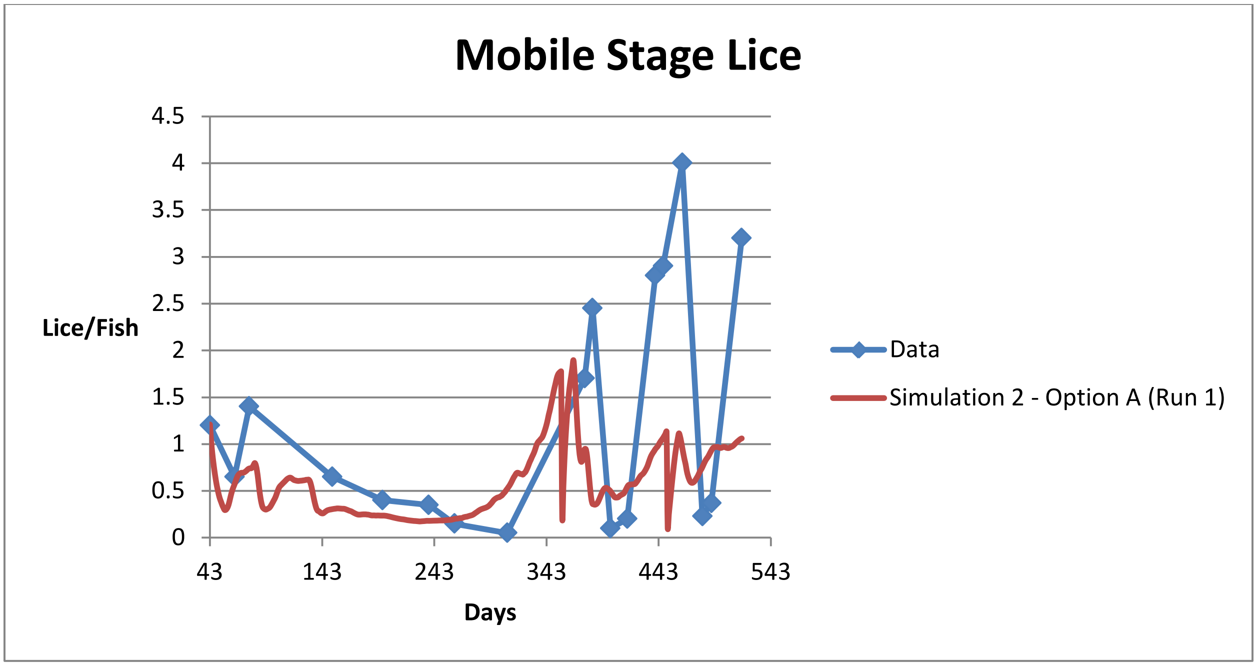

Figure 9: mobile stage lice population dynamics (option A – run 1 control strategy) comparing to data

Simulation results in figures 8 and 9 shows that the model generates similar behavior patterns as in simulation 1 but with lower infection magnitude. The reasons that option A simulation have lower infection magnitudes are: (a) the model launches a treatment event when sea lice level starts to grow (before reaching thresholds), (b) next treatment events are launched earlier than simulation 1, and (c) the consequences of early control treatment events in points (a) and (b) leads to breaking down lice population cycle and decreases the amplitude of infection.

Simulation results[8] in figures 10 and 11 show further decline of sea lice population through launching earlier treatment events. The simulation results in figures 10 and 11 show a further decline of sea lice population, comparing to figures 8 and 9, when one treatment is implemented earlier (day 320 instead of 350). However, unreported simulation results showed that dates of treatment events should be selected carefully to ensure breaking down sea lice population cycle. In other words, too early and/or too late treatment events might not be very effective. For example, implementing treatments early than day 320 (simulation outputs in figure 10 and 11) will be less efficient and late treatments are always less efficient because it will allow lice population to grow out of control and make it hard to break lice population cycle.

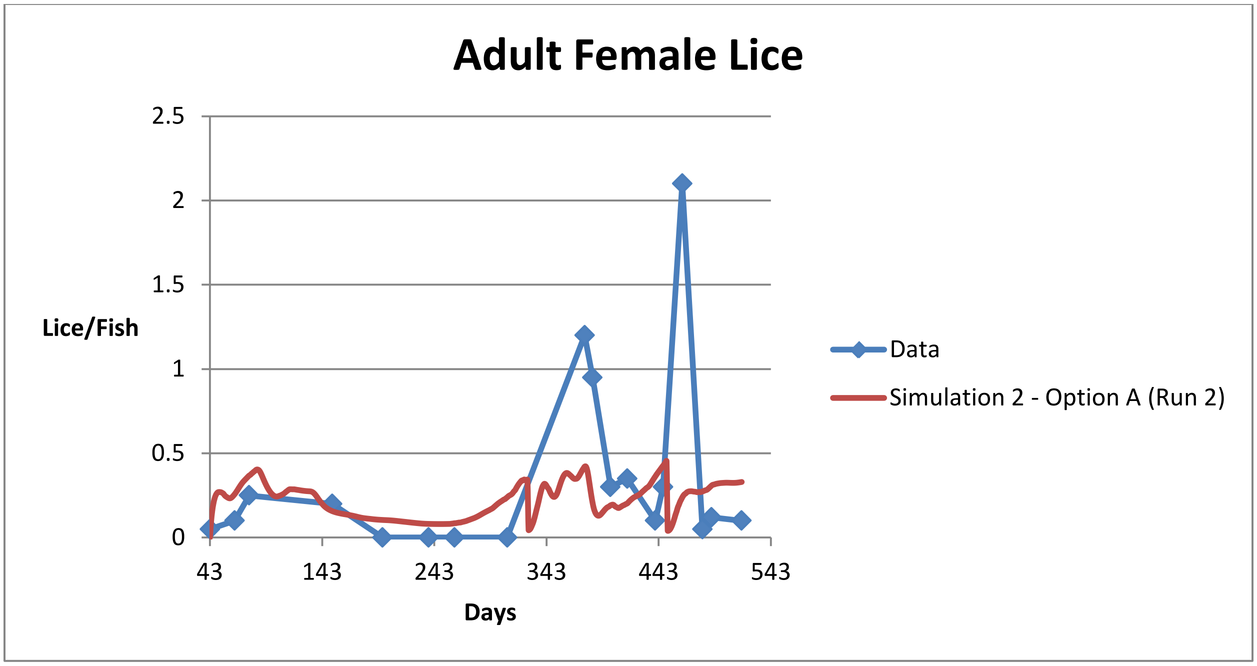

Figure 10: adult female lice population dynamics (Option A – run 2 control strategy) comparing to data

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[8] Treatment events are implemented at days 78 (in-feed treatment), 126 (in-feed treatment), 320 (chemical treatment), 370 (in-feed treatment) and 444 (chemical treatment).

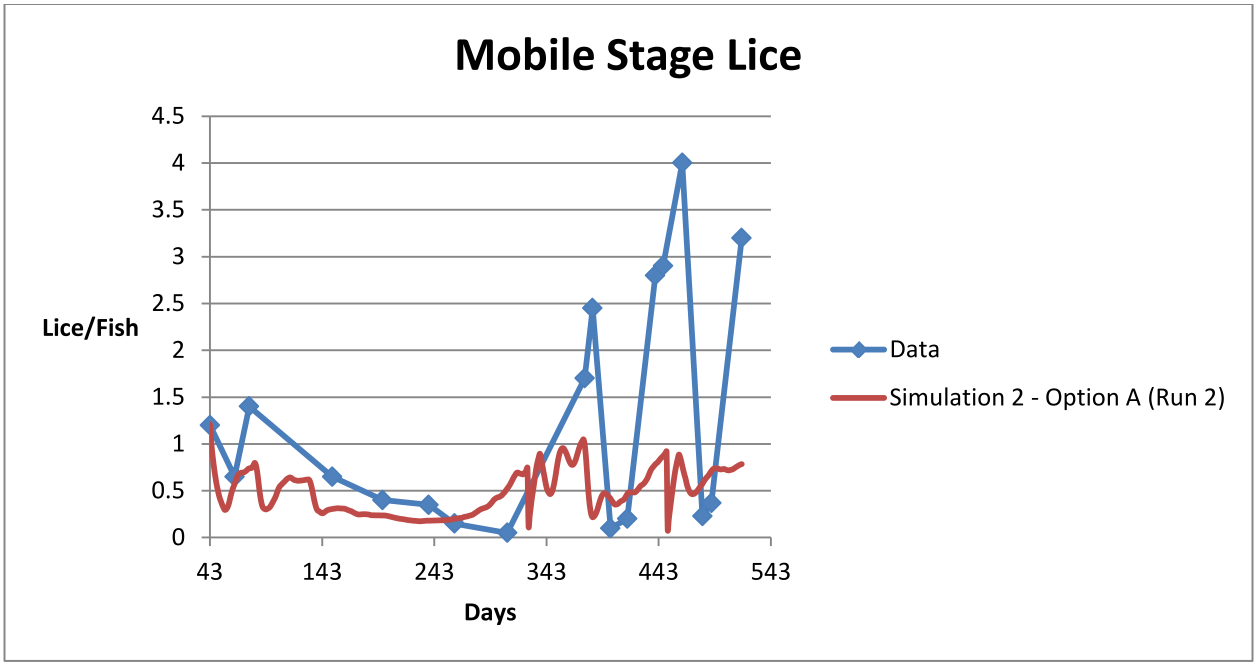

Figure 11: mobile stage lice population dynamics (Option A – run 2 control strategy) comparing to data

B) Option B:

In option A section, we tested influence of different timing of treatment events on sea lice population. In this section (Option B), we test influence of different timing along with different types of treatment events on sea lice population. As shown in option A section, timing of treatment events significantly increased the effectiveness to control sea lice population. Here we test along with timing whether changing treatment types will further improve sea lice control effectiveness.

Figures 12 and 13 show the same type of simulation as in simulation 1 and simulation 2 (option A) but here treatment events are launched[9] at different times and different types (i.e. in-feed and chemical treatments) than the previous simulations.

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[9] Treatment events are implemented at days 78 (in-feed treatment), 126 (in-feed treatment), 320 (in-feed treatment), 370 (in-feed treatment) and 444 (chemical treatment).

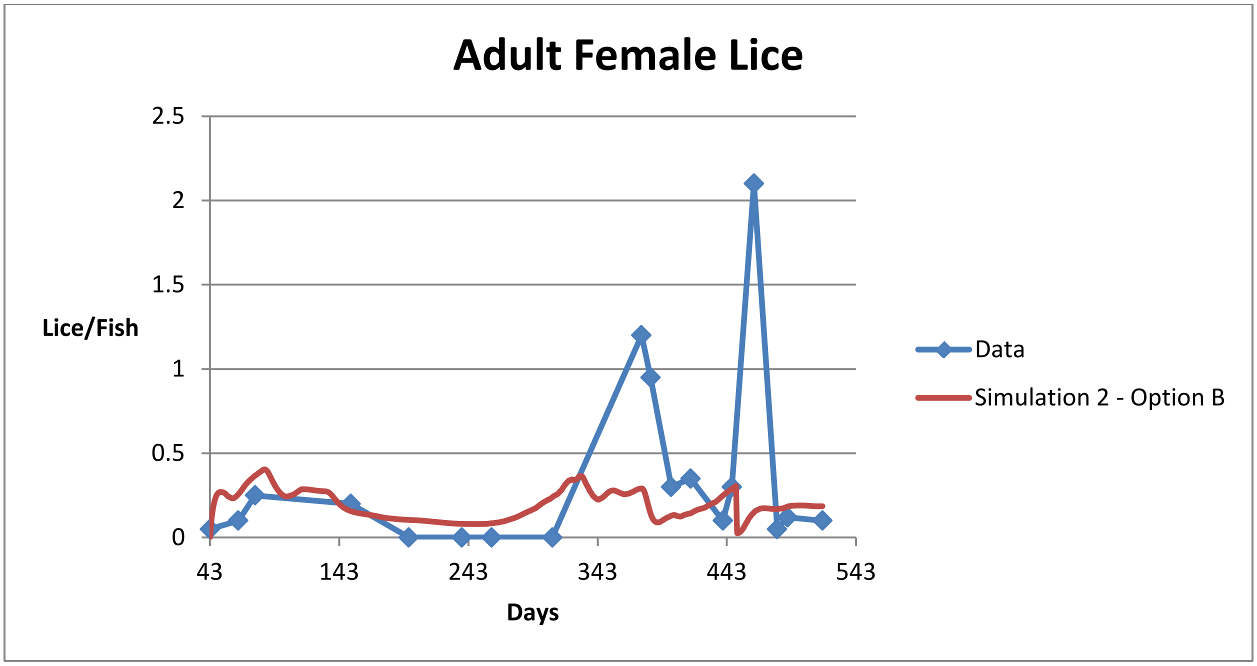

Figure 12: adult female lice population dynamics (Option B control strategy) comparing to data

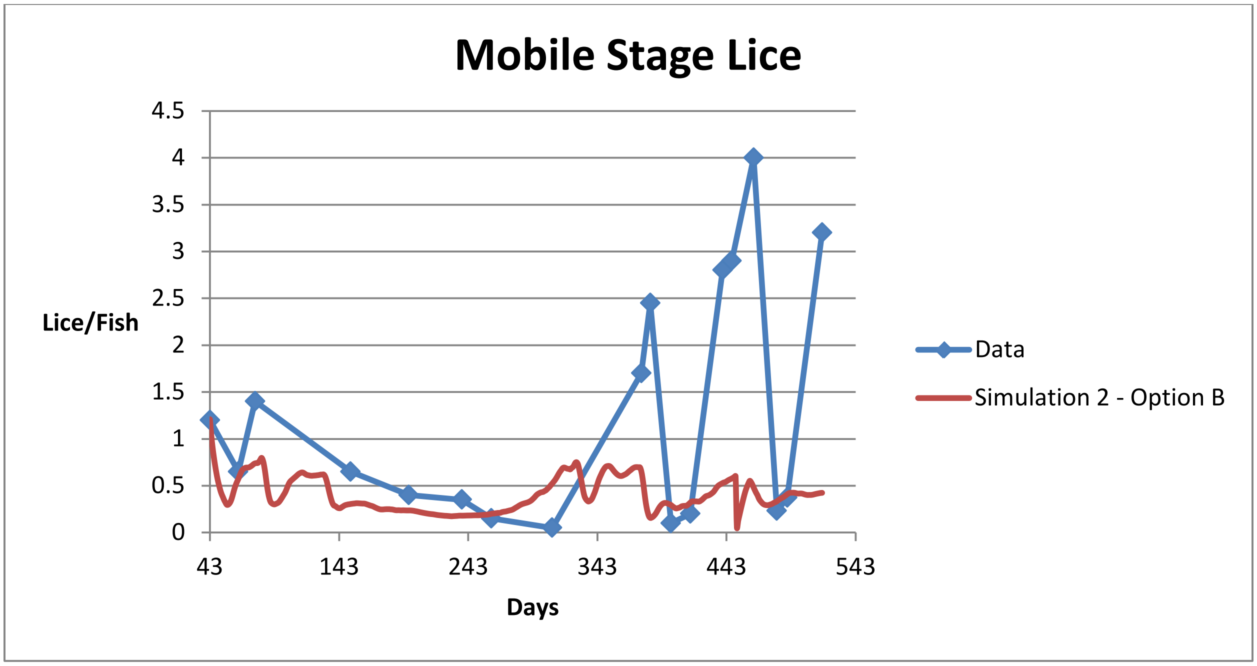

Figure 13: mobile stage lice population dynamics (Option B control strategy) comparing to data

In all simulations that are shown, we used treatment events that were used in past production cycle. But we tested changing in treatment times and switching treatment types. The timing and type of treatments seem to have significant influence on controlling sea lice population.

Changing treatment type (using in-feed treatment at day 320 instead of chemical treatment) slightly improved the effectiveness to control sea lice population. Insights from these simulation results show that early control of sea lice epidemics can assist in lowering the magnitude of high lice levels per fish. These results suggest the need of developing treatment strategies for controlling the lice population to avoid the first peak because when the lice population reaches first peak they contaminate (i.e. laying eggs) surrounding water and therefore shortly after each treatment the lice population grow again. Thus, avoiding first peak of sea lice population greatly facilitate keeping lice under desired limits per fish. We can learn from these results that treatments should target potential strategies to avoid first peak of the lice population which may lead to control lice level at desired condition and prevent the lice population peaks.

Early control of sea lice population in fish cage shows a potential strategy to avoid high level of sea lice per fish. This is an important insight that salmon industries are interested in. Therefore, to keep lice level under control, it is highly recommended to launch early treatments before reaching thresholds. The reason for that is by the time sea lice level per fish reaches thresholds, lice population are big enough to lay large number of eggs and contaminate surrounding water. Which in turn restricts the efficiency of treatment events and make it hard to keep lice under control (refer to simulation 1 section: figure 6 and 7). On the other hand, early control breaks down lice population and keeps surrounding water uncontaminated (refer to simulation 2: options A and B), which in turn keeps lice level under control. In the next section, we will evaluate the influence of tested simulations on fish growth.

• Aging and Growth Sector

Figure 14 shows the simulation results of the fish growth sector of the model for the control strategies tested in epidemiology and policy option section. Each trend on the graph in figure 14 represents the growth of fish through simulation 1, simulation 2 (option A: runs 1 and 2), and simulation 2 (option B). Simulation 1 differs from simulation 2 – Option A (run 1 and 2) by launching treatments at different times. But since the number and the type of treatments are exactly the same and they only differ in timing, the final weight of fish is slightly different (5.43 kg for simulation 1, 5.42 kg for simulation 2 – option A (run 1), and 5.43 kg for simulation 2 – option A (run 2). Simulation 2 – option B differs from simulation 1 and simulation 2 – option A (runs 1 and 2) by changing the type of one of the treatment events. That is, in day 320, instead of conducting chemical treatment we used in-feed treatment. Chemical treatments influence fish growth because the requirement to starve fish five days prior to treatment implementation. Therefore, simulation 2 – option B shows better growth of fish (5.59 kg) because of switching one chemical treatment to in-feed treatment decreased the starvation period, which in return improves fish growth.

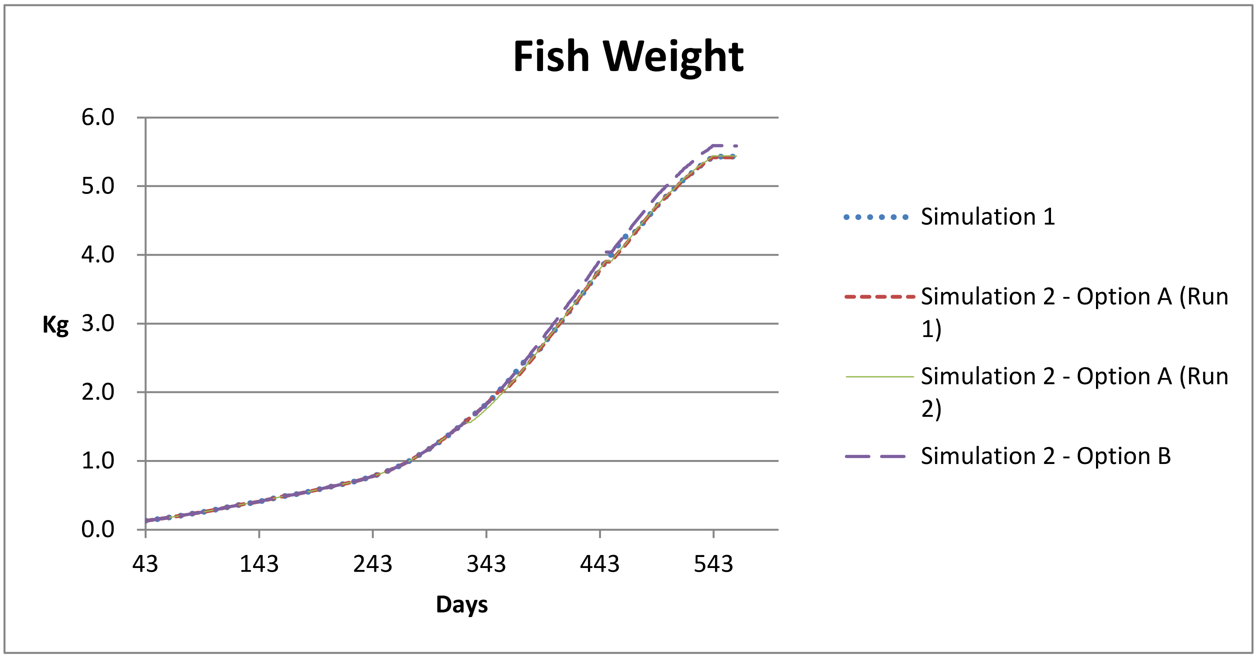

Figure 14: the influence of tested simulation on fish growth (the order of simulation are shown respectively)

It should be noted that the treatment implementation time has influence on fish weight. Early implementation has less influence on fish weight than later implementation because fish growth in early stages is already slow, while in later stages the growth rate accelerates. Thus, starving fish in later stages of the growth leads to more loss in fish weight than early starvation. Therefore, late treatment events should be avoided if possible.

Simulation results of growth sector (figure 14) of the model are described in following development phases:

1- Early stage growth (from day 1 to 260): this stage is characterized by slow growth due to the fact that fish size is very small (initial weight of smolt is 0.13 kg) in addition to water temperature declines gradually from stocking time to day 260 and therefore the feeding amount per day is low, which leads to slow growth;

2- Middle stage growth (from day 261 to 440): this stage is characterized by an exponential growth of fish weight, as fish size increases in addition to gradual rise of water temperature until day 440 which leads to an increasing daily feeding amount per fish and thus greater growth;

3- Final stage growth (from day 441 to 561): this stage is characterized by a slower growth than the middle stage growth, as reduced feed conversion ratios for larger fish lead to a slower growth in fish weight in addition to a gradual fall of water temperature from day 440 leads to decreasing daily feeding amount per day;

4- It should be noted that there are some times that fish do not grow in size because of the implementation of treatments that require starving fish five days prior to implementation.

The influences of different timing and type of treatment events on both sea lice and fish growth are shown in both aging and growth, and simulation result and analysis sectors. In the next sector, we convert these results to monetary terms to identify the costs of each simulation to provide decision makers with costs and benefits of each simulation.

- **Economic Model**

Figure 15 shows the costs (NOK) of for the control strategies tested in epidemiology and policy option section. Each time when the model launches a treatment, the costs of that treatment is added to the stock of cumulative costs of treatments (figure 15). The cumulative costs of treatments slightly increase between one treatment and another because of accumulating net present value of the costs.

All simulation launched the first two treatment events at the same time and use the same type of treatments. Thus, the costs are similar for all simulations at this time. But for the next treatment events, each simulation uses different timing and/or different types of treatments. Therefore, the costs start to vary for each simulation. Chemical treatments costs the same amount of money regardless of implementation time, while the costs of in-feed treatment depends on the timing of implementation (as fish grow in size, the costs go up). Therefore, the high step increases of the cost of all simulations from day 300 to 400 occur (for simulation 2 – Option B occurred twice). The slight decline of costs is due the feed money saved because of five days of starvation prior to implementation of chemical treatments. It should be noted that the last step increase in the costs are the costs of the cumulative loss of fish weight caused by treatment implementation, while the earlier increases are the direct costs of treatments (i.e. material and labor costs). Though simulation 2 – Option B shows higher costs than the other simulation before of the end of simulation, but it has the lower overall costs comparing to other simulations. The reason for that is simulation 2 – Option B has better growth of fish (that is, lower loss of fish weight due to treatments).

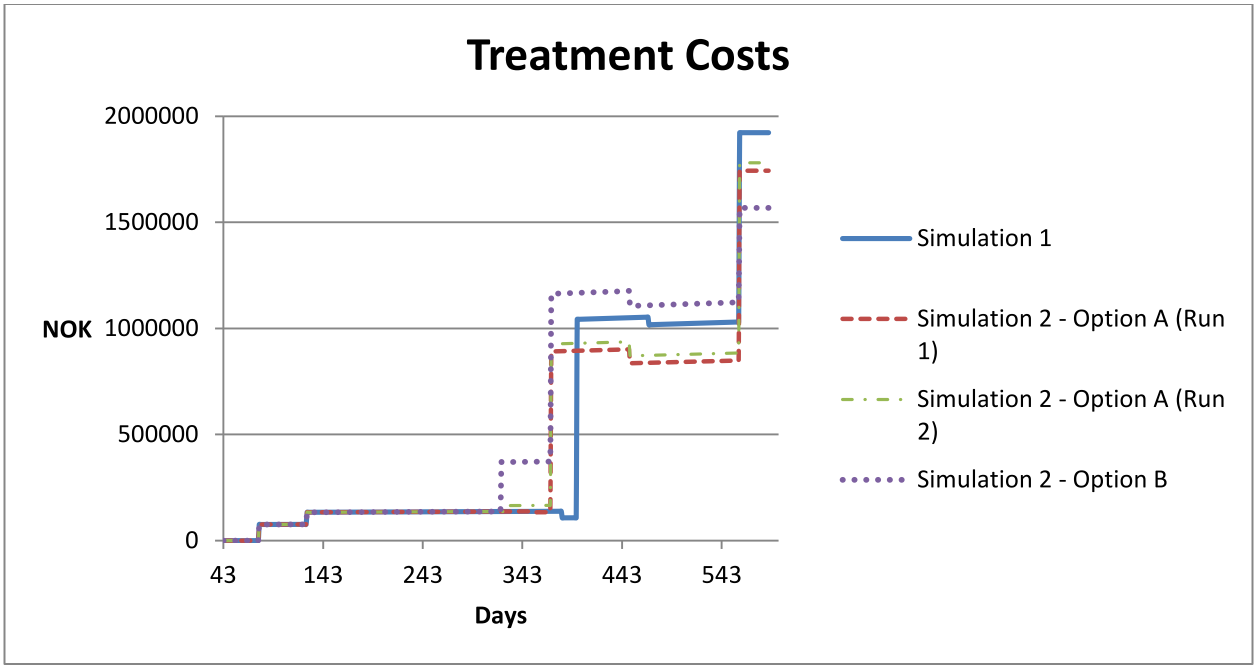

Figure 15: costs of each simulation

Our hypothesis is that early control of lice population reduces health related costs in the cage because early control may reduce the number of implemented treatments. Though sea lice are significantly reduced by implementing early treatment events, but the number of treatment events is the same in all simulations. They only differ in timing and/or type of treatments. However, the simulation results showed that early treatment events assist to decrease health related costs and to better controlling the lice population (refer to results in figure 15). But some of them harm fish growth.

The results showed that simulation 2 (option B) keeps sea lice level lower than other simulation results, fish grows better than other simulation, and the costs of controlling lice population is lower than the other simulations. On the same manner, simulation 2 (Option A: 1st run) is more cost effective than simulation 1 and simulation 2 (option A: 2nd run) and simulation 2 (option A: 2nd run) is more cost effective than simulation 1.

Conclusion

The integrated model presented in this paper has potential in developing an integrated tool that incorporates biology, epidemiology, and economics of aquatic diseases. Unlike existing models, a strength of this framework is in its ability to capture feedback mechanisms among related model sectors. It further has the potential in converting treatments and sea lice epidemics into real monetary values to guide better decision making. The results of the model showed that early control treatment events: (1) improve the efficiency of controlling lice population, (2) enhance fish growth, and (3) reduce lice control costs. The results showed that launching treatment events before reaching thresholds greatly facilitate to prevent high peaks of lice population and hence breaking lice population cycles.

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Appendices

In this section, we provide technical and analytical details about different parts of the model. Appendix 1 shows the report that is intended to be published in a scientific journal. Appendices 2 and 3 show the whole structure of the model and modules that are used in the model. Appendix 4 lists model equations. It should be noted that some of the equation are not reported because they were confidential information and we were not allowed to report. Appendix 5 reports validation tests and analysis. Finally, appendix 6 describes the model interface.

Appendix 1: The role of system dynamics approaches in aquatic disease management: an application to sea lice control in Norway

The report in this appendix is prepared for the purpose of publishing in a scientific journal. This report has been reviewed by experts and is subject for further improvement, if necessary, to improve the chances of getting it published.

The role of system dynamics approaches in aquatic disease management: an application to sea lice control in Norway

Kanar Hamza, Karl Rich, and David Wheat

Abstract

Different methodologies have been used to model the epidemiology and economics of aquaculture diseases, including input-output models, benefit-cost analysis, linear programming, simple spreadsheet-based models, compartment models based on differential equations, and spatial models. Despite the advantages that each of these different models provide, there is a need to develop a more integrated approach to the epidemiology and economics of disease that better represents and captures existing feedback mechanisms, interventions to control aquatic disease, and the economic consequences of these interventions on producer behavior. System Dynamics (SD) modeling approaches have utility in this context. While SD has been used to model terrestrial animal diseases, its application in fisheries has been limited to questions of stock management. In this paper, we apply system dynamics modeling in the context of sea lice control in Norwegian farmed salmon. Separate models of sea lice and salmon growth evolution were designed and integrated to capture the feedback between them. Different simulation scenarios highlight the benefits of the approach.

Introduction

Disease control is a key concern for the economic viability of aquaculture, particularly as bourgeoning environmental issues and food safety requirements increase production costs and complicate disease management. A critical need is the development of decision support platforms that can enhance the management of aquaculture systems and improve their sustainability. While decision support models that assess the impact of animal diseases are commonplace for terrestrial farming, they are much less utilized in aquaculture, and typically rely on simple benefit-cost frameworks. Conversely, while a variety of different economic impact assessment platforms have been applied in a number of fisheries applications, an important research gap in the aquatic health literature is the lack of direct integration between the ecology of diseases, the dynamics of disease spread, and their economic impacts among different stakeholders. These issues are important given the potential feedbacks between disease control interventions and their influence on economic incentives for producers and policymakers alike, which can potentially affect the evolution of disease and the success of subsequent control efforts (Rich 2007). Moreover, government and industry may have different objectives (social welfare vs. profit maximization) that influence their perspectives in the face of making health-related decisions. As a consequence, public policy will need to balance private and public interests, though the analytical means to assess these tradeoffs are difficult in practice.

System dynamics (SD) tools provide a platform to integrate the population and transmission dynamics of aquaculture diseases, assess the various economic consequences of disease outbreaks, quantify the costs of controlling diseases, and evaluate the cost effectiveness of different control strategies. Conrad (2004) and Rich (2008) applied SD methods in the context of modeling foot-and-mouth disease outbreaks in the United States and South America, respectively, though neither study completed the feedback loop between disease evolution and farm-level behavior. Rich (2007) developed an SD framework that embodies and integrates both the evolution of disease and the production behavior of producers over time, directly highlighting the feedbacks that exist between the evolution of disease and actions taken to control it. This paper builds and expands on this modeling framework for aquaculture systems, where disease dynamics are further complicated by complex host-parasite interactions in addition to dynamic production cycles for fish. Our goal in this analysis is two-fold. First, we motivate a generic framework that can be used more broadly in analyzing the impacts of alternative aquatic disease control strategies. We then provide some illustrative results of applying this model in the context of sea lice (*lepeophtheirus Salmonis*) control strategies in the farmed salmon industry in Norway as proof-of-concept. Our modeling framework thus integrates a variety of different modeling frameworks from different disciplines (biology, epidemiology, and economics) under a unified SD platform to improve decision making. Specific questions addressed by this paper include the following:

- How we integrate an effective fish aging-epidemiology- economic model for the purpose of developing decision tool to control salmon disease? What are the modeling challenges in achieving this?
- Does the proposed integrated model add value to existing models already in use in the field of aquatic health economics?
- What is the impact of different disease control scenarios on decision-making and how can this information be used to improve decision-making?

Before we explain the SD approach applied to aquaculture diseases, a brief literature review first highlights the uses of different non-SD methodologies to aquatic health field and the more general use of SD in other fishery issues. We then describe the case of sea lice and its control in Norway. We provide an overview of the SD approach, including a model structure couched in general terms through causal loop diagrams[1]. And we apply this model in the context of sea lice control and present simulation results of different control scenarios. The first scenario simulates treatment events to control sea lice levels per fish through using historic treatments (i.e. the same type and timing of treatment used in past production cycle) and the second scenario simulates treatment events by using different timing and/or types of treatments. We run historic treatments to test our model results with data that is provided by the industry (figure 1 and 2) because these data already include treatment events that are implemented by the industry. Thus, we introduced the treatment events that were implemented in the cage to the model. We run the second scenario to check how different treatment timing and/or types influence the lice population. We make a few runs of the second scenario treatments to see how timing and type of treatments influence the population of sea lice. We also briefly discuss frameworks for analyzing the cost-effectiveness of different strategies.

Literature Review

In this section, we first review some of the modeling approaches that analyze aquaculture diseases. We focus primarily on (i) non-SD modeling approches to aquatic diseases, and (ii) the SD literature on more general fisheries applications. Our aim is to identify those gaps in which SD techniques can add value.

On the epidemiological side, Revie et al. (2005) presented a mathematical model of the growth of sea lice in Scottish farmed Atlantic salmon. The model showed the dynamics of sea lice development over time and assessed the influence of treatment events on sea lice population

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[1] CLD is used to facilitate explaining model structure, Stock and flow diagram of the model is shown in appendix 1

dynamics. At the same time, the model was primarily an epidemiological model and did not evaluate the cost effectiveness of treatment events and their consequences on sea lice population dynamics and on fish stocks. In a similar vein, Stienl et al. (2005) used linear delayed - differential equations applied to the evolution of the number of lice at their developmental stage and their gender. It further incorporated the influence of temperature and salinity on each life stage of sea lice, on mortality at each stage, and female fecundity. Similar to Revie et al. (2005), however, their model did not evaluate how treatments influence producer behavior over time in addition to the economic consequences of these treatments.

A more simplistic epidemiological approach was developed by Heuch and Mo (2001), who used a simple, Excel-based approach to model salmon louse egg production in Norway under two different policy scenarios. While the simplicity of the approach made the model more tractable, some of the assumptions made (e.g., linearizing a few nonlinear parameters) restricted the model's realism and precluded the modeling of feedback effects. For example, the model assumed that the number of eggs per lice was constant while in reality it is temperature dependent. Furthermore, their model assumed that the number of lice per fish was considered constant (i.e. they assumed a constant number of lice per fish from beginning of model to the end) while in reality it is a variable. The model also did not show the dynamics of the louse life cycle.

In terms of economic approaches to aquatic diseases, only a few models have been advanced. Dominic & Fofana (2007) conducted a benefit-cost analysis of three salmonid diseases: infectious salmon anaemia (ISA), viral haemorrhagic septicaemia (VHS) and infectious haemorrhagic necrosis (IHN) using a relatively simple spreadsheet model based on production costs, disease control costs, and marketing losses associated with these diseases to assess the net benefits associated with disease surveillance. Thorarinsson & Powell (2006) developed a similar approach to evaluate different vaccine programs to control diseases. Both models focused primarily on accounting-type costs and did not assess the behavioral impacts associated with disease incursions. Moreover, neither model explicitly integrated epidemiological modeling techniques in conjunction with the benefit-cost analysis.

The use of SD in fishery and aquaculture applications has been limited to non-disease related issues such as stock management. For instance, Dudley (2008) applied SD to examine various fishery management policies. The model highlighted the complexity of the system in a more understandable framework, focusing in particular on the interaction between different factors (i.e. social, economic, political and environmental) that influence fisheries. Garrity (2011) recently used an SD model to identify and test different management strategies to manage fish stocks. Bala & Satter (1989) developed a model to manage the aquaculture system in the Chittagong and Khulna districts in Bangladesh that combined a system dynamics model coupled with a linear programming model. Their model was used to find the most appropriate harvesting time that maximizes the return from the analyzed aquaculture system. Other examples of using SD in aquaculture and fishery systems include Arquitt, Honggang, Johnstone (2003), Chateau and Chang (2010), Arquitt and Cornwell (2007), Arquitt, Honggang, and Ron Johnstone (2005), Bala and Satter (1989), and Garrity (2011).

So far, most of the literature in the field of aquaculture health economics has not directly integrated the epidemiology and the economic impacts of disease; rather, these analyses have been done separately. In doing so, these models ignore important feedback loops in the system. As noted earlier, SD is well suited to model the feedback loops that exist between epidemiological and economic models (Rich, 2007), which will be motivated in the context of sea lice control in the next sections.

Background – sea lice in Norway

The farming of Atlantic salmon started in Norway in 1970s. Since then, the farmed Atlantic salmon sector has developed into a global industry with a production of 1.5 million tons per year (Jory, 2011), a growth of 55-fold in the last two decades (Krkosek, Lewis and Volpe, 2005) in whole fish equivalent at the beginning of 2011. Norway is a leading global producer of farmed Atlantic salmon, producing nearly 50% of global production.

Fish diseases are major factors that limit the growth of the salmon industry (Aunsmo, 2008). Sea lice in particular are considered to be a major threat to the farmed salmon industry in Norway. Despite regularly implemented chemical treatments, fish farmers still lose considerable amounts of fish due to lice (Heuch & Mo, 2001). The losses mostly occur as a result of delousing actions. As salmon farms provide an excellent environment to host sea lice, the areas where the farmed salmon cages are located have a much higher magnitude of sea lice infection pressure on wild salmonids (Liu, 2008; Krkosek et al. 2005). Fish are susceptible to sea lice infestation during all stages of the susceptible production cycle (2-3 years). The appearance of sea lice related problems is unpredictable; it may happen from the early stage of the sea phase life cycle of fish to slaughtering time. Figure 1 and 2 illustrates the evolution of sea lice over time in one of the cages of a Norwegian salmon producer since 2008.

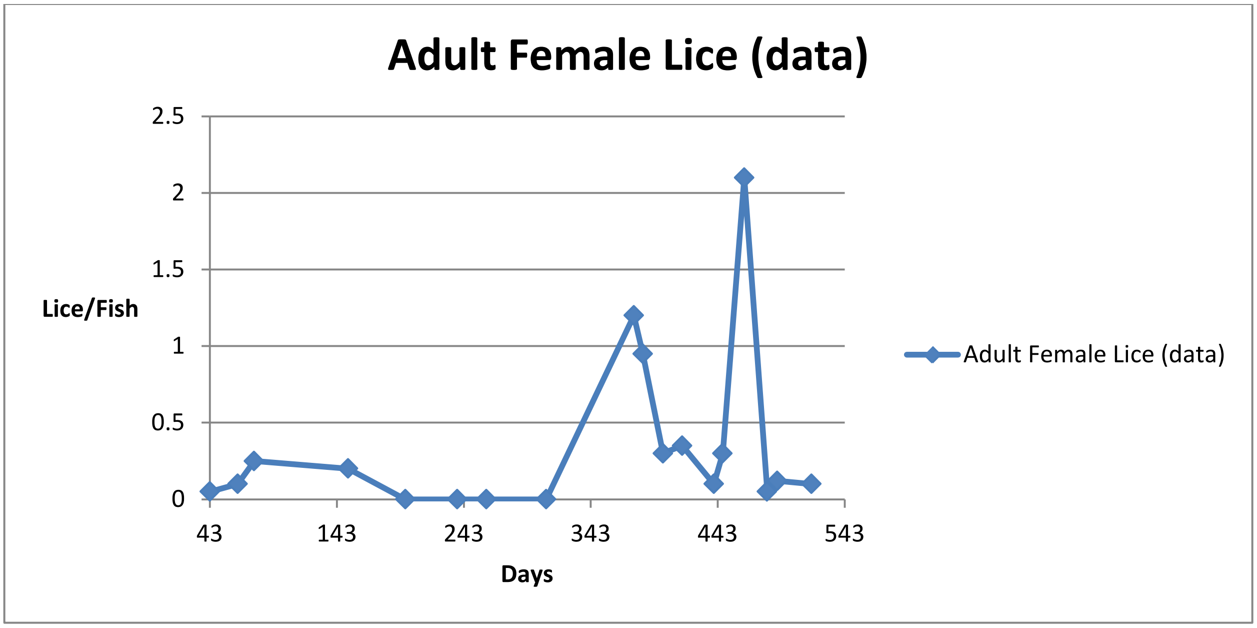

Figure 1: evolution of Adult Female L. Salmonis in modeled cage from September 2008 to April 2010 (Source: SalMar)

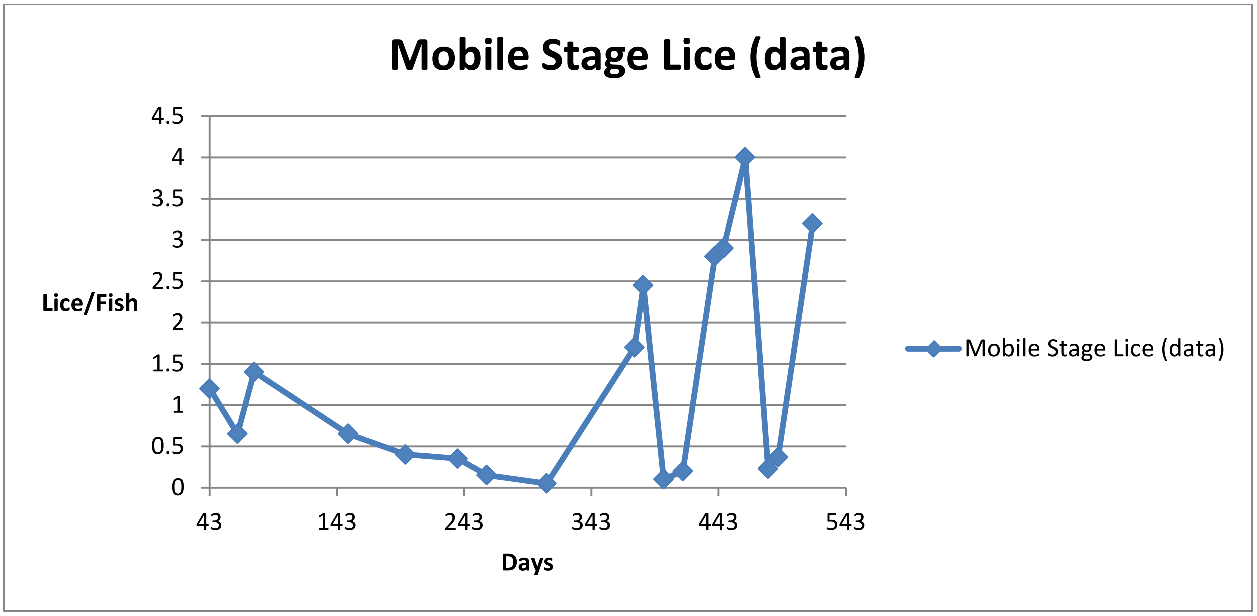

Figure 2: evolution of mobile stage L. Salmonis in modeled cage from September 2008 to April 2010 (Source: SalMar)

The shown trends in figures 1 and 2 represent the number of adult female and mobile stage lice, respectively, attached to a fish. The time horizon on the x-axis starts from September 2008 to April 2010. Mobile stage lice consists of all male lice and preadult female lice and adult female lice consists of all adult female lice (gravid and non-gravid).

Sea lice have been detected in farmed Atlantic salmon in Norway since the mid-1970s. The impact of salmon lice on wild salmon and sea trout was first reported in Norway in 1992 (Heuch and Mo, 2001). The increasing number of sea lice in farmed salmon cages leads to both direct and indirect costs, (Aunsmo, 2008) to fish farmers and the farmed salmon industry in Norway, in addition to the impact of sea lice on wild salmonids. These costs include increased mortality, reduced fish quality at slaughter stage, increased production cost per kilogram, and reduced growth performance and food conversion (Thorarinsson and Powell, 2006). These costs reduce the profitability of fish farming. Models that assess the cost effectiveness of disease control strategies are therefore clearly of interest to the farmed Atlantic salmon industries.

The first regulation in Norway to control sea lice, the National Action Plan against Lice on Salmonids, was enacted in 1996. The main objectives of this regulation were: (1) to reduce the harmful effect of lice on farmed and wild salmon to a minimum in the long term, and (2) to monitor the number of lice per fish in the short term. Lice monitoring thresholds were implemented in 1998. The monitoring goal aimed to meet the threshold of having no more than a mean of 2 adult female lice per fish in spring, increasing to a mean of 5 adult female lice per fish that are allowed in summer and autumn. This regulation was updated in 2000, and established a minimum of 0.5 adult female lice per fish or 4 mobile lice in total (preadult males and females and /or adult males) for the period from December to June (Heuch & Mo, 2001). The latest update in 2009 of regulations includes a limit of 0.5 adult female or 3 motile lice on average per fish from January 1 to August 31 of each year, and 1 adult female or 5 motile on average from September 1 to December 31 of each year (Lovdata, 2009).

The reproduction of sea lice depends significantly on the number of fish in the cages and maximum number of allowed lice per fish. As these two factors increase, the total number of lice increases (Heuch & Mo, 2001). Revie et al. (2005) found that the sea temperature has a significant impact on the growth of sea lice and its population dynamics. Research by Kakosek et al. (2005) further revealed that the oscillatory behavior of population dynamics of sea lice in farms is, in addition to water temperature, due to the lice growth dynamics that arise between treatment events at different stages of the farmed salmon production cycle (2-3 years).

Sea lice treatment options include in-feed treatment, chemical treatment, and biological treatment. In this article, we only consider in-feed and chemical treatments. In-feed treatment is a treatment that is given to a fish with their daily consumption of feed. Chemical treatment is implemented through placing medicines in the pen for several hours, during which time the pen is isolated from surrounding water. Chemical treatment further requires starving fish for five days prior to implementation. Biological treatments are those that use sea wrasse (also called “cleaner fish”) in the fish cage. In this treatment, sea wrasse eats sea lice off the salmon and can be used in subsequent production cycles as well.

General structure of an SD model of aquatic disease

We pointed out earlier a need for an integrated model for aquatic health economics to bridge the gap work in the aquatic field that is done separately by epidemiologists or economists. This model provides a unique integrated platform that incorporates as sub-models the biological, epidemiological and economic aspect of aquatic diseases. The overall model (a) captures the dynamic interactions between sub-models over time, and (b) provides a tool that converts the consequences of epidemics to monetary values in real time. These two characteristics of the model assist in making better decisions for controlling aquatic epidemics.

Our model is divided into four major components or sub models: (1) fish aging, (2) epidemiology, (3) policy, and (4) economics. Figure 3 illustrates how each of these model components interacts with the others. In this section, we examine the general structure by using causal loop diagrams (CLD) of the model that focus on the interconnectedeness of the model components, as well as provide specific details on the components themselves.

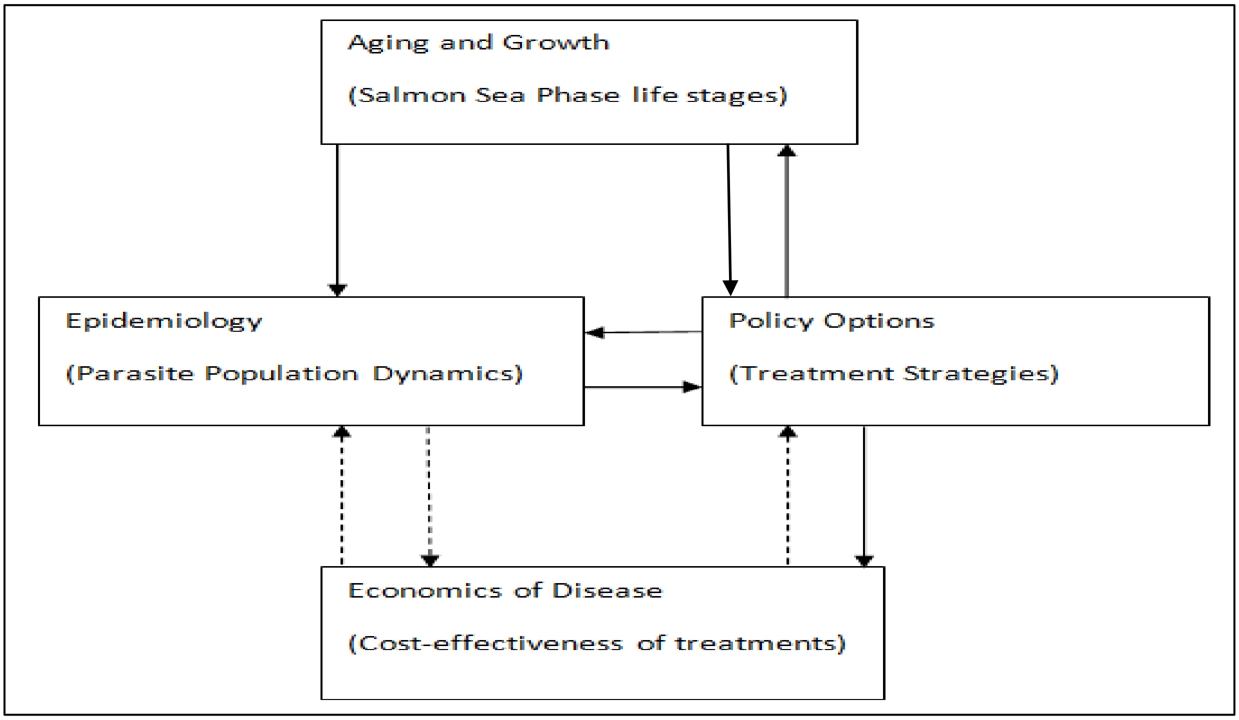

Figure 3: Model sector interactions

The fish aging and growth sub model represents cages in the open sea. The aging model is connected to the epidemiological model of sea lice growth, since the population of sea lice begins to grow when there are fish in the cage. It is worth noting that there is no feedback from the parasite population to the growth and development of fish in cages. That is because parasite control strategies in salmon industries prevent the growth of the parasite population to the levels that damage fish growth and development. The epidemiological model is linked to the policy model. Sea lice populations over the threshold level trigger control strategies that combat sea lice. Implemented treatments decrease parasite population, thus closing the feedback loop between the sectors.

The influences of the parasite population on fish growth and development is through treatment strategies (i.e. the policy options component of the model). Launching a treatment strategy to control parasite populations influences the growth and development of fish in two ways: (1) mechanical actions involved in treatments leads to the death of some fish, and (2) some treatment strategies require the starving of fish for five days prior to implementing a treatment which leads to decreased fish growth. Thus, the influence of the parasite population on fish growth and development happens indirectly through treatment actions and their consequences. The link from policy options to the aging and growth sub model represents the influence of control strategies (treatments) to the fish growth and development sub model and closes feedback loops among aging and growth, epidemiology, and policy sub models. Reduced fish growth and fish death due to treatments influence the amount of medicines used in in-feed treatments. This influence is represented by the link from aging and growth and policy options sub-models.

On the economic side of the model, the solid arrow represents a direct link from the policy sub model to economic sub model as a means of measuring the costs of implemented treatments. The other dashed arrows represent the insights that the user (decision maker) gets from looking at the cost-effectiveness of different treatment strategies that might influence his/her next decision which influences, and is influenced by, the parasite population and the previous set of decisions. Thus, the dashed arrows represent the insights that the user gets from running different decision and intervention scenarios, and which are considered open loops in the model to help the user to learn from different simulation results through model interface to identify the most cost effective course of actions to control lice in salmon farms. Appendix 6 presents details about the model interface.

- **Aging Sector**

The aging sector of the model represents the life stages of farmed Atlantic salmon. Salmon life cycle goes through different stages till adulthood. Theses stages include fresh water and sea water phase. The fresh water phase of salmon life cycle includes eggs, fry, and parr. Smolts and adults are sea phase life stages of salmon. Adults return to fresh water to spawn and lay eggs[2].

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[2] http://www.mesa.edu.au/aquaculture/aquaculture12.asp

However, in farmed salmon the return does not occur because adult salmon is harvested when reached adulthood. We only include the sea phase (i.e. smolt) life stages of farmed Atlantic salmon in the model because farmed fish is vulnerable to sea lice infection when it is in the open sea cages. Figure 4 shows the causal loop diagram (CLD) of the fish development and growth model.

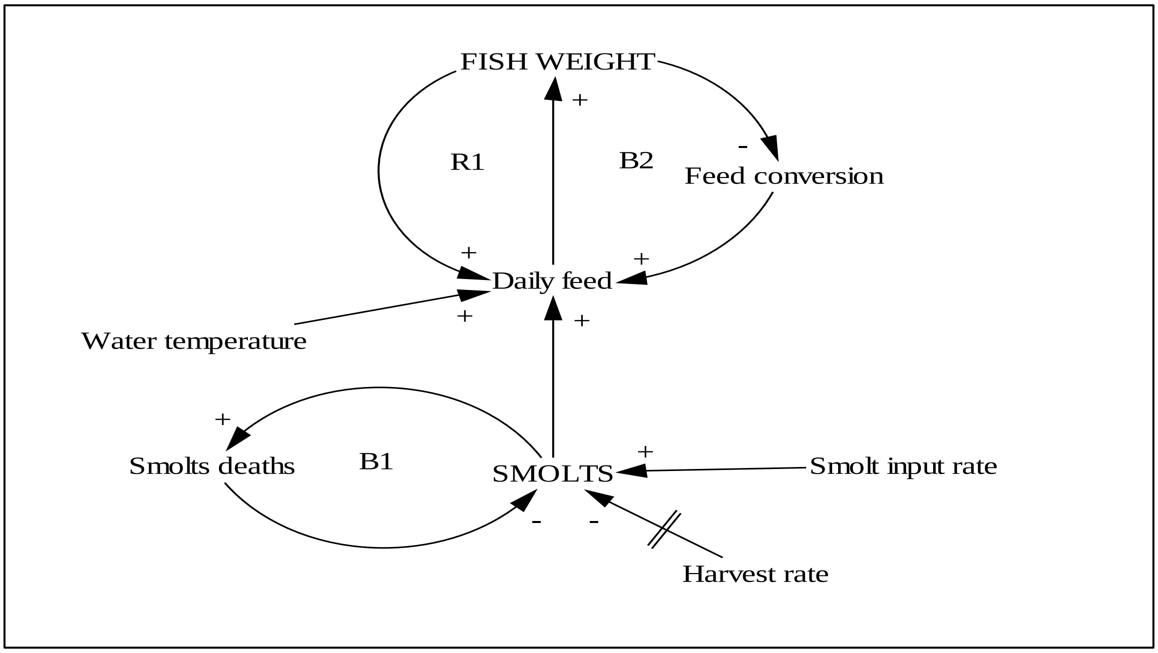

Figure 4: CLD of fish development and growth model

R is reinforcing feedback loop or positive feedback loop. “Positive loops are self-reinforcing.” The more feed given to fish, more fish growth, leading to still more feed given to fish, and so on. B is balancing feedback loop or negative feedback loop. “Negative loops are self-correcting.” The more fish growth, less feed conversion ratio, which leads to lower feed given to fish than what it would normally be, and less fish growth, and so on (Sterman, 2000).

The fish aging section of the model tracks the development of fish from one life stage to another (i.e. from smolts to mature). The growth section of the model represents the growth of fish weight from stocking time until slaughtering/harvesting time. The model starts through *smolt input rate*. That is, the process starts when smolts are introduced to the pen, after which the stock of fish remains at the smolt stage until it grows and reaches marketable size (i.e. *harvest rate*). Feedback loop B1 represents deaths occurring at the smolt stage.

As long as there are fish in the cage, the growth model is active. Two feedback loops govern fish growth, R1 and B1. R1 represents the effect of daily amount of feed that is given to existing fish stocks. The daily amount of feed is a function of fish weight and water temperature. The daily amount of feed increases when there is an increase in fish weight and/or water temperature.

B1 represents the influence of fish weight on the feed conversion ratio, which is the ratio of fish meal that is converted to fish weight. As fish grow in size (weight), the feed conversion ratio declines. That means fish grow faster at early stages and then at a slower rate as the feed conversion ratio falls.

- **Epidemiology**

The epidemiological section of the model includes sea lice (*lepeophtheirus Salmonis*) population dynamics. The causal loop diagram shown in figure 5 represents a simplified version of the model that replicates sea lice population dynamics.

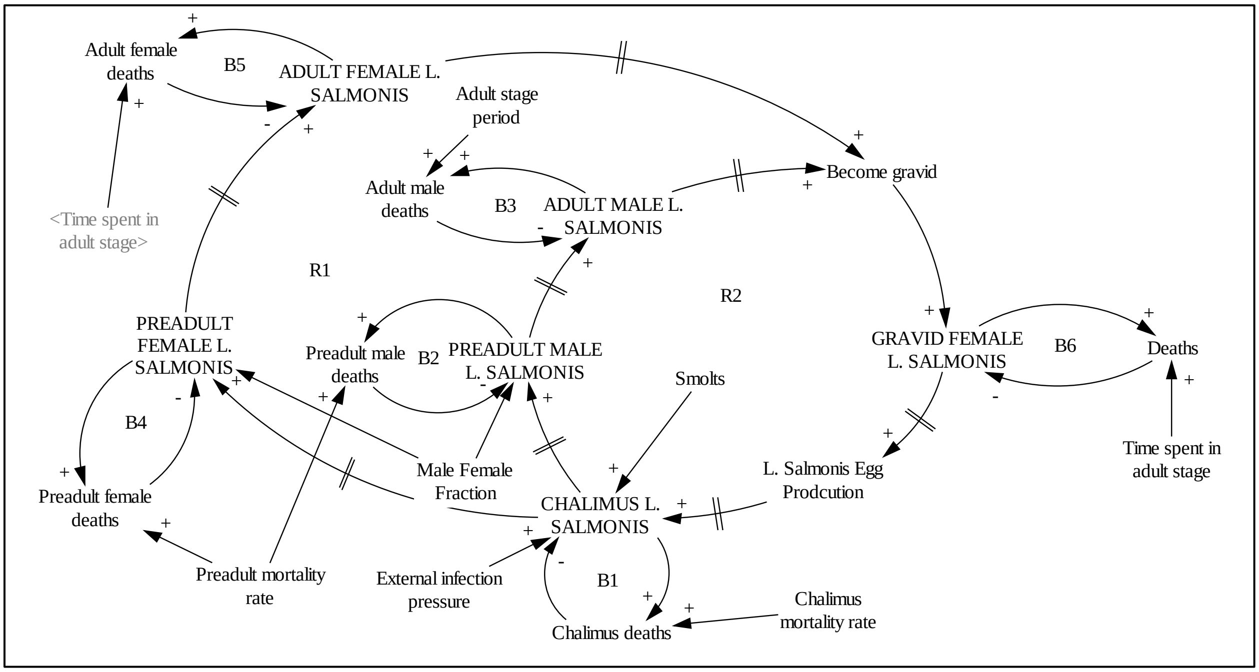

Figure 5: Sea lice population model

The CLD in figure 5 starts at *Chalimus L. Salmonis. Chalimus L. Salmonis* get attached to fish (i.e. smolts) via *External infection pressure* (i.e. free living chalimus around fish cage). From this point, R1 loop represent the development of chalimus L. Salmonis to preadult and adult male and R2 loop represent the same process for female lice. Then male lice fertilize female lice to produce eggs and the lice population cycle repeats in a reinforcing feedback loop.

The epidemiological model is active as long as there are fish in the cage (i.e. the stock “smolts”). When the cage is initially smoltified, fish are louse free. Sea lice are introduced to the cage through wild salmonids and nearby cages, *external infection pressure* represents free living chalimus. When chalimus is attached to the body of the fish, after some time the chalimus develop to either preadult male or preadult female stages. The parameter “*male female* *fraction*" identifies the fraction of chalimus that become male or female; an even distribution of males and females is assumed.

The development of sea lice from one life stage to the next is temperature dependent. As temperatures rise, the sea lice life cycle becomes shorter and vice versa. The life cycle of male lice is relatively shorter than that of female lice. The CLD in figure 5 is a simplified representation of a larger quantitative stock and flow model. Thus, for simplicity purposes, variables that represent time delays are not shown in the CLD, and are instead indicated by the delay marks (//) between sea lice life stages.

Sea lice population model, as shown in figure 5, start when a free living chalimus (see variable "*external infection pressure*") finds a host (i.e. a fish) to be attached to in order to survive. Sea lice life stages, after the chalimus stage, are separated into male and female lice. After some time, 50 % of *chalimus L. Salmonis* become pre-adult males and then adult males. Male lice will fertilize female lice, creating gravid females, which will lay eggs and start a new life cycle. This is represented by R1. The other 50% of *L. Salmonis chalimus* male go through a similar feedback loop represented by R2.

During each life stage of sea lice, only a fraction of lice survive. Feedback loops B1 to B6 represent deaths at each life stage of sea lice growth. The death rate varies among different stages of sea lice life. During the chalimus and earlier stages, the death rate is much higher than the death rate in pre-adult and later life stages due to the fact that the chalimus must find a host (i.e. a fish) in which to attach; in other stages, by contrast, the surviving lice are already attached to a fish. The evolution of the lice population initially starts exogenously through external infection pressure and then the internal reproduction process. R1 and R2 feedback loops dominate the growth of lice population in the farmed salmon cage.

- **Policy Options**

The policy option section of the model represents the decision making process to control sea lice population in fish cages. The CLD[3] in Figure 6 shows a simplified generic structure of the policy options model. This section of the model takes inputs from the epidemiological model (figure 5) and its output correspondingly influences the epidemiological model. The connection points are through the stocks "preadult male L. Salmonis", "preadult female L. Salmonis", "adult male L. Salmonis", "adult female L. Salmonis", and "gravid Female L. Salmonis". The dynamic changes of these stocks occur in the epidemiological model as shown in figure 5. In this section, we only take these stocks as an input to the policy option model because decisions to control

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[3] In the CLD, both "*treatments*" and "*implemented treatment effectiveness per each stage*" are aggregated versions of different treatments in the model. We aggregated them for communication purposes. The polarities at the head of arrows that link thresholds to treatments are active only when one and/or both of the thresholds are on.

the sea lice population in fish cages are made based on the level of adult and mobile[4] lice per fish. The overall model (with different sub-models) includes more feedback loops but here we only describe how the policy option model works and show the important loops that describe the sea lice control strategy decision process.

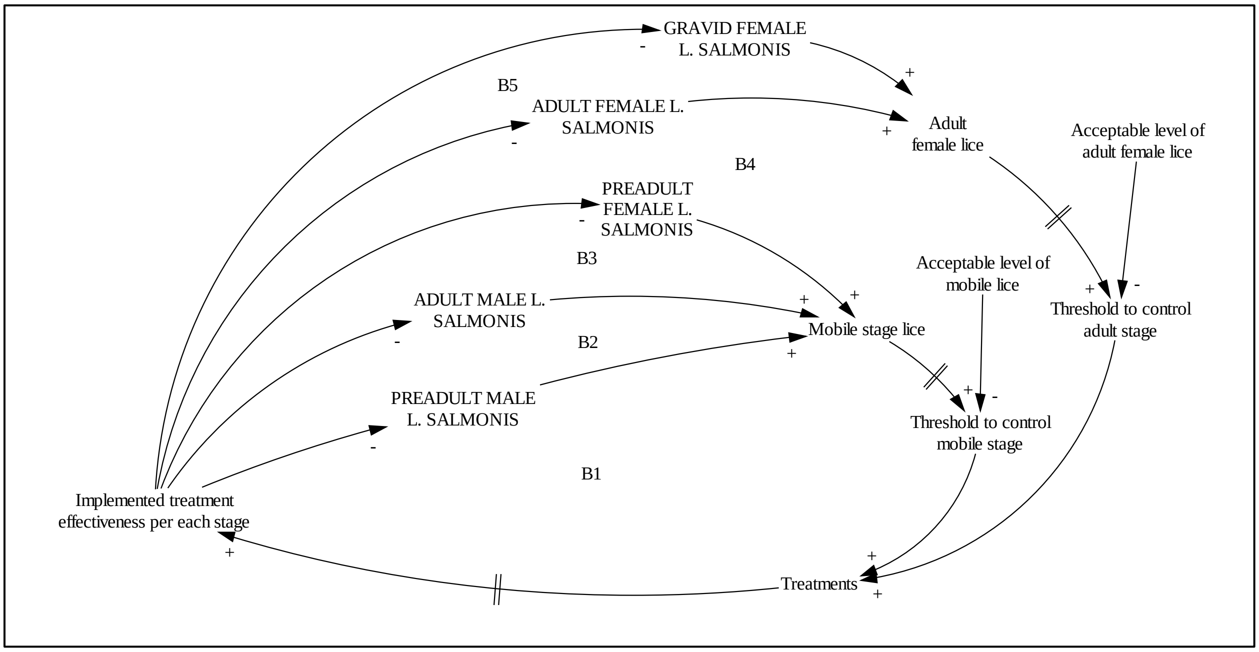

Figure 6: Policy option section of the model

In figure 6, the decision to launch a treatment strategy depends on the level of adult female lice and mobile stage lice per fish. The model launches a treatment as soon as adult female lice and/or mobile stage lice exceed their acceptable level (i.e. 0.5 or 1 adult female and 3 or 5 mobile stage lice per fish). At this point, the model selects a treatment to reduce the level of sea lice per fish. After a short time delay (i.e. 5 days, only for chemical treatments) due to treatment preparation, a treatment is implemented which reduces the sea lice population at each life stage (at different levels of effectiveness depending on the treatment chosen). This has a feedback effect on the lice populations. After a treatment is implemented, the model identifies whether there is a need for another treatment or not based on the level of sea lice per fish. Feedback loops B1 to B5 in figure 5 represent the process of controlling sea lice population at each stage in fish cages.

- **Economic Model**

The economic section of the model measures the costs of treatment to control sea lice level in a cage. A simplified structure of the model is shown in figure 7. The economic model takes

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[4] By adult female lice we mean L. Salmonis Adult Female (gravid and non-gravid). By mobile lice we mean all male lice and L. Salmonis Preadult Female lice.

inputs from the policy option sub model and its output provides an overview of the costs of different types of treatment strategies. The economic model becomes active whenever a treatment is implemented. There are four types of costs associated with the model: (1) operational costs, (2) material costs, (3) cumulative losses of fish weight due to treatments, and (4) net present value of costs. Some treatments require starving fish for five days prior to implementation, the amount of money saved through not feeding fish is subtracted from treatment costs.

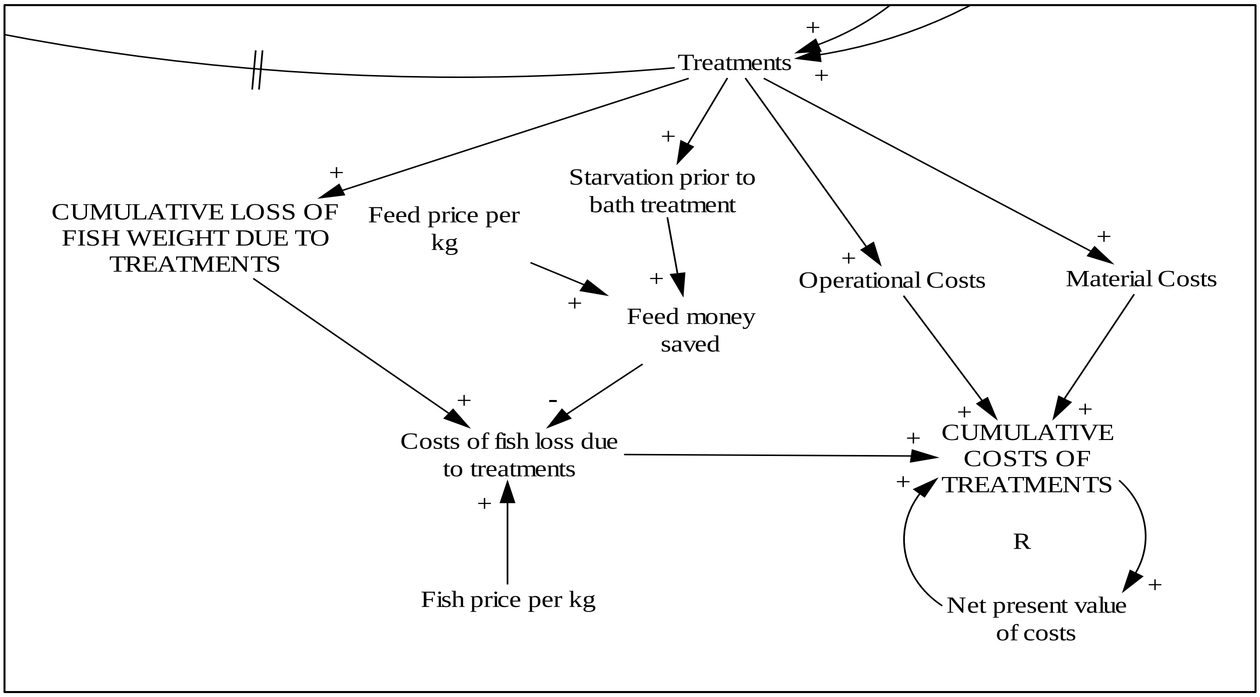

Figure 7: Economic section of the model

Operational costs are denoted as the cost of labor and equipment uses in preparing and implementing a treatment. Material costs are expenditures incurred when buying treatment materials such as medicines. The cumulative loss of fish weight due to treatments represents the loss of fish production, as some treatments require starving fish for five days prior to implementation which leads to reduced fish growth, and loss of fish due to direct deaths through mechanical actions involved in treatment implementation. The cumulative loss of fish weight due to treatments is converted into monetary terms by the variable “costs of fish loss due to treatments”; these are then added together in a stock “cumulative cost of treatments”. To this stock, net present value of costs is added, which represents the net present value of funds that are spent on treatments over time. Feedback loop R represents the process of accumulating net present value of costs, as the cumulative cost increases net present value of costs in a reinforcing feedback loop. In this manner, direct and indirect costs of treatments are accumulated in the economic model from stocking to harvesting time.

Hypothesis

We conduct simulation experiments to different treatment strategies to test different hypothesis. Our hypothesis is that early control of sea lice population results in a more effective control of sea lice population because of breaking sea lice population cycle and avoiding high peaks. The identified threshold to launch sea lice control treatments is 0.5 adult female lice and 3 mobile stage lice per fish from January 1st to August 31st of each year and 1 adult female lice and 5 mobile stage lice per fish from September 1st to December 31st of each year. We hypothesize that launching early treatment events before allowing lice population to reach these thresholds especially before approaching summer times were water temperature gets high will highly improve control effectiveness of sea lice population and keeps the magnitude of infection low. On the other hand, a late launch of treatment reduces the effectiveness of treatments especially when water temperature is high because lice grow extremely rapid under high water temperature case. Thus, by the time treatment is implemented; gravid female lice already lay enough eggs to contaminate surrounding water.

On the fish growth side of the model, early control of lice population leads to a healthier growth of fish and reduces treatment costs because early control may prevent the lice population peaks which results in decreased frequency of treatment events. We also hypothesize that increased number of chemical treatment events negatively influence fish growth because chemical treatments require starving fish for five days prior implementation which leads to decrease fish growth. Thus, as number of treatments (i.e. chemical treatments) increase, the lice population decline, costs increase, and fish get slower growth rate because of starvation prior to treatment implementation. But switching chemical treatments to in-feed treatments (if feasible) leads to better fish growth comparing to the case of using chemical treatments.

On the economic part of the model, our hypothesis is that increased number of treatments lead to a greater cost because (i) increases material and operational costs, (ii) greater loss of fish weight (in case of chemical treatments) because of increased starvation period and fish deaths, and (iii) increases in the net present value of costs . Thus, early treatments to control sea lice population should decrease fish health related costs through controlling sea lice population before reaching high peaks which leads to decreasing number of treatments. Thus, in order to choose the most cost effectiveness course of actions to control lice population, the goal is reducing lice population along with having acceptable level of fish growth.

Simulation Results and Analysis

The model is run in daily time increments over a simulated time horizon of 561 (i.e. one production cycle time) days with DT set to 1. The DT is set to 1 because the shortest time delay in the model is 2.5 days.

Epidemiology (Sea Lice Population Dynamics) and Policy Options

As long as there are fish in the cage, the epidemiological sector of the model is active, and parasites (i.e. sea lice) will begin to attach to fish and reproduce in the fish cage. This section shows three simulation outputs from the epidemiological sector of the model. The time horizon of all simulation outputs shown in figures 8 to 17 is similar. That is, from September 2008 to April 2010 (i.e. duration of past production cycle). We conduct different experiments over the same time horizon to test what would have happened if actions done differently. These experiments assists to learn from past and improve decision making in the future through learning from simulations.

The first one illustrates simulation results of sea lice population dynamics over time through inputting treatment events from past production cycle into the model. That is, the same type and timing of treatments over the same time horizon as in data (figure 8 and 9). The purposes of this run are to evaluate the replication of sea lice population data (from past production cycle) by the model and to provide a benchmark to evaluate different treatment options (that is, different timing of implementation over the same time horizon as in data) in the next simulation. The second result shows simulation of sea lice population dynamics through implementing treatments at different times. In this case, the user can pause the model (or the model automatically pause when sea lice population exceeds thresholds) whenever necessary to decide whether to launch a treatment to control sea lice. Two runs (figures 10, 11, 12, and 13) are reported to evaluate whether different timing of treatment event influence the efficiency of sea lice controls. The third result show the influence of experimenting different timing along with switching treatment types on sea lice population (figures 14 and 15).

Simulation 1: reference mode replication

Figures 8 and 9 show data and simulation[5] results of adult female and mobile stage sea lice per fish, respectively. The model generates results shown in figures 8 and 9 by introducing treatment events from past production cycle to the model to control sea lice level per fish.

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[5] Five treatment events are implemented in this simulation at days 78 (in-feed treatment), 126 (in-feed treatment), 377 (chemical treatment), 397 (in-feed treatment) and 464 (chemical treatment).

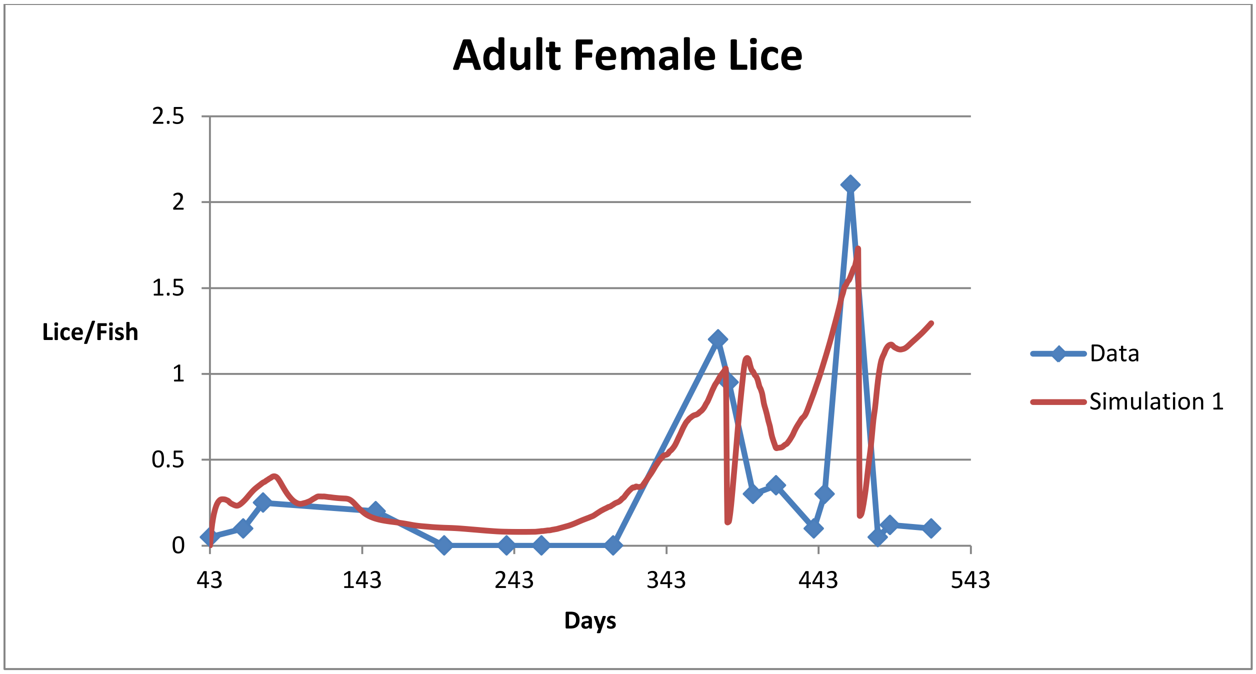

Figure 8: reference mode comparison (adult female lice)

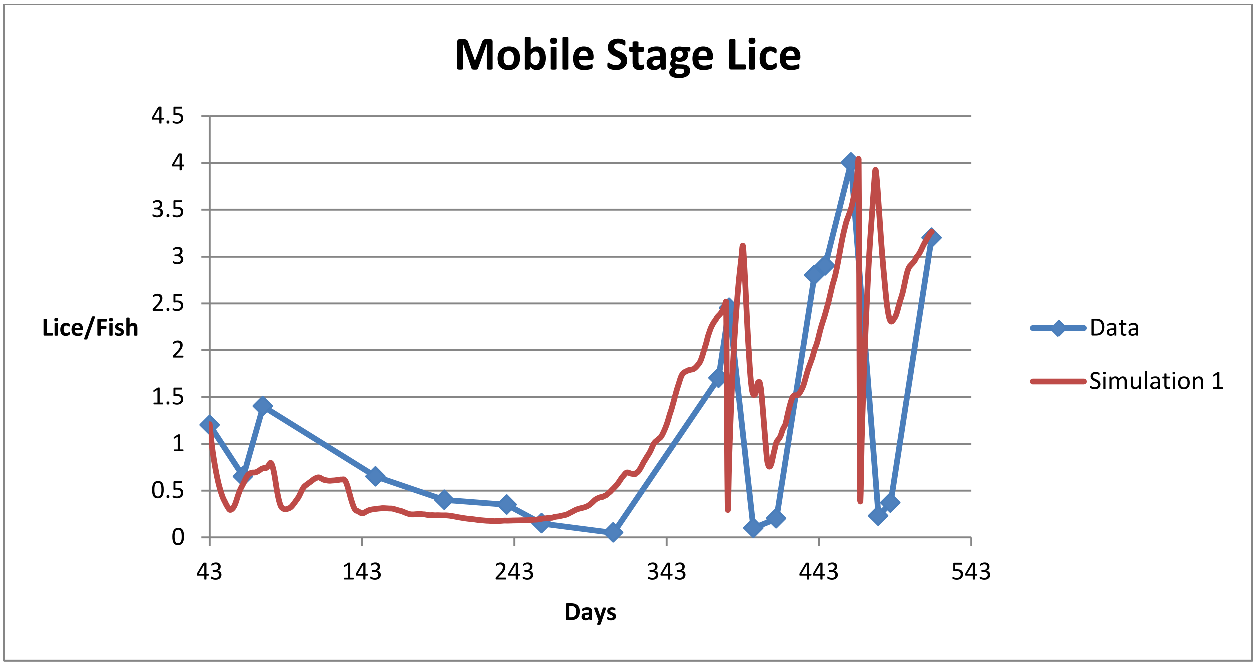

Figure 9: reference mode comparison (mobile stage lice)

The behavior patterns of simulation results[6] shown in figures 8 and 9 are described as follows:

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[6] Note: the data trend in the figures 8 to 13 are based on samples (that is, the dots in the trend) while simulation results are continuous from day 43 to the end of simulation.

1- The level (i.e. both adult female and mobile stage lice) of sea lice per fish is low at the beginning of the simulation because fish are lice-free when first stocked in the cage[7];
2- Sea lice are initially introduced to a cage from outside sources, after which lice begin to reproduce internally in the cage. The growth rate is temperature dependent; as temperature increases, their growth increases, and vice versa.
3- The level of sea lice until day 240 (day 300 for data) is relatively lower compared to later days of the production cycle. This is because fish are stocked in September and the water temperature starts to decline until late April (day 240) and therefore the magnitude of background infection pressure is low. In addition, the reproduction of sea lice in low water temperatures is much lower than the reproduction of sea lice in high water temperatures.
4- The level of sea lice per fish starts to grow from day 240 due to the fact that the water temperature begins to increase and so too does the magnitude of background infection pressure. In addition, sea lice reproduce at a faster rate internally and therefore the level of sea lice per fish increases extremely rapidly.
5- The continuous sharp growth and then decline in both data and simulation results occur as a result of implementing treatments to control sea lice levels per fish. Thus, each time sea lice reach or exceed a threshold level, the model launches a treatment strategy, and therefore the sea lice levels per fish decline sharply. But due to high water temperatures at this time, which leads to high lice reproduction rate, sea lice again grow at a faster rate. It should be noted that even at high levels of lice per fish, lice reproduction rates are high because even during treatment periods, the gravid female lice will have already laid enough eggs before the treatment to contaminate water around the cage.

As stated in hypothesis section, the purpose of this simulation 1 is to compare model behavior with data. The results in figure 8 and 9 show a reasonable fit of model behavior to data.

- **Simulation 2: alternative control strategies**

A) Option A:

Figures 10 and 11 show the same type of simulation as in figures 8 and 9 but here treatment events are launched at different times than the previous simulation. That is, the user decides when to launch a treatment. The purpose of this option is to test how early control of sea lice influences sea lice population dynamics. Thus, we use the same treatments as in simulation 1 but at different times[8].

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[7] Cages are located in the open sea.

[8] Treatment events are implemented at days 78 (in-feed treatment), 126 (in-feed treatment), 350 (chemical treatment), 370 (in-feed treatment) and 444 (chemical treatment).

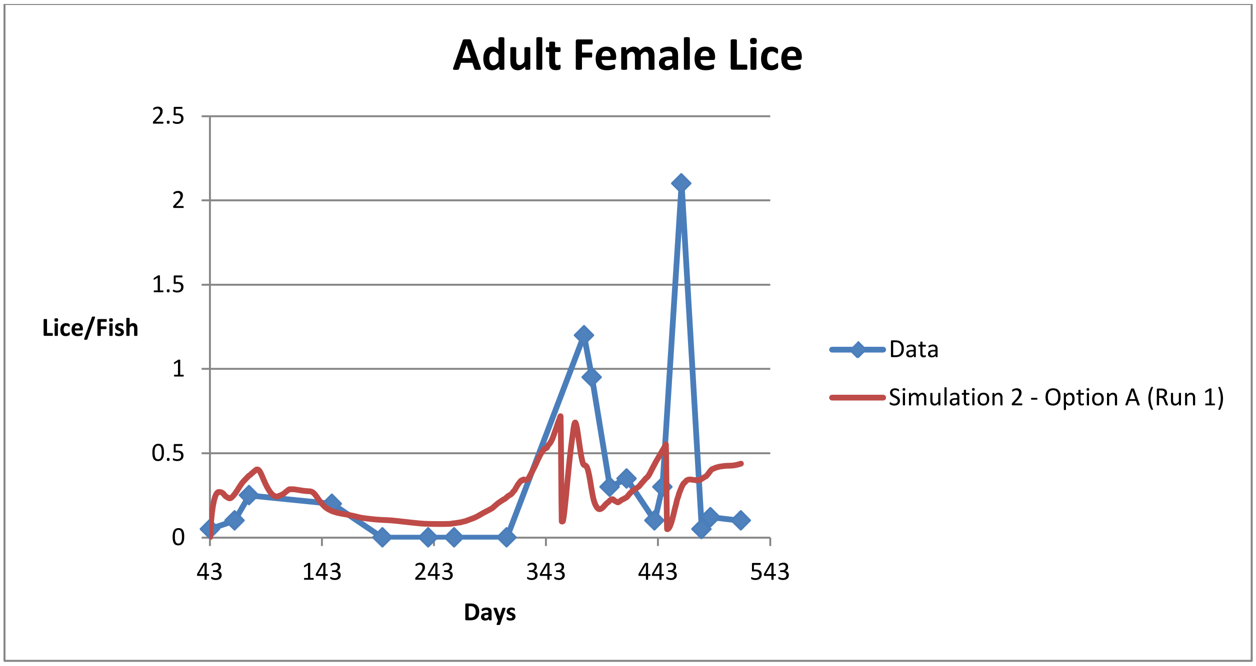

Figure 10: adult female lice population dynamics (option A – run 1 control strategy) comparing to data

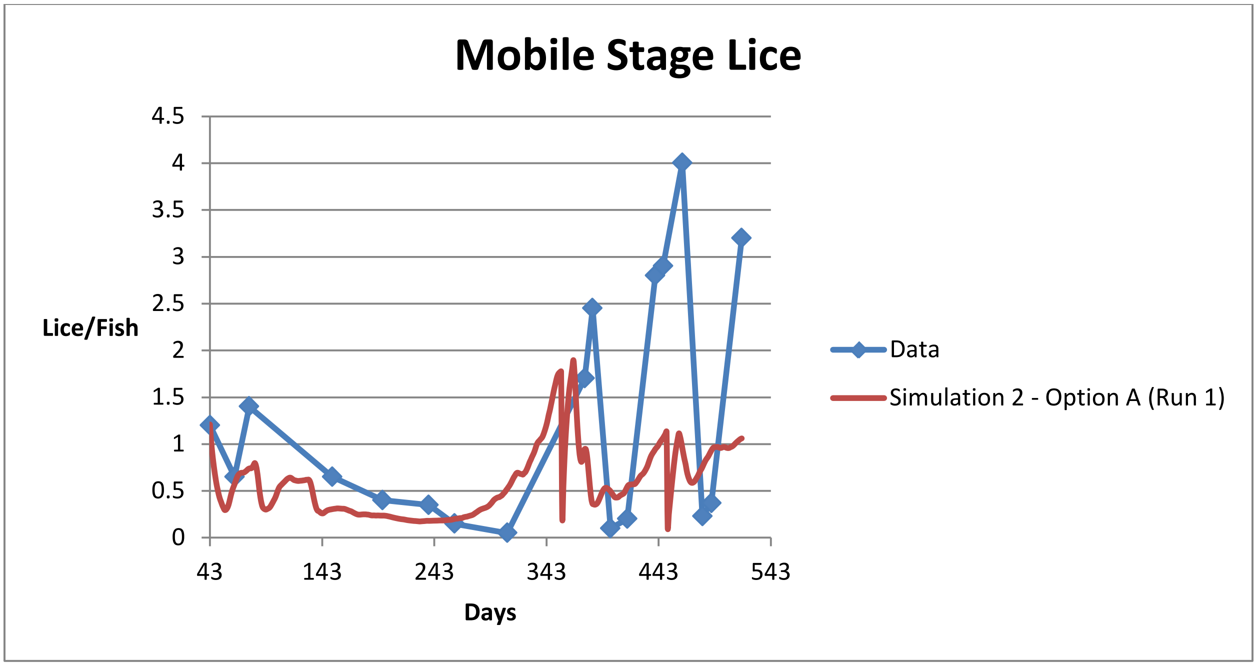

Figure 11: mobile stage lice population dynamics (option A – run 1 control strategy) comparing to data

Simulation results in figures 10 and 11 shows that the model generates similar behavior patterns as in simulation 1 but with lower infection magnitude. The reasons that option A simulation have lower infection magnitudes are: (a) the model launches a treatment event when sea lice level starts to grow (before reaching thresholds), (b) next treatment events are launched earlier than simulation 1, and (c) the consequences of early control treatment events in points (a) and (b) leads to breaking down lice population cycle and decreases the amplitude of infection.

Simulation results[9] in figures 12 and 13 show further decline of sea lice population through launching earlier treatment events. The simulation results in figures 12 and 13 show a further decline of sea lice population, comparing to figures 10 and 11, when one treatment is implemented earlier (day 320 instead of 350). However, unreported simulation results showed that dates of treatment events should be selected carefully to ensure breaking down sea lice population cycle. In other words, too early and/or too late treatment events might not be very effective. For example, implementing treatments early than day 320 (simulation outputs in figure 12 and 13) will be less efficient and late treatments are always less efficient because it will allow lice population to grow out of control and make it hard to break lice population cycle.

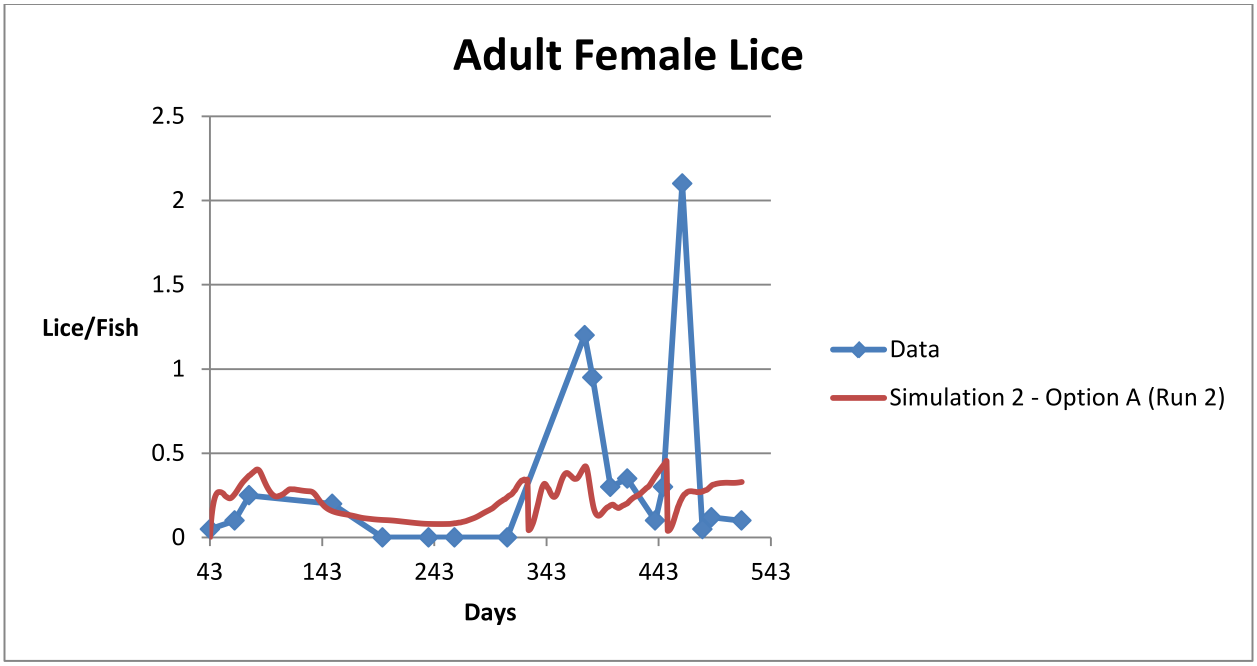

Figure 12: adult female lice population dynamics (Option A – run 2 control strategy) comparing to data

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[9] Treatment events are implemented at days 78 (in-feed treatment), 126 (in-feed treatment), 320 (chemical treatment), 370 (in-feed treatment) and 444 (chemical treatment).

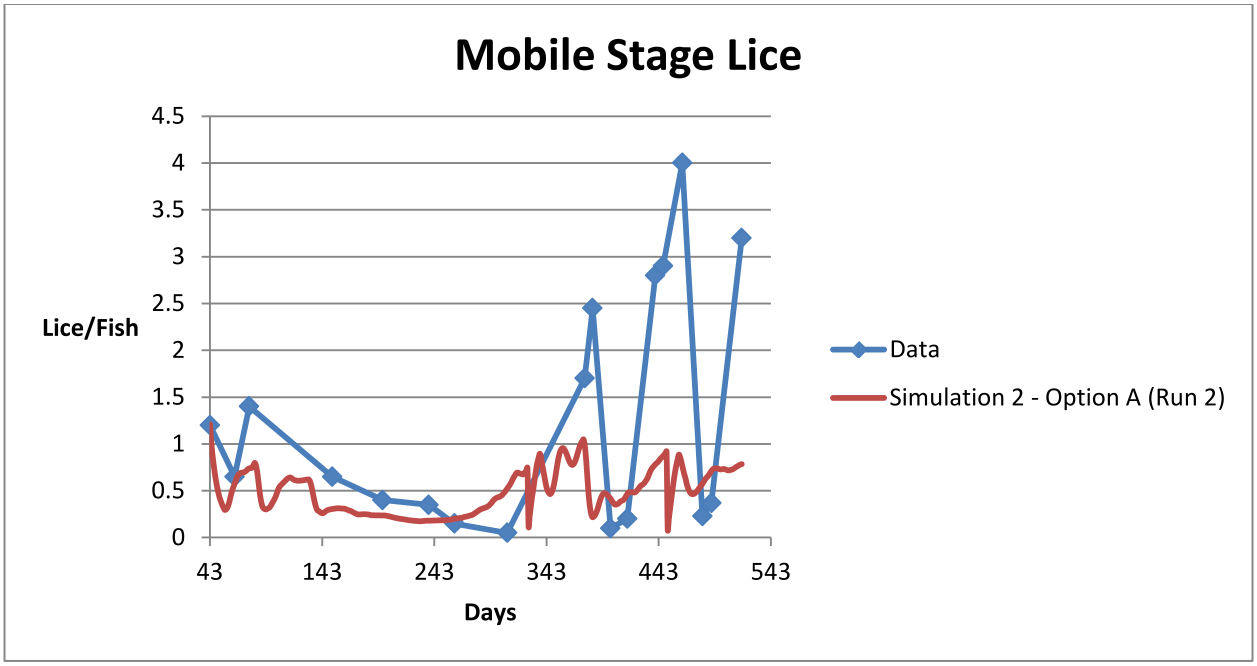

Figure 13: mobile stage lice population dynamics (Option A – run 2 control strategy) comparing to data

B) Option B:

In option A section, we tested influence of different timing of treatment events on sea lice population. In this section (Option B), we test influence of different timing along with different types of treatment events on sea lice population. As shown in option A section, timing of treatment events significantly increased the effectiveness to control sea lice population. Here we test along with timing whether changing treatment types will further improve sea lice control effectiveness.

Figures 14 and 15 show the same type of simulation as in simulation 1 and simulation 2 (option A) but here treatment events are launched[10] at different times and different types (i.e. in-feed and chemical treatments) than the previous simulations.

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[10] Treatment events are implemented at days 78 (in-feed treatment), 126 (in-feed treatment), 320 (in-feed treatment), 370 (in-feed treatment) and 444 (chemical treatment).

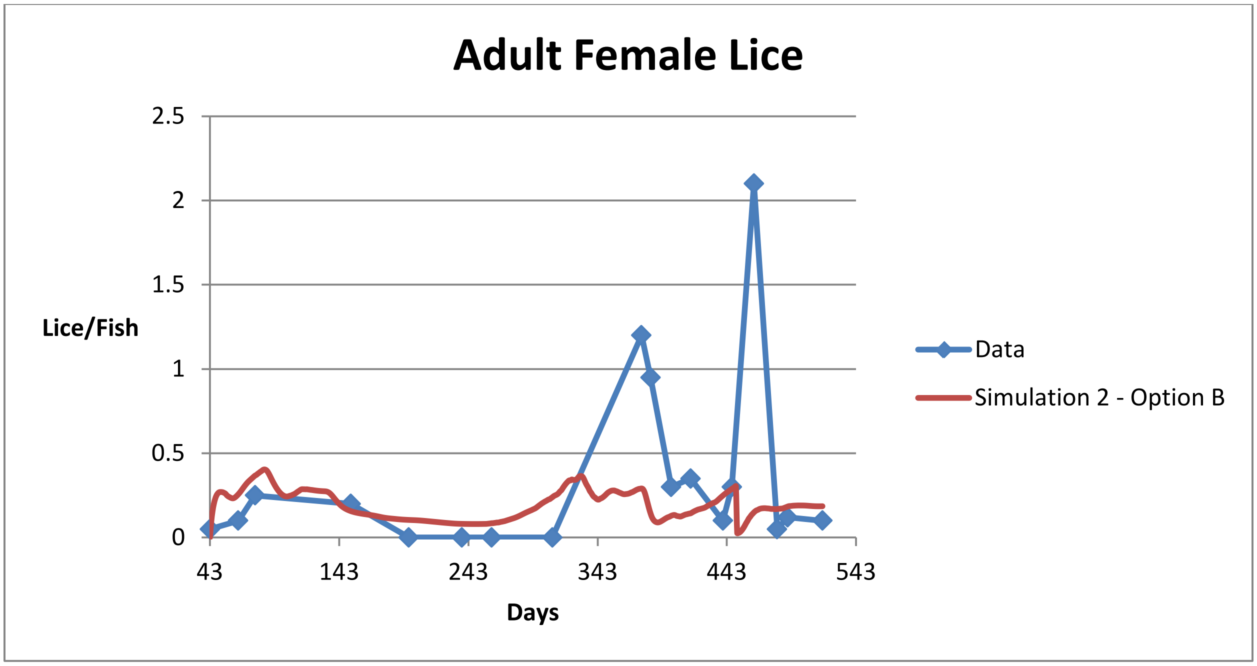

Figure 14: adult female lice population dynamics (Option B control strategy) comparing to data

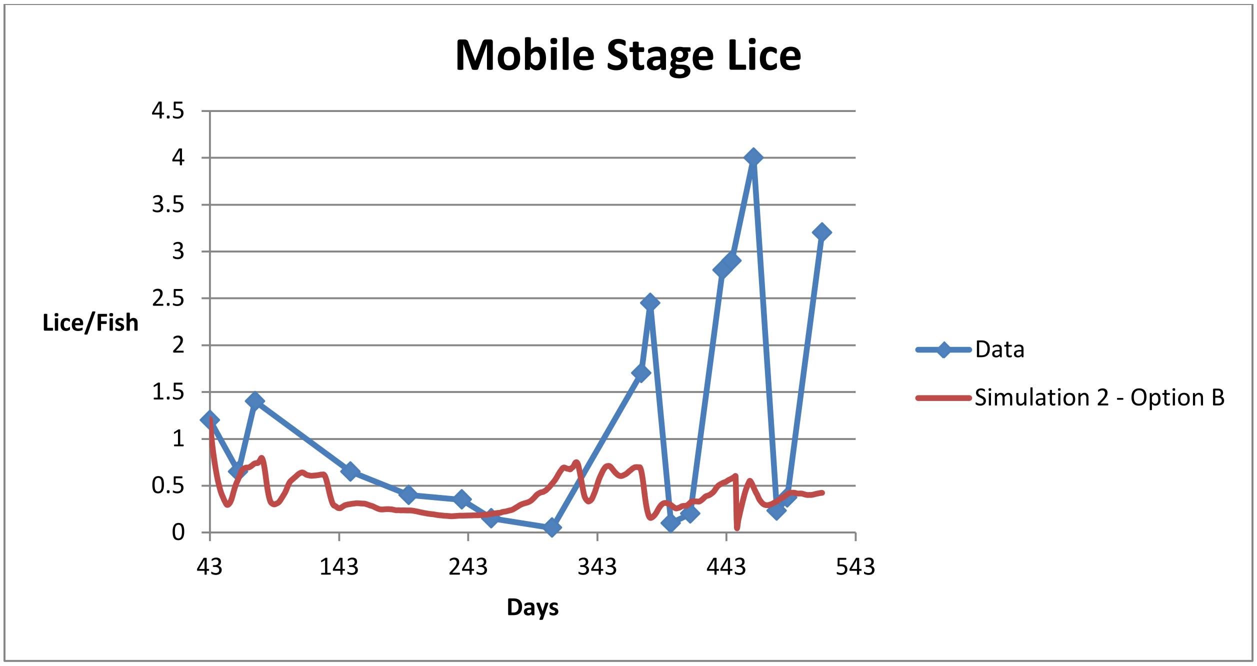

Figure 15: mobile stage lice population dynamics (Option B control strategy) comparing to data

In all simulations that are shown, we used treatment events that were used in past production cycle. But we tested changing in treatment times and switching treatment types. The timing and type of treatments seem to have significant influence on controlling sea lice population.

Changing treatment type (using in-feed treatment at day 320 instead of chemical treatment) slightly improved the effectiveness to control sea lice population. Insights from these simulation results show that early control of sea lice epidemics can assist in lowering the magnitude of high lice levels per fish. These results suggest the need of developing treatment strategies for controlling the lice population to avoid the first peak because when the lice population reaches first peak they contaminate (i.e. laying eggs) surrounding water and therefore shortly after each treatment the lice population grow again. Thus, avoiding first peak of sea lice population greatly facilitate keeping lice under desired limits per fish. We can learn from these results that treatments should target potential strategies to avoid first peak of the lice population which may lead to control lice level at desired condition and prevent the lice population peaks.

Early control of sea lice population in fish cage shows a potential strategy to avoid high level of sea lice per fish. This is an important insight that salmon industries are interested in. Therefore, to keep lice level under control, it is highly recommended to launch early treatments before reaching thresholds. The reason for that is by the time sea lice level per fish reaches thresholds, lice population are big enough to lay large number of eggs and contaminate surrounding water. Which in turn restricts the efficiency of treatment events and make it hard to keep lice under control (refer to simulation 1 section: figure 8 and 9). On the other hand, early control breaks down lice population and keeps surrounding water uncontaminated (refer to simulation 2: options A and B), which in turn keeps lice level under control. In the next section, we will evaluate the influence of tested simulations on fish growth.

• Aging and Growth Sector

Figure 16 shows the simulation results of the fish growth sector of the model for the control strategies tested in epidemiology and policy option section. Each trend on the graph in figure 16 represents the growth of fish through simulation 1, simulation 2 (option A: runs 1 and 2), and simulation 2 (option B). Simulation 1 differs from simulation 2 – Option A (run 1 and 2) by launching treatments at different times. But since the number and the type of treatments are exactly the same and they only differ in timing, the final weight of fish is slightly different (5.43 kg for simulation 1, 5.42 kg for simulation 2 – option A (run 1), and 5.43 kg for simulation 2 – option A (run 2). Simulation 2 – option B differs from simulation 1 and simulation 2 – option A (runs 1 and 2) by changing the type of one of the treatment events. That is, in day 320, instead of conducting chemical treatment we used in-feed treatment. Chemical treatments influence fish growth because the requirement to starve fish five days prior to treatment implementation. Therefore, simulation 2 – option B shows better growth of fish (5.59 kg) because of switching one chemical treatment to in-feed treatment decreased the starvation period, which in return improves fish growth.

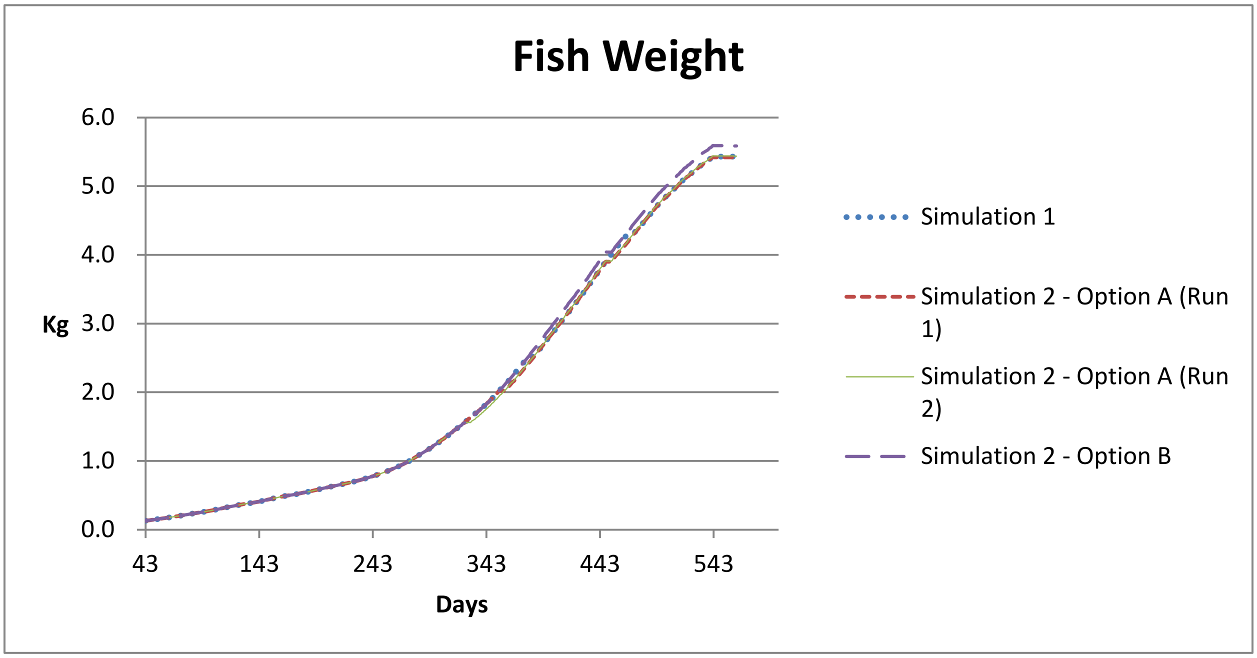

Figure 16: the influence of tested simulation on fish growth (the order of simulation are shown respectively)

It should be noted that the treatment implementation time has influence on fish weight. Early implementation has less influence on fish weight than later implementation because fish growth in early stages is already slow, while in later stages the growth rate accelerates. Thus, starving fish in later stages of the growth leads to more loss in fish weight than early starvation. Therefore, late treatment events should be avoided if possible.

Simulation results of growth sector (figure 16) of the model are described in following development phases:

1- Early stage growth (from day 1 to 260): this stage is characterized by slow growth due to the fact that fish size is very small (initial weight of smolt is 0.13 kg) in addition to water temperature declines gradually from stocking time to day 260 and therefore the feeding amount per day is low, which leads to slow growth;

2- Middle stage growth (from day 261 to 440): this stage is characterized by an exponential growth of fish weight, as fish size increases in addition to gradual rise of water temperature until day 440 which leads to an increasing daily feeding amount per fish and thus greater growth;

3- Final stage growth (from day 441 to 561): this stage is characterized by a slower growth than the middle stage growth, as reduced feed conversion ratios for larger fish lead to a slower growth in fish weight in addition to a gradual fall of water temperature from day 440 leads to decreasing daily feeding amount per day;

4- It should be noted that there are some times that fish do not grow in size because of the implementation of treatments that require starving fish five days prior to implementation.

The influences of different timing and type of treatment events on both sea lice and fish growth are shown in both aging and growth, and simulation result and analysis sectors. In the next sector, we convert these results to monetary terms to identify the costs of each simulation to provide decision makers with costs and benefits of each simulation.

- **Economic Model**

Figure 17 shows the costs (NOK) of for the control strategies tested in epidemiology and policy option section. Each time when the model launches a treatment, the costs of that treatment is added to the stock of cumulative costs of treatments (figure 17). The cumulative costs of treatments slightly increase between one treatment and another because of accumulating net present value of the costs.

All simulation launched the first two treatment events at the same time and use the same type of treatments. Thus, the costs are similar for all simulations at this time. But for the next treatment events, each simulation uses different timing and/or different types of treatments. Therefore, the costs start to vary for each simulation. Chemical treatments costs the same amount of money regardless of implementation time, while the costs of in-feed treatment depends on the timing of implementation (as fish grow in size, the costs go up). Therefore, the high step increases of the cost of all simulations from day 300 to 400 occur (for simulation 2 – Option B occurred twice). The slight decline of costs is due the feed money saved because of five days of starvation prior to implementation of chemical treatments. It should be noted that the last step increase in the costs are the costs of the cumulative loss of fish weight caused by treatment implementation, while the earlier increases are the direct costs of treatments (i.e. material and labor costs). Though simulation 2 – Option B shows higher costs than the other simulation before of the end of simulation, but it has the lower overall costs comparing to other simulations. The reason for that is simulation 2 – Option B has better growth of fish (that is, lower loss of fish weight due to treatments).

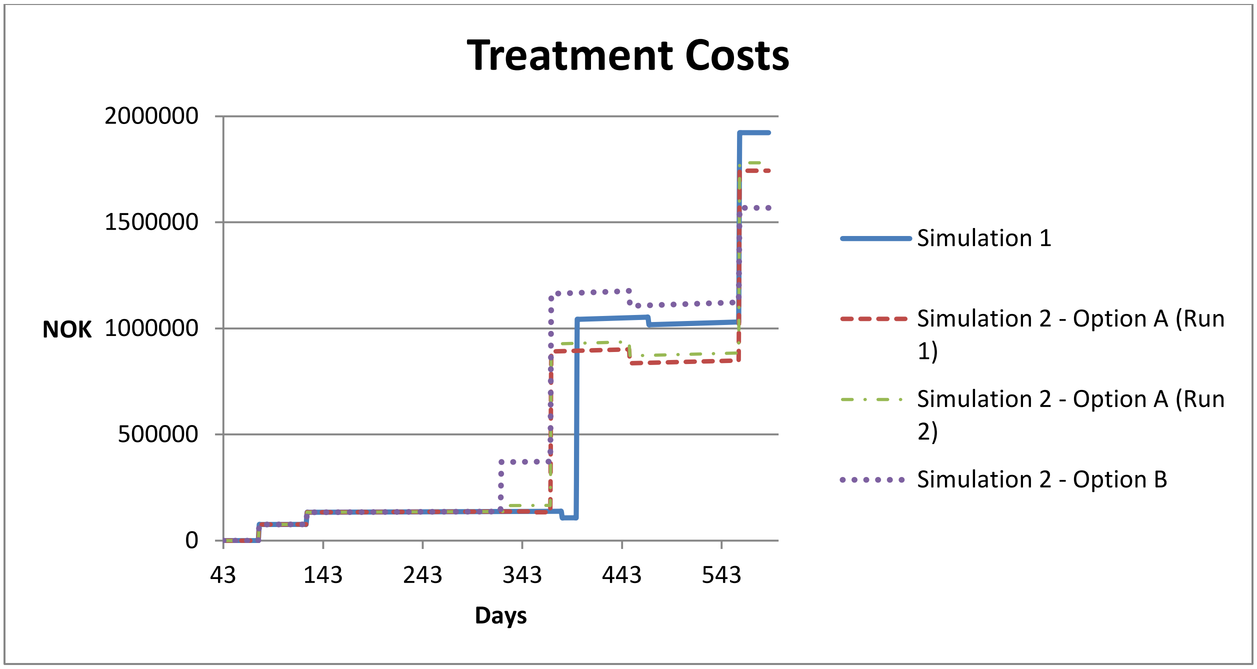

Figure 17: costs of each simulation

Our hypothesis is that early control of lice population reduces health related costs in the cage because early control may reduce the number of implemented treatments. Though sea lice are significantly reduced by implementing early treatment events, but the number of treatment events is the same in all simulations. They only differ in timing and/or type of treatments. However, the simulation results showed that early treatment events assist to decrease health related costs and to better controlling the lice population (refer to results in figure 17). But some of them harm fish growth.

The results showed that simulation 2 (option B) keeps sea lice level lower than other simulation results, fish grows better than other simulation, and the costs of controlling lice population is lower than the other simulations. On the same manner, simulation 2 (Option A: 1st run) is more cost effective than simulation 1 and simulation 2 (option A: 2nd run) and simulation 2 (option A: 2nd run) is more cost effective than simulation 1.

Conclusion

The integrated model presented in this paper has potential in developing an integrated tool that incorporates biology, epidemiology, and economics of aquatic diseases. Unlike existing models, a strength of this framework is in its ability to capture feedback mechanisms among related model sectors. It further has the potential in converting treatments and sea lice epidemics into real monetary values to guide better decision making. The results of the model showed that early control treatment events: (1) improve the efficiency of controlling lice population, (2) enhance fish growth, and (3) reduce lice control costs. The results showed that launching treatment events before reaching thresholds greatly facilitate to prevent high peaks of lice population and hence breaking lice population cycles.

Acknowledgments

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Appendix 2: Model Structure

In this appendix, we show the Stock and Flow diagrams (SFD) of model sections. In general structure of an SD model of aquatic disease section (pages 8 to 14), we described model structure through Causal Loop Diagrams (CLD). Here, we show stock and flow diagram for each CLD presented in general structure of and SD model of aquatic disease section. Check the caption of below figures to see the SFD refers to which CLD.

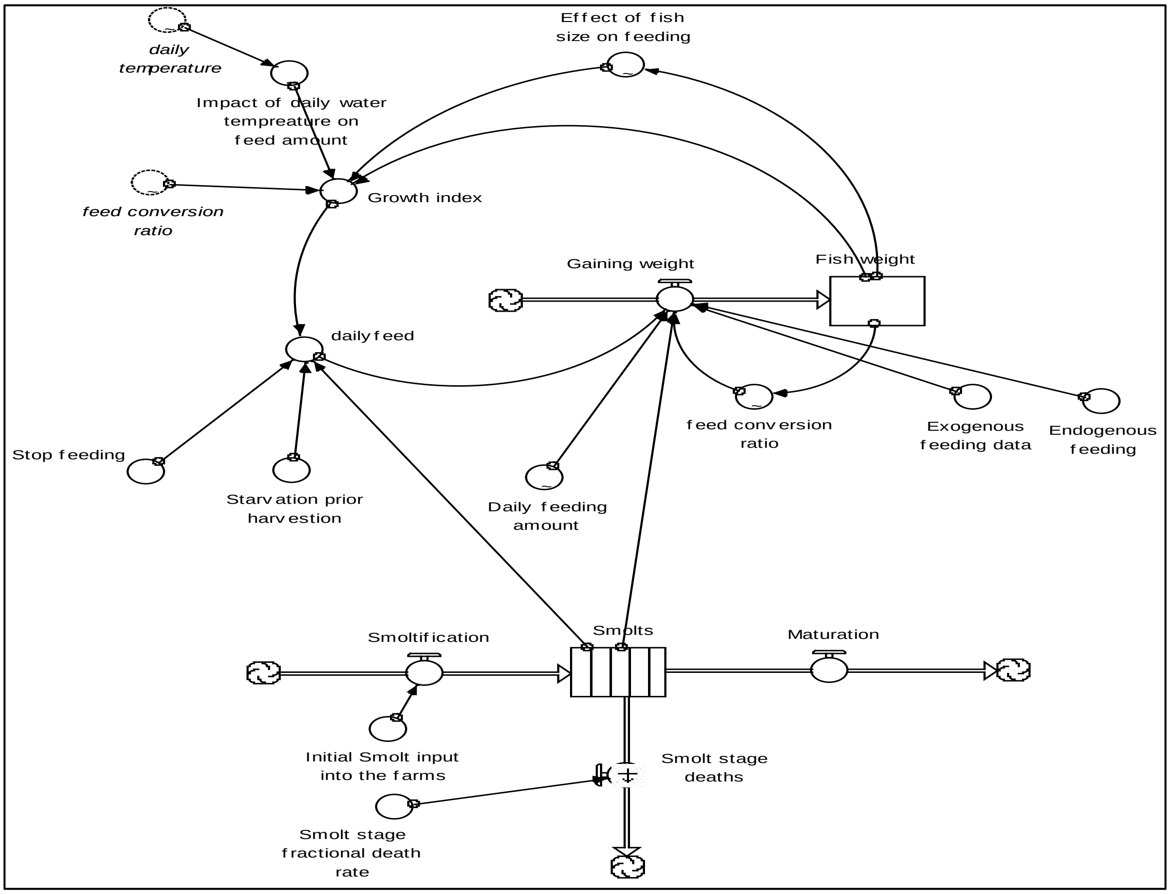


Figure 18: Stock and flow diagram of fish aging and growth section of the model (CLD is shown in figure 4 - page 33)

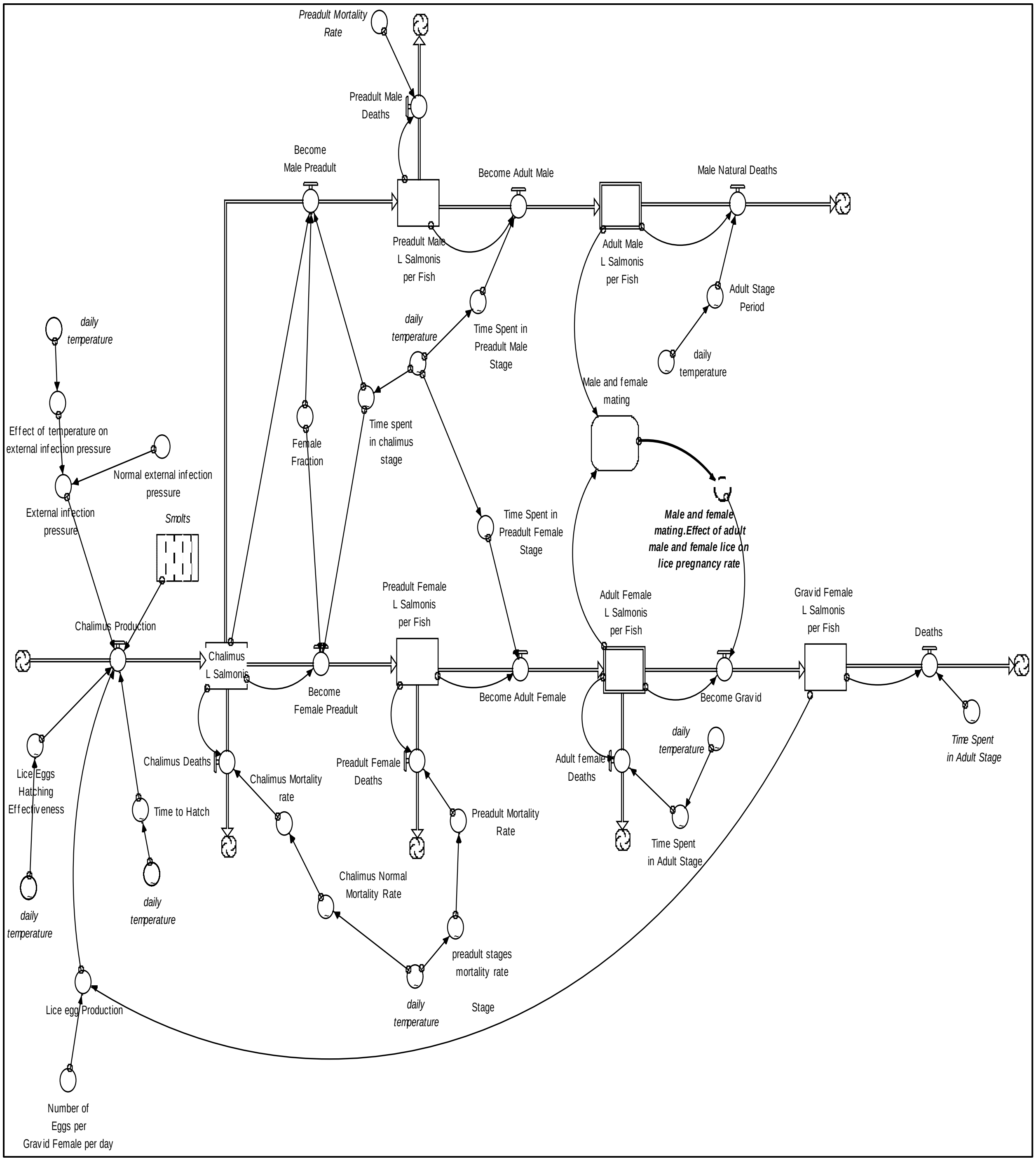


Figure 19: Stock and flow diagram of sea lice population dynamics section of the model (CLD is shown in figur5 – page 34)

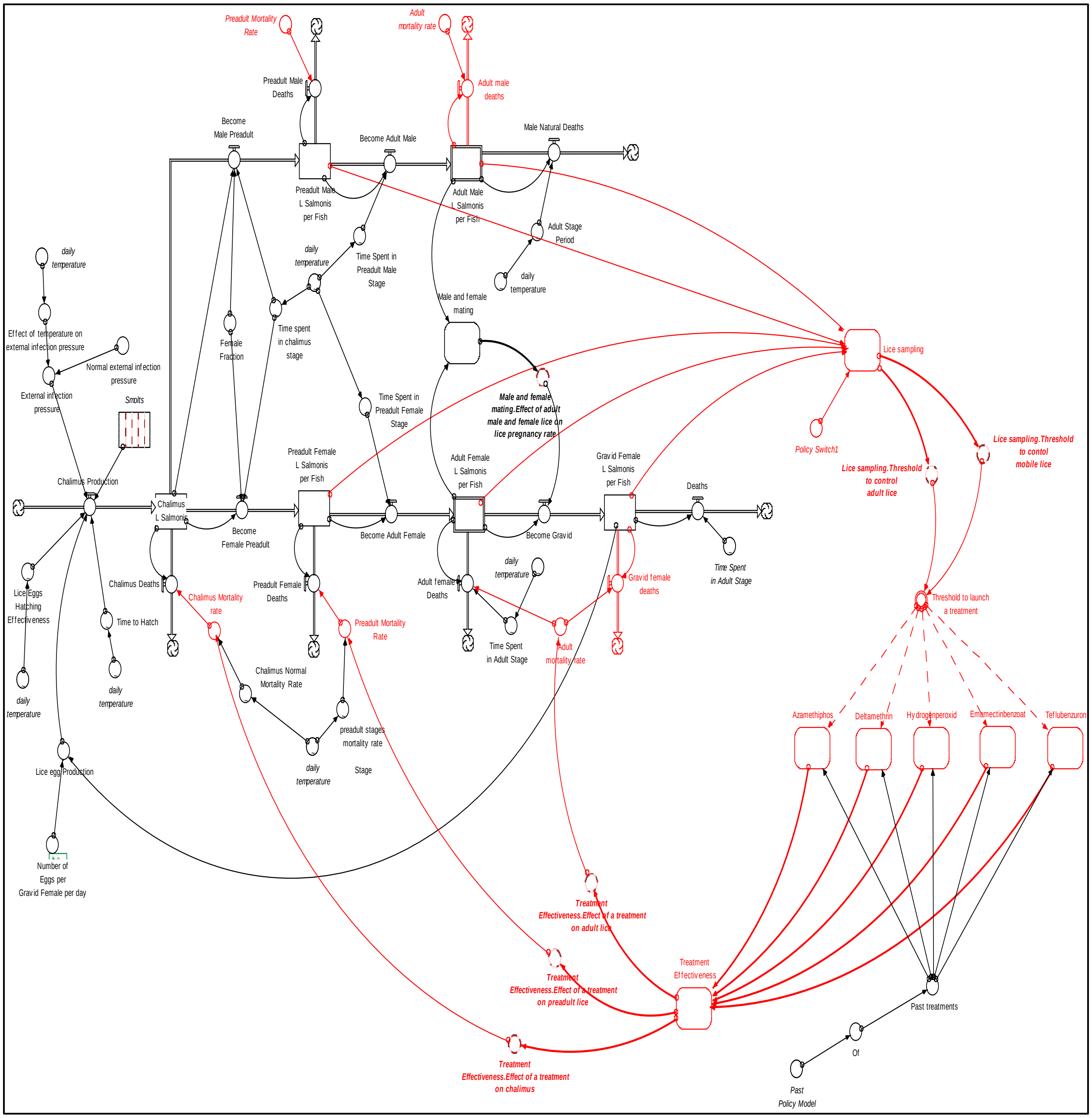


Figure 20: stock and flow diagram of policy options section of the model (CLD is shown in figure 6: page 36)

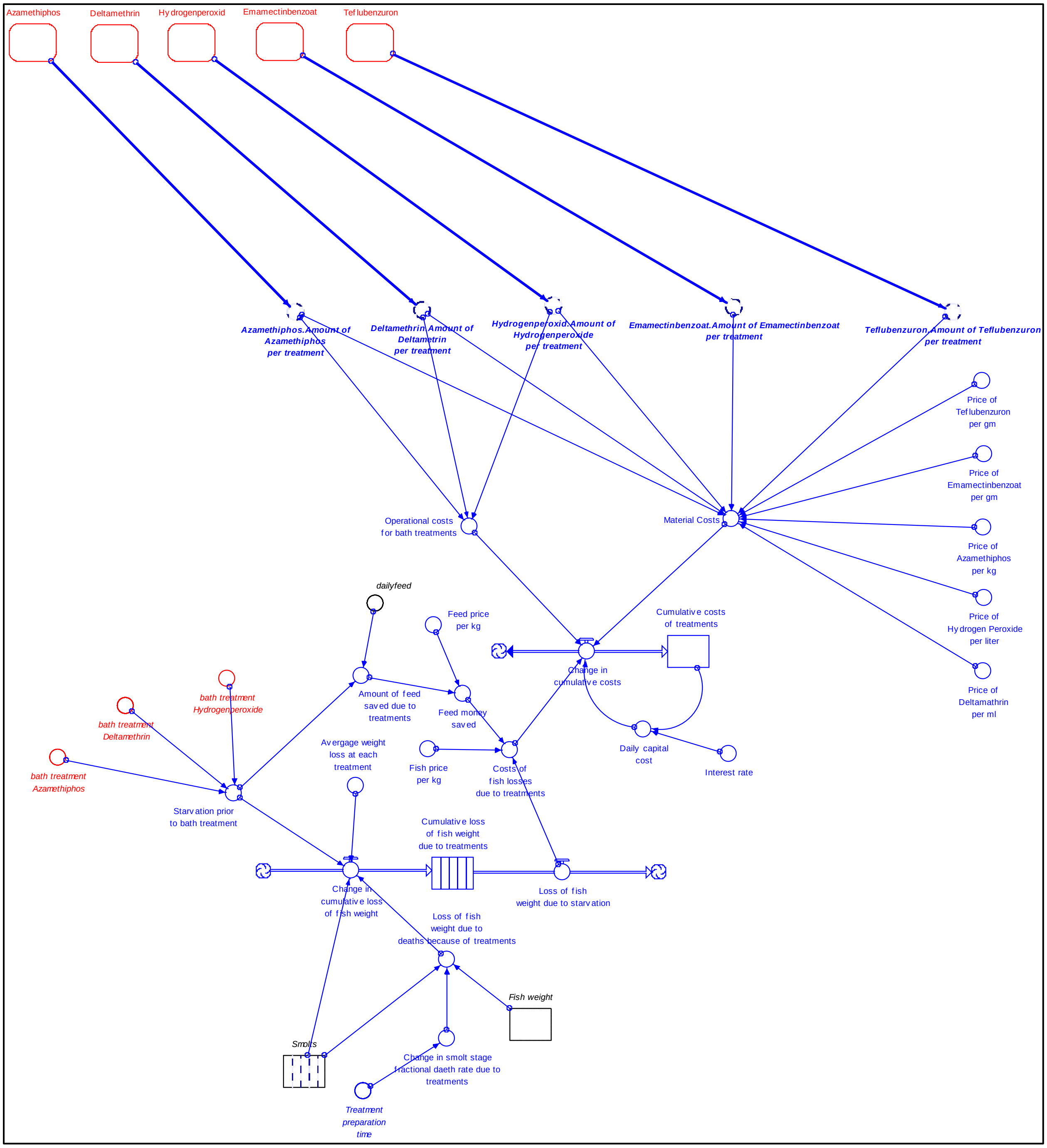


Figure 21: stock and flow diagram of economic section of the model (CLD is shown in figure 7- page 37)

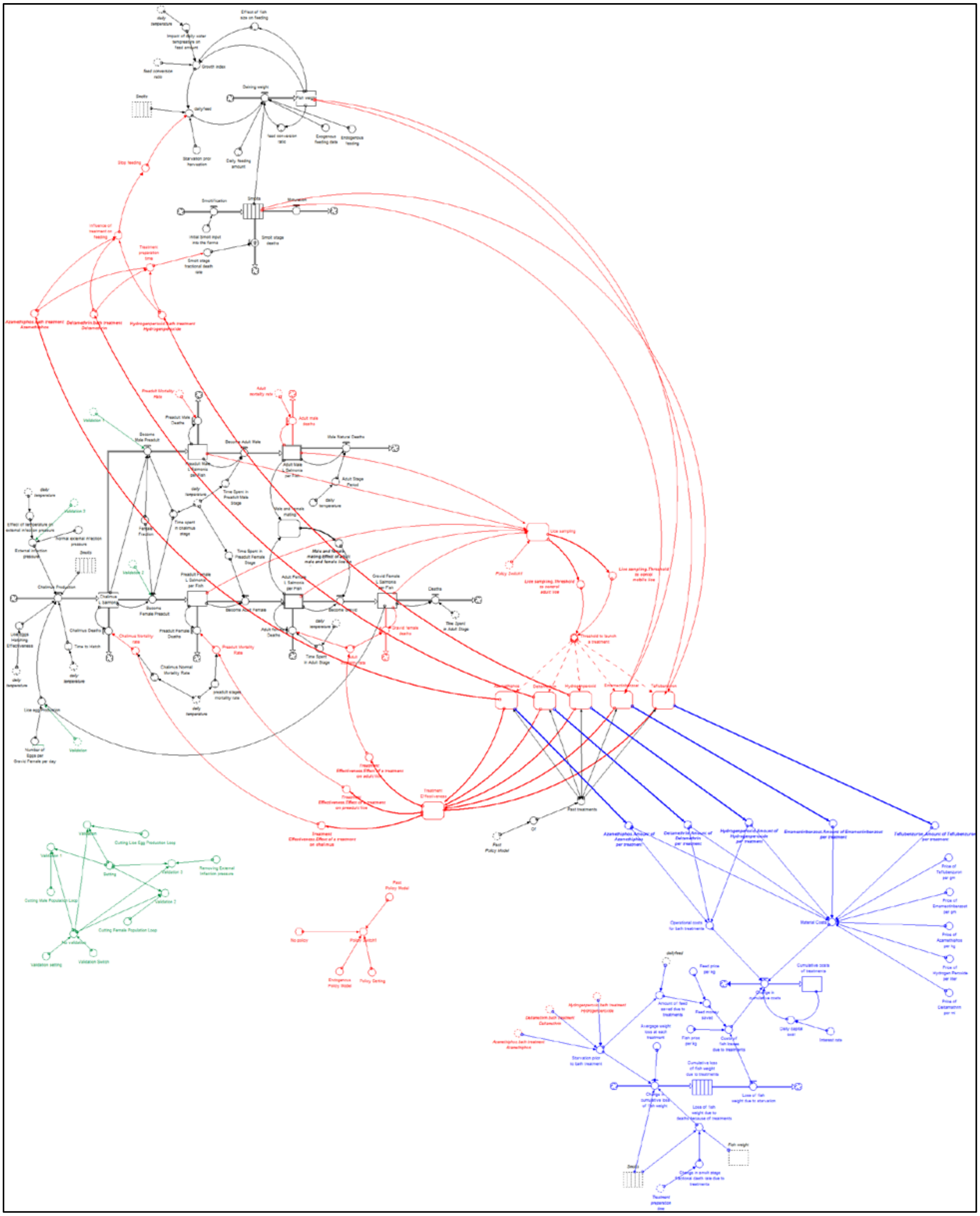


Figure 22: overall model structure

Appendix 3: Modules Structure

In this appendix, we will show the structure of each modules used in the model. Figure 23 shows the used modules in the model.

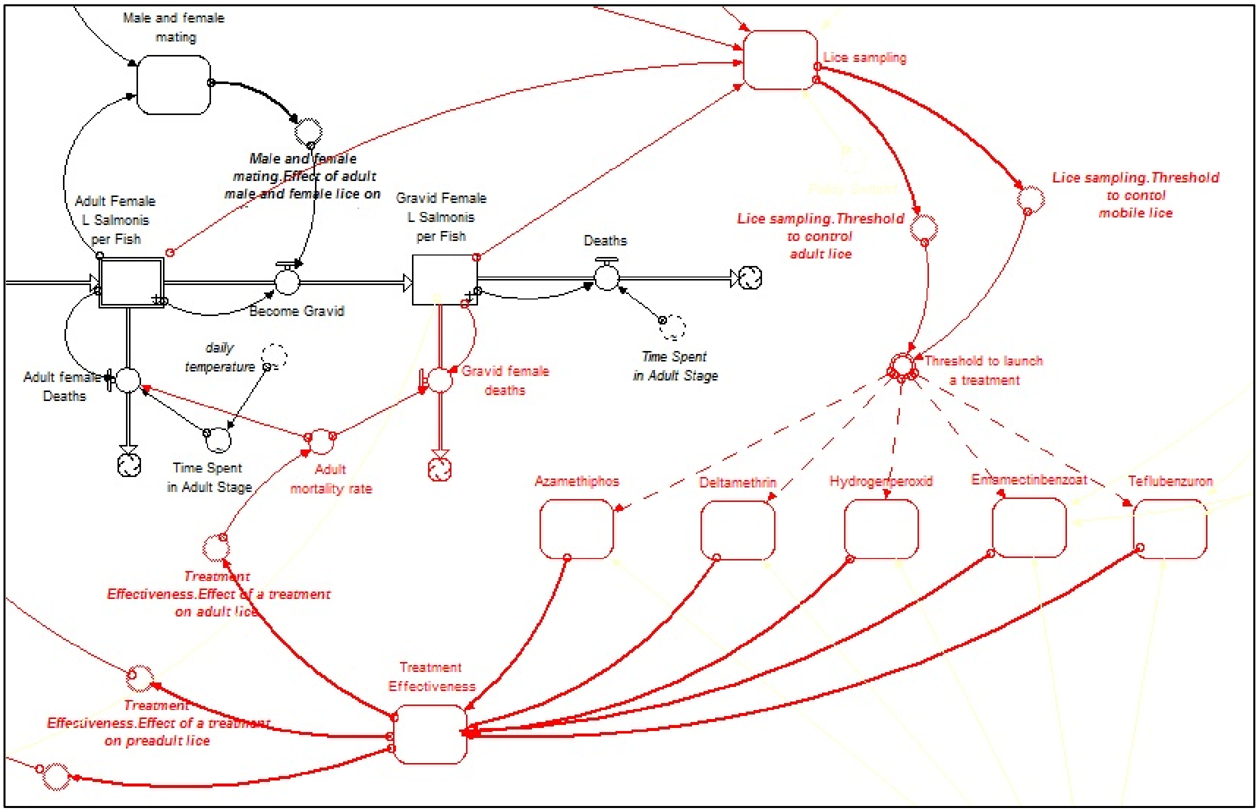


Figure 23: modules used in the model

The following models are used in the model: (1) male and female mating, (2) lice sampling, (3) teflubenzuron, (4) emamectinbenzoat, (5) hydrogenperoxid, (6) deltamathrin, (7) azamethiphos, and (8) treatment effectiveness. In the following figures in this appendix, we will show the structure inside each of these modules.

- **Male and female mating**

This module represents the reproduction mechanism of adult female lice. The reproduction rate (i.e. female pregnancy rate depends on two factors: (1) total number of adult lice, and (2) male to female ratio. As number of adult lice increases, the probability of adult female lice pregnancy increases. As male to female ratio increases, the probability of adult female lice increases. Figure 24 shows the structure of the model of male and female mating module.

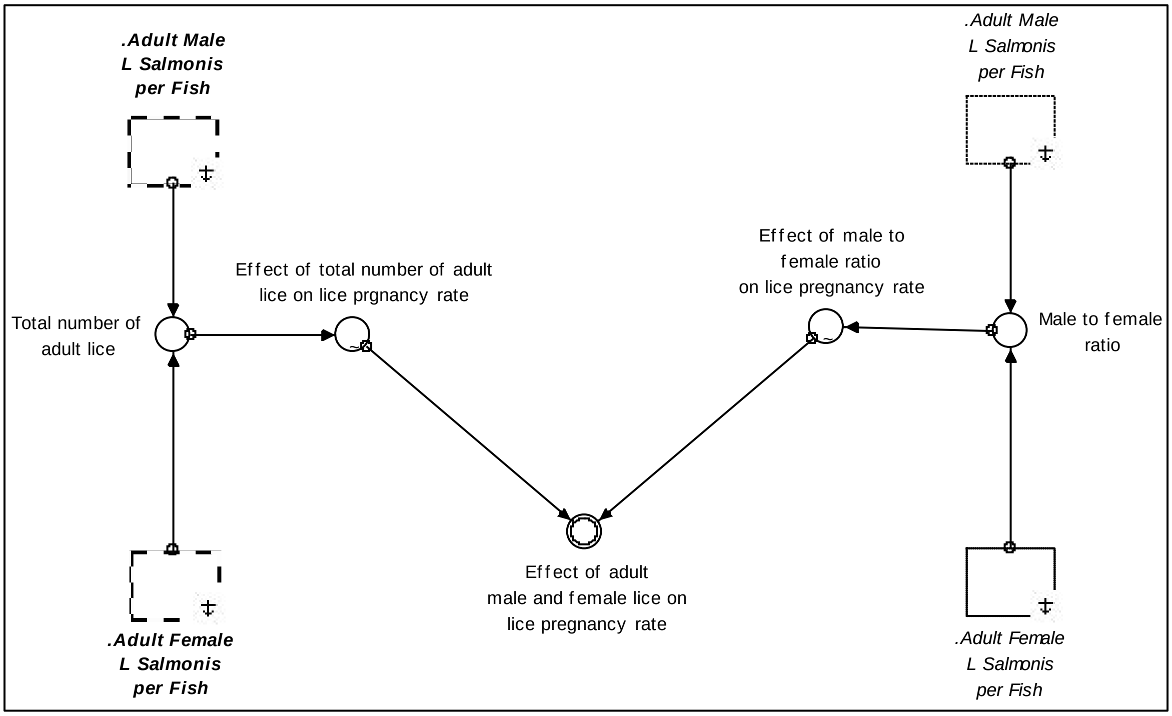


Figure 24: male and female mating process

- **Lice Sampling**

This module represents the sampling process of sea lice population. Salmon industries monitor sea lice population once each fifteen days. Salmon industries also cluster sea lice population into mobile stage lice (i.e. preadult male, preadult female, and adult female) and adult female lice (i.e. adult female and gravid female). This module also includes the limits of sea lice (both mobile stage and adult female lice) per fish that is identified by the government. Figure 25 shows the structure of lice sampling module.

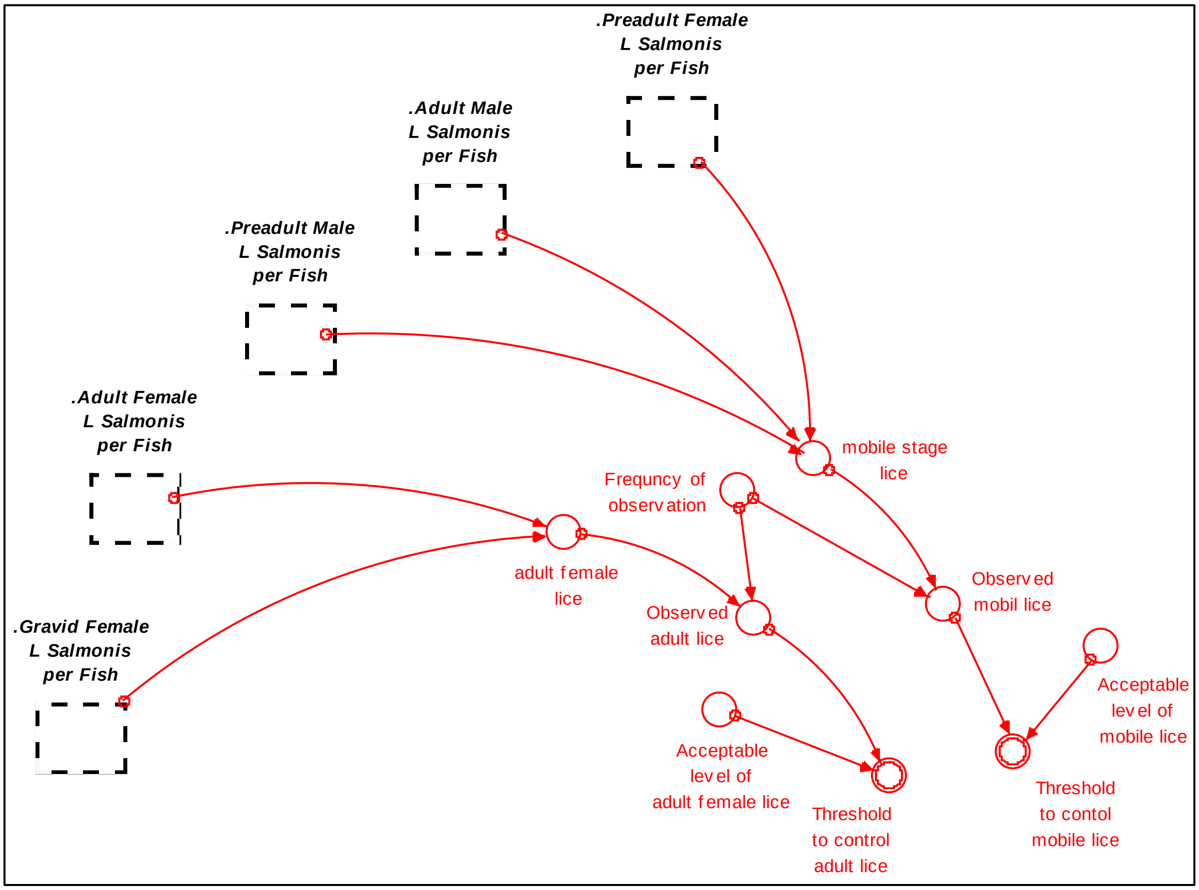


Figure 25: the structure of sea lice sampling process

- **Teflubenzuron**

This module shows the procedure of using teflubenzuron (in-feed treatment to control sea lice) to control sea lice population in fish cage. Figure 26 shows the structure of this module.

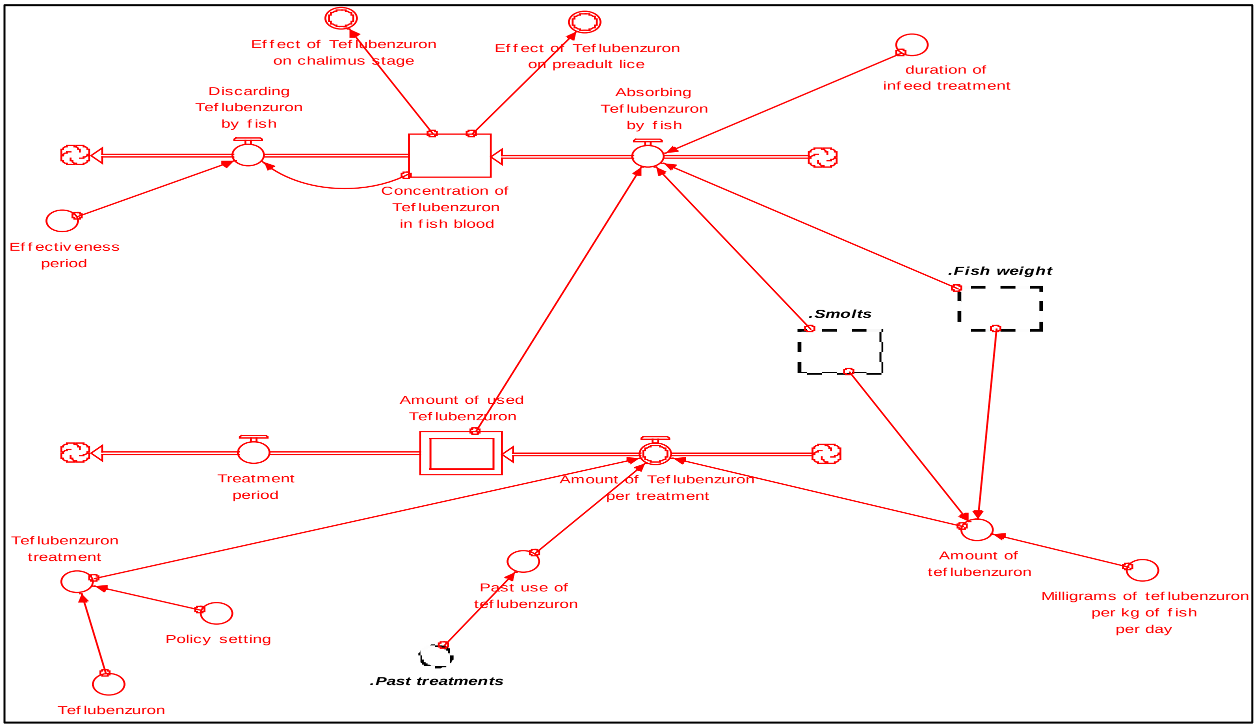


Figure 26: the procedure of using teflubenzuron to control sea lice

There are two ways to introduce in-feed treatment to the model: (1) through forcing past treatments to the model, and (2) manually by allowing the user to choose the type and timing of a treatment. When teflubenzuron treatment is used, the amount of in-feed treatment is introduced to the model. It should be noted that the amount is per day and in-feed treatment occurs for 7 consecutive days, thus inside the flow equation (amount of teflubenzuron per treatment) the value is multiplied by 7. We used "oven" concept to save the whole amount of feed for 7 days and then the content of "oven" is divided by "duration[11] of in-feed treatment" to ensure that the oven content is divided by 7 when given to fish. The content of the "oven" gets empty after 7 days (that is, duration of in-feed treatment).

The level of treatment effectiveness depends on the concentration of in-feed medicines (teflubenzuron) in fish blood. The concentration of in-feed treatment in fish blood increases through absorbing (eating) in-feed medicines (teflubenzuron) by fish and decreases through discarding it. Stocks of smolts and fish weight are added to convert the amount of medicine used for the whole pen to one fish because we are modeling lice/fish (one fish).

---

[11] 7 days

- **Emamectinbenzoat**

This is another in-feed treatment used as a sea lice treatment in salmon farms. Figure 27 shows the structure of emamectinbenzoat module. Both emamectinbenzoat and teflubenzuron have the same structure but the only difference is emamectinbenzoat has a longer effectiveness period than teflubenzuron. In addition to that, the amount of emamectinbenzoat used for in-feed treatment is determined as 50 mg of emamectinbenzoat per 1 kg of fish. But for teflubenzuron is 10 mg of teflubenzuron per 1 kg of fish.

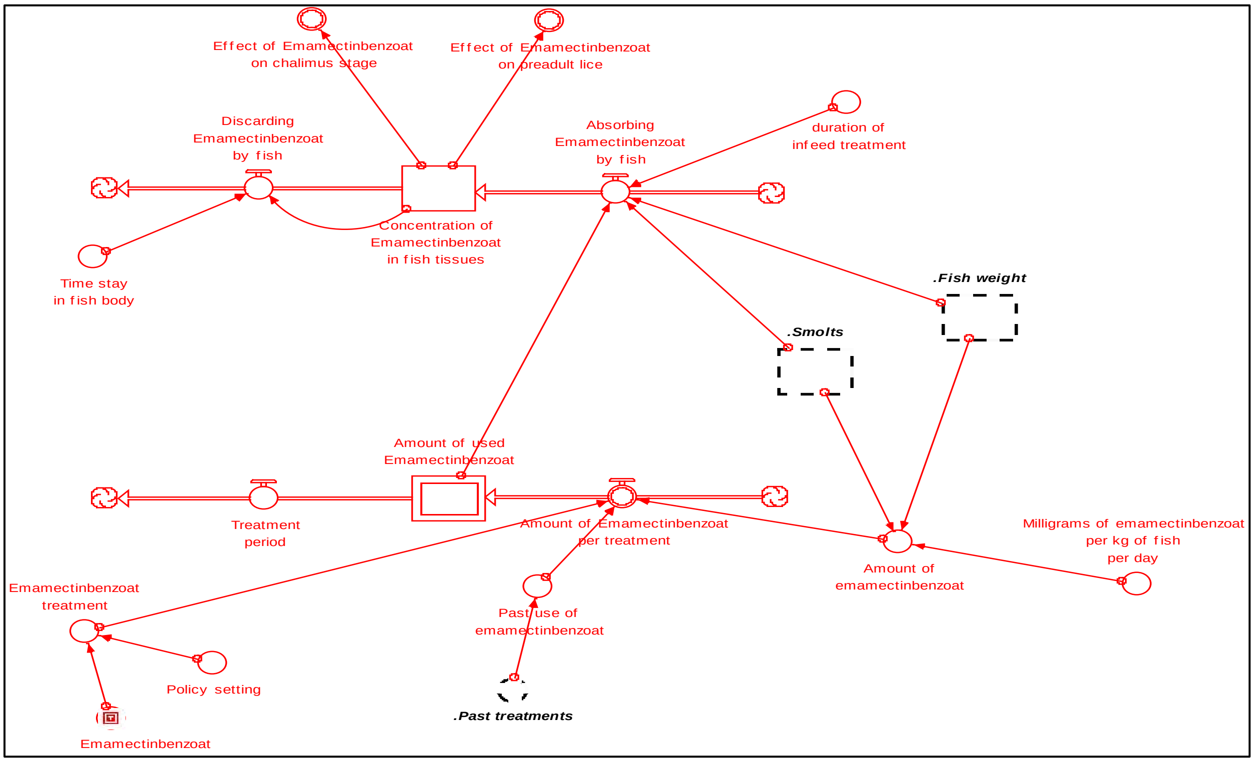


Figure 27: the procedure of using emametinbenzoat to control sea lice

- **Hydrogenperoxide**

Hydrogneperoxide is a chemical treatment used to treat sea lice in salmon farms. Figure 28 shows the structure of hydrogenperoxid module.

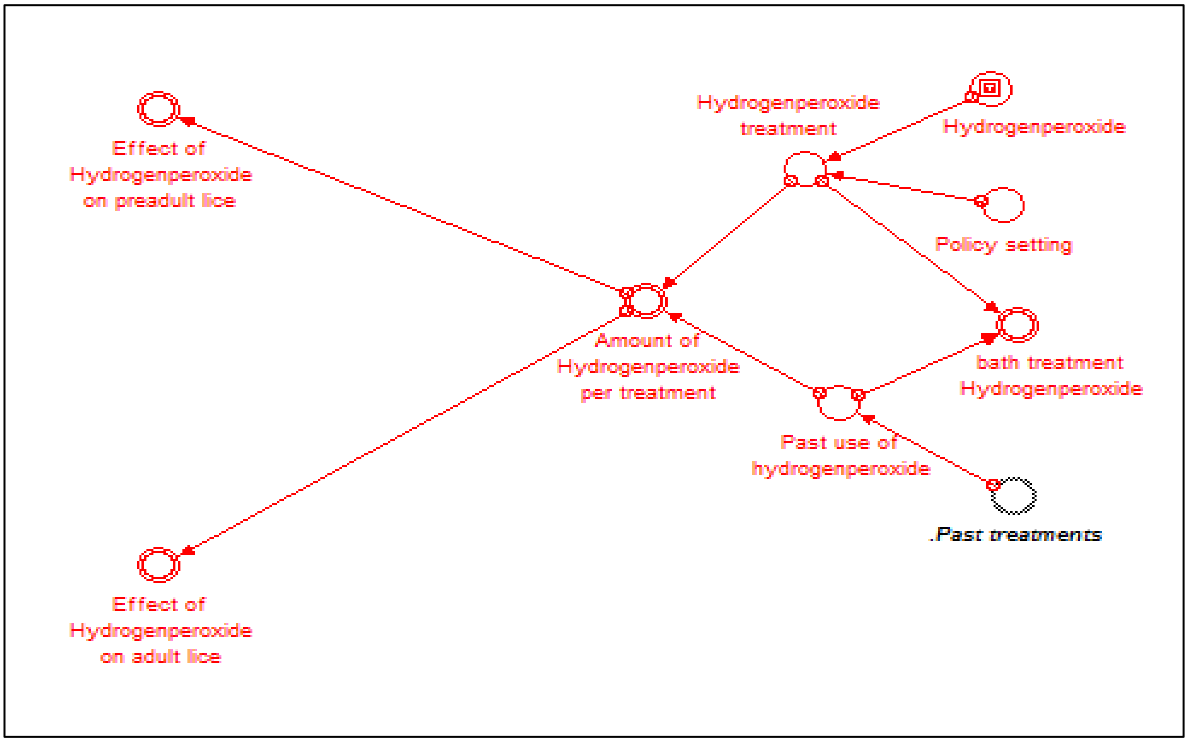


Figure 28: the procedure of using hydrogenperoxide to control sea lice

There are two ways to introduce hydrogenperoxide treatment to the model: (1) through forcing past treatments to the model, and (2) manually by allowing the user to choose the type and timing of a treatment. When hydrogenperoxide treatment is used, a fixed amount of hydrgenperoxide will be used. The effectiveness of chemical treatments is instantaneous. The duration of chemical treatment effectiveness is one day.

- **Deltamethrin**

Deltamethrin is another chemical treatment use to treat sea lice in salmon farms. All chemical treatments have similar structure. They only differ in effectiveness and amount of used chemicals. Figure 29 shows the structure of deltamethrin module.

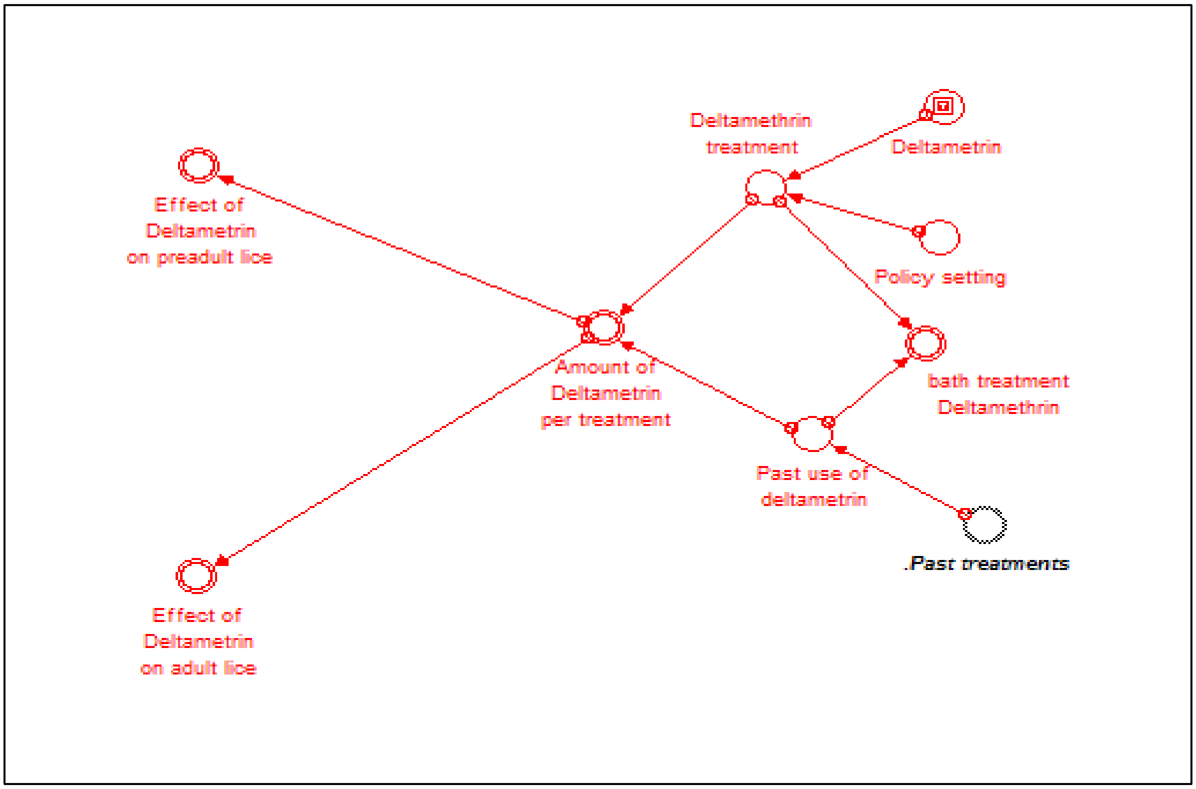


Figure 29: the procedure of using deltamethrin to control sea lice

- **Azamethiphos**

Azamethiphos is another chemical treatment to treat sea lice in salmon farms. Figure 30 shows the structure of azamethiphos module.

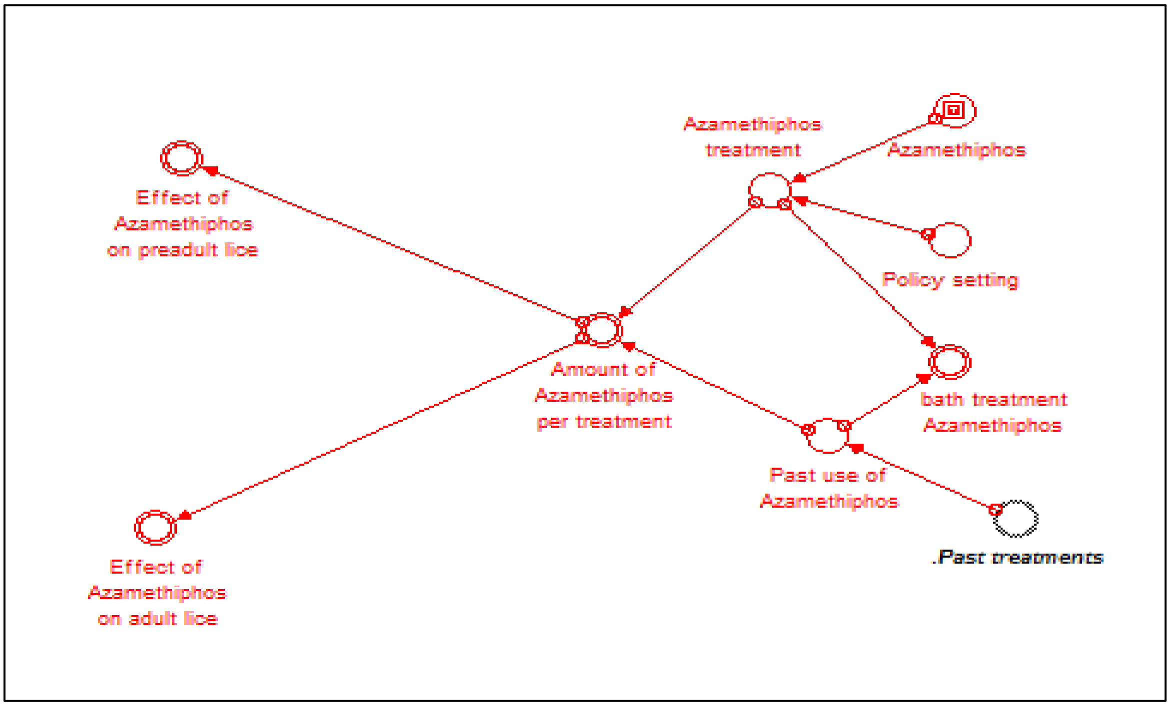


Figure 30: the procedure of using azamethiphos to control sea lice

- **Treatment Effectiveness**

Treatment effectiveness modeule put together treatment effectiveness of each treatment. The purpose of this module is to simplify main model structure. Figure 31 shows the structure of treatment effectiveness module.

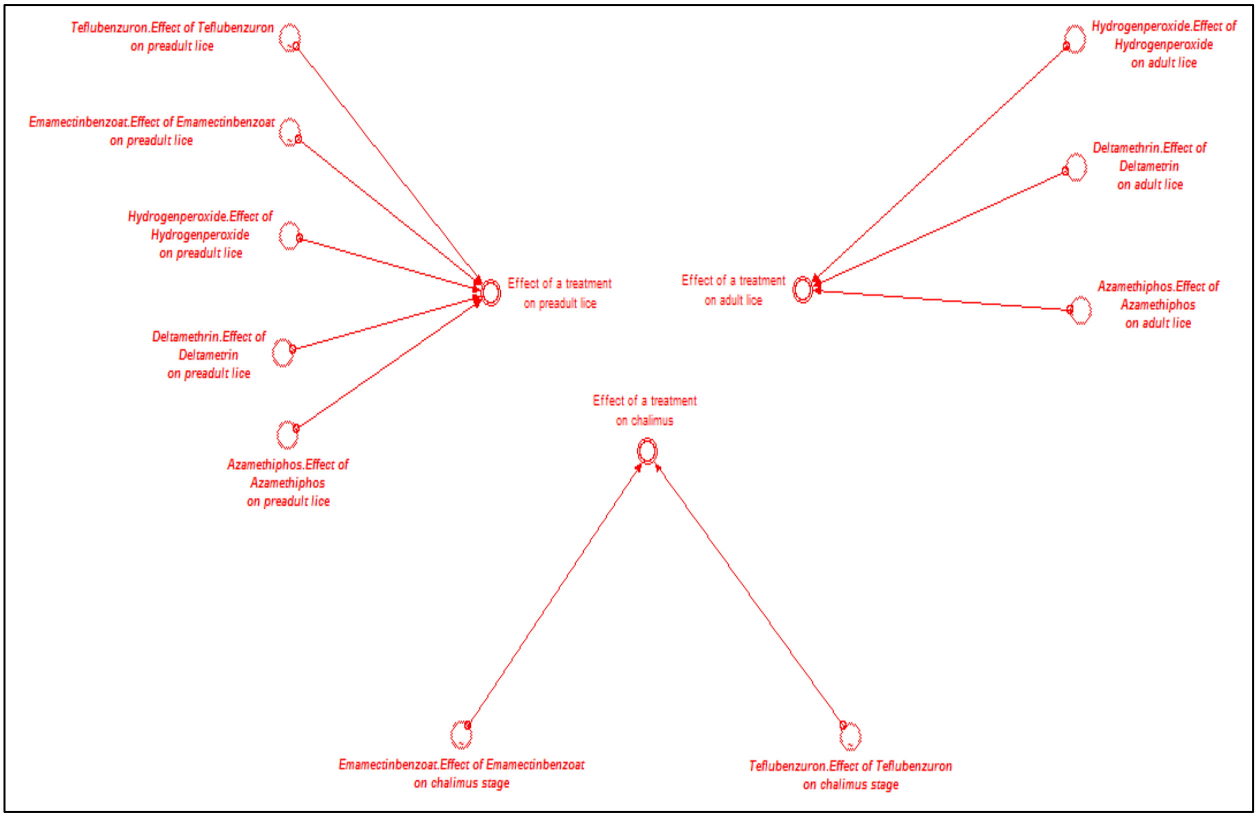


Figure 31: effect of treatments on sea lice

Appendix 4: Model Equations

Adult Female L Salmonis per Fish (t) = Adult Female L Salmonis per Fish (t - dt) + (Become Adult Female – Become Gravid – Adult female Deaths) * dt

INIT Adult Female L Salmonis per Fish = 0.00001+0.000001

{Lice/fish}

INFLOWS:

Become Adult Female = Preadult Female L Salmonis per Fish/Time Spent in Preadult Female Stage

{Lice/fish/day}

OUTFLOWS:

Become Gravid = Adult Female L Salmonis per Fish*Male and female mating. Effect of adult male and female lice on lice pregnancy rate

{Lice/fish/day}

Adult female Deaths = ((Adult Female L Salmonis per Fish/Time Spent in Adult Stage)+(Adult Female L Salmonis per Fish*Adult mortality rate))

{Lice/fish/day}

Adult Male L Salmonis per Fish (t) = Adult Male L Salmonis per Fish (t - dt) + (Become Adult Male – Male Natural Deaths – Adult male deaths) * dt

INIT Adult Male L Salmonis per Fish = 0.2+0.000001

{Lice/fish}

INFLOWS:

Become Adult Male = Preadult Male L Salmonis per Fish/Time Spent in Preadult Male Stage

{Lice/fish/day}

OUTFLOWS:

Male Natural Deaths = Adult Male L Salmonis per Fish/Adult Stage Period

{Lice/fish/day}

Adult male deaths = (Adult Male L Salmonis per Fish*Adult mortality rate)

{Lice/fish/day}

Chalimus L Salmonis (t) = Chalimus L Salmonis (t - dt) + (Chalimus Production – Become Female Preadult – Become Male Preadult – Chalimus Deaths) * dt

INIT Chalimus L Salmonis = 0

{Lice/fish}

INFLOWS:

Chalimus Production = ((((DELAY (Lice egg Production, Time to Hatch)*Lice Eggs Hatching Effectiveness))

+External infection pressure)*(IF (Smolts>0) then (1) else (0)))

{Lice/fish/day}

OUTFLOWS:

Become Female Preadult = ((Chalimus L Salmonis/Time spent in chalimus stage)*Female Fraction)*Validation 2

{Lice/fish/day}

Become Male Preadult = ((Chalimus L Salmonis/Time spent in chalimus stage)*Female Fraction)*Validation 1

{Lice/fish/day}

Chalimus Deaths = (Chalimus L Salmonis*Chalimus Mortality rate)

{Lice/fish/day}

Cumulative costs of treatments (t) = Cumulative costs of treatments (t - dt) + (Change in cumulative costs) * dt

INIT Cumulative costs of treatments = 0

{NOK}

INFLOWS:

Change in cumulative costs = Material Costs+Operational costs for bath treatments+Daily capital cost+ Costs of fish losses due to treatments

{NOK/day}

Cumulative loss of fish weight due to treatments (t) = Cumulative loss of fish weight due to treatments (t - dt) + (Change in cumulative loss of fish weight – Loss of fish weight due to starvation) * dt

INIT Cumulative loss of fish weight due to treatments = 0

{Kg}

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:

Change in cumulative loss of fish weight = (Average weight loss at each treatment*Starvation prior to bath treatment*Smolts) + Loss of fish weight due to deaths because of treatments

{Kg/day}

OUTFLOWS:

Loss of fish weight due to starvation = CONVEYOR OUTFLOW

TRANSIT TIME = 561-time

{Kg/day}

Fish weight (t) = Fish weight (t - dt) + (Gaining weight) * dt

INIT Fish weight = 0.13

{Kg/fish}

INFLOWS:

Gaining weight = (Daily feeding amount*Exogenous feeding data + daily feed*Endogenous feeding)/feed conversion ratio/Smolts

{Kg/fish/day}

Gravid Female L Salmonis per Fish (t) = Gravid Female L Salmonis per Fish (t - dt) + (Become Gravid - Deaths – Gravid female deaths) * dt

INIT Gravid Female L Salmonis per Fish = 0

{Lice/fish}

INFLOWS:

Become Gravid = Adult Female L Salmonis per Fish*Male and female mating. Effect of adult male and female lice on lice pregnancy rate

{Lice/fish/day}

OUTFLOWS:

Deaths = (Gravid Female L Salmonis per Fish/Time Spent in Adult Stage)

{Lice/fish/day}

Gravid female deaths = (Gravid Female L Salmonis per Fish*Adult mortality rate)

{Lice/fish/day}

Preadult Female L Salmonis per Fish (t) = Preadult Female L Salmonis per Fish (t - dt) + (Become Female Preadult – Become Adult Female – Preadult Female Deaths) * dt

INIT Preadult Female L Salmonis per Fish = 0.6

{Lice/fish}

INFLOWS:

Become Female Preadult = ((Chalimus L Salmonis/Time spent in chalimus stage)*Female Fraction)*Validation 2

{Lice/fish/day}

OUTFLOWS:

Become Adult Female = Preadult_Female__L_Salmonis_per_Fish/Time_Spent_in_Preadult_Female_Stage

{Lice/fish/day}

Preadult Female Deaths = Preadult Female L Salmonis per Fish*Preadult Mortality Rate

{Lice/fish/day}

Preadult Male L Salmonis per Fish (t) = Preadult Male L Salmonis per Fish (t - dt) + (Become Male Preadult – Become Adult Male – Preadult Male Deaths) * dt

INIT Preadult Male L Salmonis per Fish = 0.41

{Lice/fish}

INFLOWS:

Become Male Preadult = ((Chalimus L Salmonis/Time spent in chalimus stage)*Female Fraction)*Validation 1

{Lice/fish/day}

OUTFLOWS:

Become Adult Male = Preadult Male L Salmonis per Fish/Time Spent in Preadult Male Stage

{Lice/fish/day}

Preadult Male Deaths = (Preadult Male L Salmonis per Fish*Preadult Mortality Rate)

{Lice/fish/day}

Smolts (t) = Smolts (t - dt) + (Smoltification - Maturation – Smolt stage deaths) * dt

INIT Smolts = 0.00001

{Fish}

TRANSIT TIME = 518

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:

Smoltification = Initial Smolt input into the farms

{Fish/day}

OUTFLOWS:

Maturation = CONVEYOR OUTFLOW

Smolt stage deaths = LEAKAGE OUTFLOW

LEAKAGE FRACTION = (Smolt stage fractional death rate)

{Fish/day}

NO LEAK ZONE = 0

Adult mortality rate = Treatment Effectiveness. Effect of a treatment on adult lice

{1/day}

Amount of feed saved due to treatments = daily feed*Starvation prior to bath treatment

{KgFeed/day}

Average weight loss at each treatment = 0.022

{Kg/day}

Chalimus Mortality rate = Chalimus Normal Mortality Rate+Treatment Effectiveness. Effect of a treatment on chalimus

{1/day}

Change in smolt stage fractional death rate due to treatments = IF (Treatment preparation time>0) THEN (0.00014) ELSE (0)

{1/day}

Costs of fish losses due to treatments = ((Loss of fish weight due to starvation)*Fish price per kg)-Feed money saved

{NOK/day}

Cutting Female Population Loop = 1

{Unitless}

Cutting Lice Egg Production Loop = 1

{Unitless}

Cutting Male Population Loop = 1

{Unitless}

Daily feed = (((Growth index*Smolts)/1000)*(Stop feeding))*Starvation prior harvesting

{KgFeed/day}

Daily capital cost = Cumulative costs of treatments*Interest rate

{NOK/day}

Endogenous feeding = 0

{Unitless}

Endogenous Policy Model = 0

{Unitless}

Exogenous feeding data = 1

{Unitless}

External infection pressure = (Normal external infection pressure*Effect of temperature on external infection pressure)*Validation 3

{Lice/fish/day}

Feed money saved = Delay ((Amount of feed saved due to treatments*Feed price per kg), 5)

{NOK/day}

Feed price per kg = 9.2

{NOK/kgFeed}

Female Fraction = 0.5

{Unitless}

Fish price per kg = 25

{NOK/kg}

Growth index = (Impact of daily water temperature on feed amount*Effect of fish size on feeding)*feed conversion ratio*Fish weight

{GmFeed/fish/day}

Influence of treatment on feeding = Delay3 (Azamethiphos.bath treatment Azamethiphos+Deltamethrin.bath treatment Deltamethrin+Hydrogenperoxid.bath treatment Hydrogenperoxide, 5)

Initial Smolt input into the farms = ((STEP (170399, 43)-STEP (170399, 44)))

Interest rate = 0.00014

{1/day}

Lice egg Production = ((Gravid Female L Salmonis per Fish*Number of Eggs per Gravid Female per day))*Validation

{Egg/day}

Loss of fish weight due to deaths because of treatments = (Smolts*Change in smolt stage fractional death rate due to treatments)*Fish weight

{Kg/day}

Material Costs = (Azamethiphos. Amount of Azamethiphos per treatment*Price of Azamethiphos per kg) + (Deltamethrin. Amount of Deltametrin per treatment*Price of Deltamathrin per ml) + (Emamectinbenzoat. Amount of Emamectinbenzoat per treatment*Price of Emamectinbenzoat per gm) + (Hydrogenperoxid. Amount of Hydrogenperoxide per treatment*Price of Hydrogen Peroxide per liter) + (Teflubenzuron. Amount of Teflubenzuron per treatment*Price of Teflubenzuron per gm)

{NOK/day}

Normal external infection pressure = 0.1

{Lice/fish/day}

No policy = 1

{Unitless}

No validation = IF (Validation Switch) = 1Then (1) Else (Validation setting)

{Unitless}

Number of Eggs per Gravid Female per day = 50

{Egg/lice/fish/day}

Of = IF (Past Policy Model=0) then (0) else (1)

{Unitless}

Operational costs for bath treatments = If (Azamethiphos. Amount of Azamethiphos per treatment + Deltamethrin. Amount of Deltametrin per treatment + Hydrogenperoxid. Amount of Hydrogenperoxide per treatment)>0 Then (43690) Else (0)

{NOK/day}

Past treatments = ((If(INT(time)=78)then(4)else(0)+(IF(INT(TIME)=126)THEN(2)ELSE(0))+(IF(INT(TIME)=377)THEN(3)ELSE(0))+(IF(INT(TIME)=397)THEN(4)ELSE(0))+(IF(INT(TIME)=464)THEN(5)ELSE(0))))*Of

{Unitless}

Past Policy Model = 1

{Unitless}

Policy Setting = 1

{Unitless}

Policy Switch1 = (if(Past Policy Model=1)then(0)else(Policy Setting*Endogenous Policy Model))*(if(No policy=1)then(0)else(1))

{Unitless}

Preadult Mortality Rate = preadult stages mortality rate Stage + Treatment Effectiveness. Effect of a treatment on preadult lice

{1/day}

Price of Hydrogenperoxide per liter = 67

{NOK/liter}

Price of Azamethiphos per kg = 18993

{NOK/kg}

Price of Deltamethrin per ml = 22

{NOK/ml}

Price of Emamectinbenzoat per gm = 2.67

{NOK/gm}

Price of Teflubenzuron per gm = 29.7

{NOK/gm}

Removing External Infection pressure = 1

{Unitless}

Setting = 1

{Unitless}

Smolt stage fractional death rate = 0.00014 + (IF (Treatment preparation time) = 1Then (0.00014) else (0))

{1/day}

Starvation prior to bath treatment = IF (Azamethiphos. Bath treatment Azamethiphos + Deltamethrin. bath treatment Deltamethrin + Hydrogenperoxid. Bath treatment Hydrogenperoxide>0) THEN (5) ELSE (0)

{Unitless}

Starvation prior harvesting = If (561-time) < 20 Then (0) else (1)

Stop feeding = If (Influence of treatment on feeding) > 0.05 Then (0) Else (1)

{Unitless}

Threshold to launch a treatment = IF (Lice sampling. Threshold to control adult lice + Lice sampling. Threshold to control mobile lice) > 0 Then (pause) ELSE (0)

{Unitless}

Treatment preparation time = Delay (Azamethiphos. bath treatment Azamethiphos + Deltamethrin. bath treatment Deltamethrin + Hydrogenperoxid. bath treatment Hydrogenperoxide, 5)

{Unitless}

Validation = (IF (Cutting Lice Egg Production Loop) = 1 Then (0) ELSE (Setting))*No validation

{Unitless}

Validation 1 = (IF (Cutting Male Population Loop) = 1 Then (0) ELSE (Setting))*No validation

{Unitless}

Validation 2 = (IF (Cutting Female Population Loop) = 1Then (0) ELSE (Setting))*No validation

{Unitless}

Validation 3 = (IF (Removing External Infection pressure) = 1Then (0) ELSE (Setting))*No validation

{Unitless}

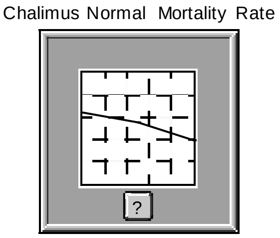
Validation setting = 1

{Unitless}

Validation Switch = 1

{Unitless}

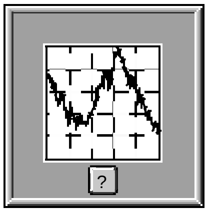
Chalimus Normal Mortality Rate = GRAPH (daily temperature)



{1/day}

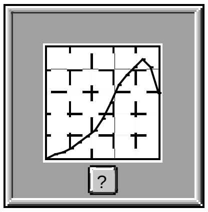
Daily temperature = GRAPH (TIME)

daily temperature



Effect of temperature on external infection pressure = GRAPH (daily temperature)

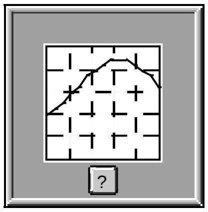
Effect of temperature on external infection pressure



{Unitless}

Lice Eggs Hatching Effectiveness = GRAPH (daily temperature)

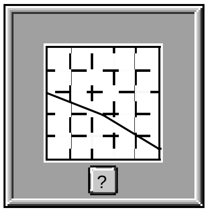
Lice Eggs Hatching Effectiveness



{Lice/egg/fish}

Preadult stages mortality rate = GRAPH (daily temperature)

preadult stages mortality rate



{1/day}

Azamethiphos:

Amount of Azamethiphos per treatment = Delay ((IF (Azamethiphos treatment + Past use of Azamethiphos) = 1Then (5) ELSE (0)), 5)

{Kg/day}

Azamethiphos = 1

{Unitless}

Azamethiphos treatment = IF (Azamethiphos) = 1Then (1) ELSE (Policy setting)

{Unitless}

Bath treatment Azamethiphos = Azamethiphos treatment + Past use of Azamethiphos

{Unitless}

Effect of Azamethiphos on adult lice = IF (Amount of Azamethiphos per treatment)>1 then (0.88) ELSE (0)

{1/day}

Effect of Azamethiphos on preadult lice = IF (Amount of Azamethiphos per treatment)>1 Then (0.88) ELSE (0)

{1/day}

Interface 5 = If (Azamethiphos treatment)>0 Then (pause) else (0)

{Unitless}

Past use of Azamethiphos = If (.Past treatments=3) then (1) else (0)

{Unitless}

Policy setting = 0

{Unitless}

Deltamethrin:

Amount of Deltametrin per treatment = Delay ((IF (Deltamethrin treatment + Past use of deltametrin) = 1Then (4000) ELSE (0)), 5)

{ml/day}

Bath treatment Deltamethrin = Deltamethrin treatment + Past use of deltametrin

{Unitless}

Deltamethrin treatment = IF (Deltametrin) = 1Then (1) ELSE (Policy setting)

{Unitless}

Deltametrin = 1

{Unitless}

Effect of Deltamethrin on adult lice = IF (Amount of Deltamethrin per treatment)>0 then (0.93) ELSE (0)

{1/day}

Effect of Deltamethrin on preadult lice = IF (Amount of Deltametrin per treatment)>0 Then (0.93) ELSE (0)

{1/day}

Interface 4 = If (Deltamethrin treatment)>0 Then (pause) else (0)

{Unitless}

Past use of deltametrin = If (.Past treatments) = 5 then (1) else (0)

{Unitless}

Policy setting = 0

{Unitless}

Emamectinbenzoat:

Amount of used Emamectinbenzoat (t) = Amount of used Emamectinbenzoat (t - dt) + (Amount of Emamectinbenzoat per treatment – Treatment period) * dt

INIT Amount of used Emamectinbenzoat = 0

{gm}

COOK TIME = 7

CAPACITY = INF

FILL TIME = 1

INFLOWS:

Amount of Emamectinbenzoat per treatment = (Amount of emamectinbenzoat*7*(Emamectinbenzoat treatment + Past use of emamectinbenzoat))/1000

{gm/day}

OUTFLOWS:

Treatment period = CONTENTS OF OVEN AFTER COOK TIME, ZERO OTHERWISE

Concentration of Emamectinbenzoat in fish tissues (t) = Concentration of Emamectinbenzoat in fish tissues (t - dt) + (Absorbing Emamectinbenzoat by fish – Discarding Emamectinbenzoat by fish) * dt

INIT Concentration of Emamectinbenzoat in fish tissues = 0

{gm/kg}

INFLOWS:

Absorbing Emamectinbenzoat by fish = Delay ((((Amount of used Emamectinbenzoat/duration of infeed treatment)/.Smolts)/.Fish_weight), 3)

{gm/day/kg}

OUTFLOWS:

Discarding Emamectinbenzoat by fish = Concentration of Emamectinbenzoat in fish tissues/Time stay in fish body

{gm/day}

Amount of emamectinbenzoat = .Fish weight*Milligrams of emamectinbenzoat per kg of fish per day*.Smolts

{mg/day}

Duration of infeed treatment = 7

{day}

Emamectinbenzoat = 1

{Unitless}

Emamectinbenzoat treatment = IF (Emamectinbenzoat) =1Then (1) ELSE (Policy setting)

{Unitless}

Interface 2 = IF (Emamectinbenzoat treatment>0) then (pause) else(1)

{Unitless}

Milligrams of emamectinbenzoat per kg of fish per day = 50

{mg/kg/day}

Past use of emamectinbenzoat = If (.Past_treatments) = 2 Then (1) Else (0)

{Unitless}

Policy setting = 0

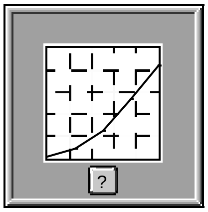
{Unitless}

Time stay in fish body = 16

{day}

Effect of Emamectinbenzoat on chalimus stage = GRAPH (Concentration of Emamectinbenzoat in fish tissues

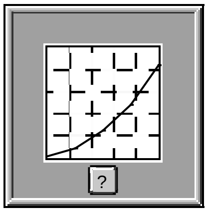
Emamectinbenzoat.Effect of Emamectinbenzoat on chalimus stage



{1/day})

Effect of Emamectinbenzoat on preadult lice = GRAPH (Concentration of Emamectinbenzoat in fish tissues

Emamectinbenzoat.Effect of Emamectinbenzoat on preadult lice



{1/day})

Hydrogenperoxid:

Amount of Hydrogenperoxide per treatment = Delay ((IF (Hydrogenperoxide treatment + Past use of hydrogenperoxide) = 1Then (5000) ELSE (0)), 5)

{Liter/day}

Bath treatment Hydrogenperoxide = Hydrogenperoxide treatment + Past use of hydrogenperoxide

{Unitless}

Effect of Hydrogenperoxide on adult lice = IF (Amount of Hydrogenperoxide per treatment)>0 then (0.86) ELSE (0)

{1/day}

Effect of Hydrogenperoxide on preadult lice = IF (Amount of Hydrogenperoxide per treatment)>0 Then (0.86) ELSE (0)

{1/day}

Hydrogenperoxide = 1

{Unitless}

Hydrogenperoxide treatment = IF (Hydrogenperoxide) = 1Then (1) ELSE (Policy setting)

{Unitless}

Interface 3 = If (Hydrogenperoxide treatment)>0 Then (pause) else (0)

{Unitless}

Past use of hydrogenperoxide = If (.Past treatments) =1 Then (1) Else (0)

{Unitless}

Policy setting = 0

{Unitless}

Lice sampling:

Acceptable level of mobile lice = 5

{Lice/fish}

Acceptable level of adult female lice = 1

{Lice/fish}

Adult female lice = .Adult Female L Salmonis per Fish + .Gravid Female L Salmonis per Fish

{Lice/fish}

Frequncy of observation = 15

{day}

Lice per fish = mobile stage lice + Adult female lice

{Lice/fish}

Lice threshold adjustment Jan to Aug = IF (time) = (127*.Policy Switch1) Then (pause) Else (0)

Lice threshold adjustment Jan to Aug 1 = IF (time) = (493*.Policy Switch1) Then (pause) Else (0)

Lice threshold adjustment Sep to Dec = If (time) = (370*.Policy Switch1) Then (pause) Else (0)

Mobile stage lice = .Preadult Male L Salmonis per Fish + .Adult Male L Salmonis per Fish + .Preadult Female L Salmonis per Fish

{Lice/fish}

Observed adult lice = PULSE (adult female lice, 15, frequency of observation)

{Lice/fish}

Observed mobile lice = PULSE (mobile stage lice, 15, frequency of observation)

{Lice/fish}

Threshold to control adult lice = (MAX (Observed adult lice-Acceptable level of adult female lice, 0))*.Policy Switch1

{Lice/fish}

Threshold to control mobile lice = (MAX (Observed mobile lice-Acceptable level of mobile lice, 0))*.Policy Switch1

{Lice/fish}

Male and female mating:

Effect of adult male and female lice on lice pregnancy rate = Effect of total number of adult lice on lice pregnancy rate*Effect of male to female ratio on lice pregnancy rate

{1/day}

Male to female ratio = .Adult Male L Salmonis per Fish/.Adult Female L Salmonis per Fish

{Unitless}

Total number of adult lice = .Adult Female L Salmonis per Fish + .Adult Male L Salmonis per Fish

{Lice/fish}

Teflubenzuron:

Amount of used Teflubenzuron (t) = Amount of used Teflubenzuron (t - dt) + (Amount of Teflubenzuron per treatment – Treatment period) * dt

INIT Amount of used Teflubenzuron = 0

{gm}

COOK TIME = 7

CAPACITY = INF

FILL TIME = 1

INFLOWS:

Amount of Teflubenzuron per treatment = (Amount of teflubenzuron*7*(Teflubenzuron treatment + Past use of teflubenzuron)/1000)

{gm/day}

OUTFLOWS:

Treatment period = CONTENTS OF OVEN AFTER COOK TIME, ZERO OTHERWISE

Concentration of Teflubenzuron in fish blood (t) = Concentration of Teflubenzuron in fish blood (t - dt) + (Absorbing Teflubenzuron by fish – Discarding Teflubenzuron by fish) * dt

INIT Concentration of Teflubenzuron in fish blood = 0

{gm/kg}

INFLOWS:

Absorbing Teflubenzuron by fish = Delay ((((Amount of used Teflubenzuron/duration of infeed treatment)/.Fish weight)/.Smolts), 3)

{gm/day/kg}

OUTFLOWS:

Discarding Teflubenzuron by fish = Concentration of Teflubenzuron in fish blood/Effectiveness period

{gm/day/kg}

Amount of teflubenzuron = .Fish weight*Milligrams of teflubenzuron per kg of fish per day*.Smolts

{mg/day}

Duration of infeed treatment = 7

{day}

Effectiveness period = 11

{day}

Interface = IF (Teflubenzuron treatment>0) then (pause) else (0)

{Unitless}

Milligrams of teflubenzuron per kg of fish per day = 10

{mg/kg/day}

Past use of teflubenzuron = (IF (.Past treatments=4) then (1) else (0))

{Unitless}

Policy setting = 0

{Unitless}

Teflubenzuron = 1

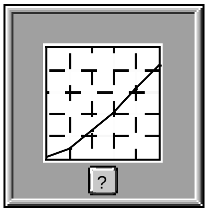
{Unitless}

Teflubenzuron treatment = IF (Teflubenzuron) = 1 Then (1) ELSE (Policy setting)

{Unitless}

Effect of Teflubenzuron on chalimus stage = GRAPH (Concentration of Teflubenzuron in fish blood)

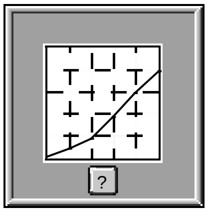
Teflubenzuron.Effect of Teflubenzuron on chalimus stage



{1/day}

Effect of Teflubenzuron on preadult lice = GRAPH (Concentration of Teflubenzuron in fish blood)

Teflubenzuron.Effect of Teflubenzuron on preadult lice



{1/day}

Treatment Effectiveness:

Effect of a treatment on chalimus = Emamectinbenzoat.Effect of Emamectinbenzoat on chalimus stage + Teflubenzuron.Effect of Teflubenzuron on chalimus stage

{1/day}

Effect of a treatment on adult lice = Azamethiphos.Effect of Azamethiphos on adult lice + Deltamethrin.Effect of Deltametrin on adult lice + Hydrogenperoxid.Effect of Hydrogenperoxyd on adult lice

{1/day}

Effect of a treatment on preadult lice = Deltamethrin.Effect of Deltametrin on preadult lice + Emamectinbenzoat.Effect of Emamectinbenzoat on preadult lice + Hydrogenperoxid.Effect of Hydrogenperoxyd on preadult lice + Teflubenzuron.Effect of Teflubenzuron on preadult lice + Azamethiphos.Effect of Azamethiphos on preadult lice

{1/day}

Appendix 5: Validation Tests and Analysis

In this appendix, we report validation tests that are conducted to check the robustness of the model. The following validation tests are conducted: (1) phase validity, (2) unit consistency, (3) reference model comparison, (4) structure-behavior test, and (5) extreme condition test.

- **Phase Validity**

Veterinarian experts from Norwegian School of Veterinary Science reviewed the model structure and outputs during the process of building this model through presentations and internal meetings. The model structure and output were also presented to the international partners (academic and industrial) of SALMODIS projects at different stages of the model building process through two workshops held in Norway in May (Oslo) and October (Trondheim) 2011. Industrial partners of SALMODIS project were part of the model review process and provided comments on the model structure and the feasibility of model application for salmon industries. Thus, the experts in the field reviewed the model and provided comments on the structure and outputs of the model, which in turn improves the credibility of the model.

- **Unit Consistency**

The equations and units that are used in the model are shown in Appendix 3. Please refer to Appendix three to review unit consistency. A few table (graph) functions are not reported because they are confidential information and we are not allowed to report.

- **Reference Mode Comparison**

Reference mode comparison with model output for adult female lice and mobile stage lice is shown in figures 32 and 33, respectively. The model output did capture the population peaks of both adult female and mobile stage lice. Capturing sea lice population peaks improves the validity of the model and increases model credibility to base policy options on. But the model output (for both adult female and mobile stage lice) did not show perfect fit to the data. However, capturing population peaks is more important than the accuracy of fit because the data that are used for reference mode include sampling errors.

That is, industries take small fish sample to count sea lice on fish, 10 fish out of about 170 thousand fish per cage. The data that are used are based on discrete sampling events; therefore it is not known how lice population trend between two samples are. But the simulation results are continuous and thus capturing population peaks give us a good indication about approximate lice population size in a continuous manner which allows us to evaluate different policy options. Therefore, capturing population peaks is sufficient to evaluate the robustness of the model.

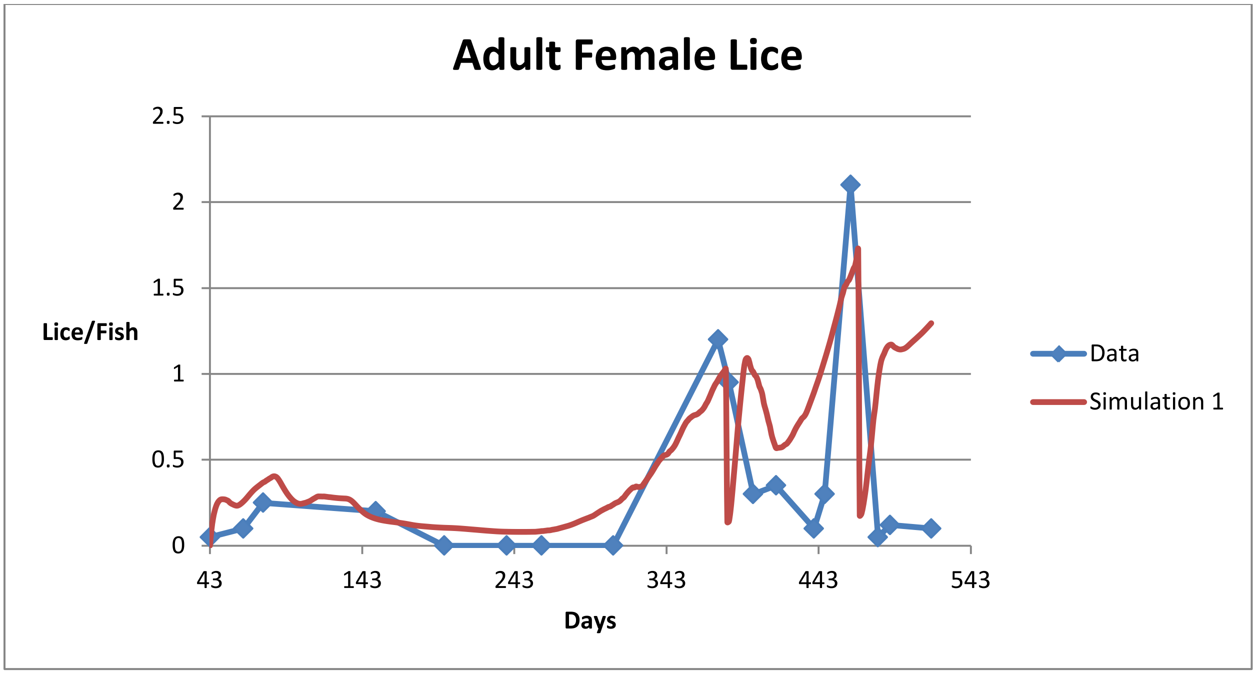


Figure 32: reference mode comparison (adult female lice)

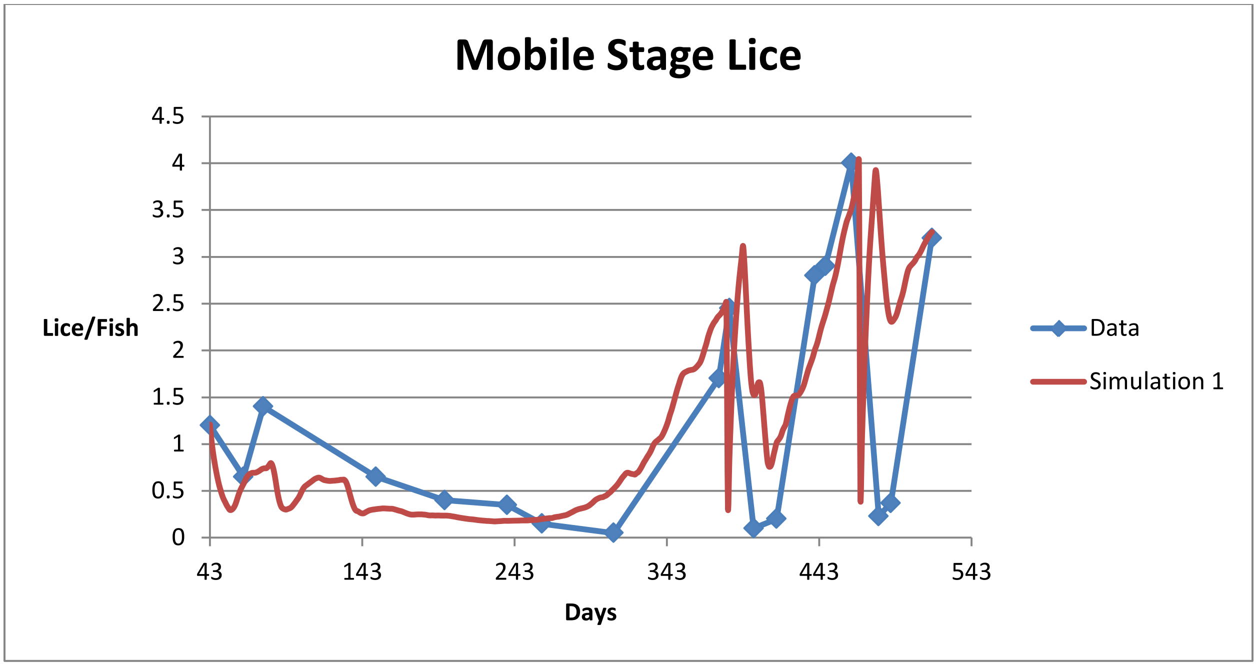


Figure 33: reference mode comparison (mobile stage lice)

- **Structure-behavior Test**

We conducted a few structure-behavior tests to evaluate the source of model behavior. We cut different feedback loops to identify the dominance feedback loop(s) that has the most influence on model behavior and to identify whether the model behavior is generated endogenously or exogenously. We compare simulation outputs of these tests with simulation 1 (i.e. simulation to replicate reference mode) outputs. Figure 34 shows the places that these tests are conducted.

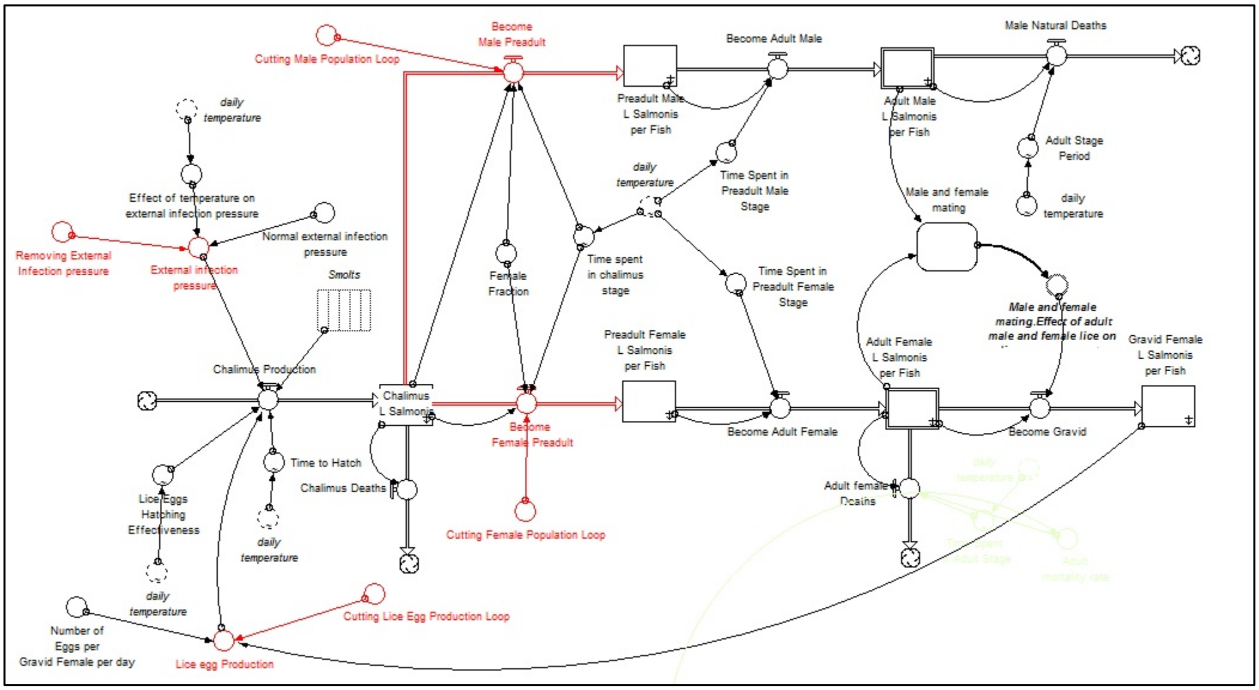


Figure 34: feedback loops that were subject to structure-behavior test

The following structure-behavior tests were conducted:

1- *Removing External Infection Pressure*

By removing external infection pressure we assume that there are no external sources of sea lice infection. In this case, lice infection should not occur because fish is louse free when first introduced to the open sea cages and initially fish gets infected from outside sources before internal reproduction process takes over. Therefore, by assuming no external infection pressure fish should remain lice free until harvest time. However, in order to conduct this test we must set initial value of stocks to zero because that model starts in day 43 (i.e. because the first lice report was available in day 43) and we initialized stocks based on data reported in day 43. Though, we keep the initial value of both stocks "adult male L. Salmonis" and "adult female L. Salmonis" slightly over zero to avoid division by zero when we run the model.

It is also important to set policy setting to "no policy" from the interface to ensure that there would not be any external influence that declines lice population. It should be noted removing external infection pressure means sea lice will not occur and therefore fish grows normally (i.e. no starvation because of chemical treatments) and treatment costs will be zero because there is no need for treatments. Figures 35, 36, 37 and 38 show the model output when external infection pressure is removed.

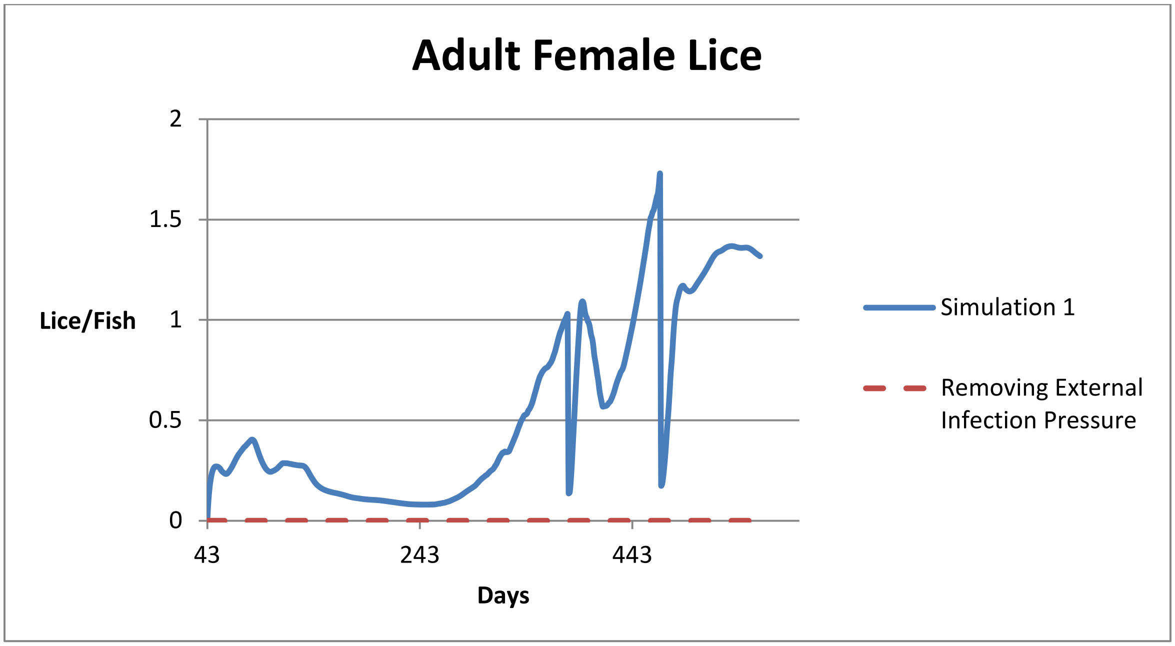


Figure 35: adult female lice population dynamics (removing external infection pressure) comparing to simulation 1

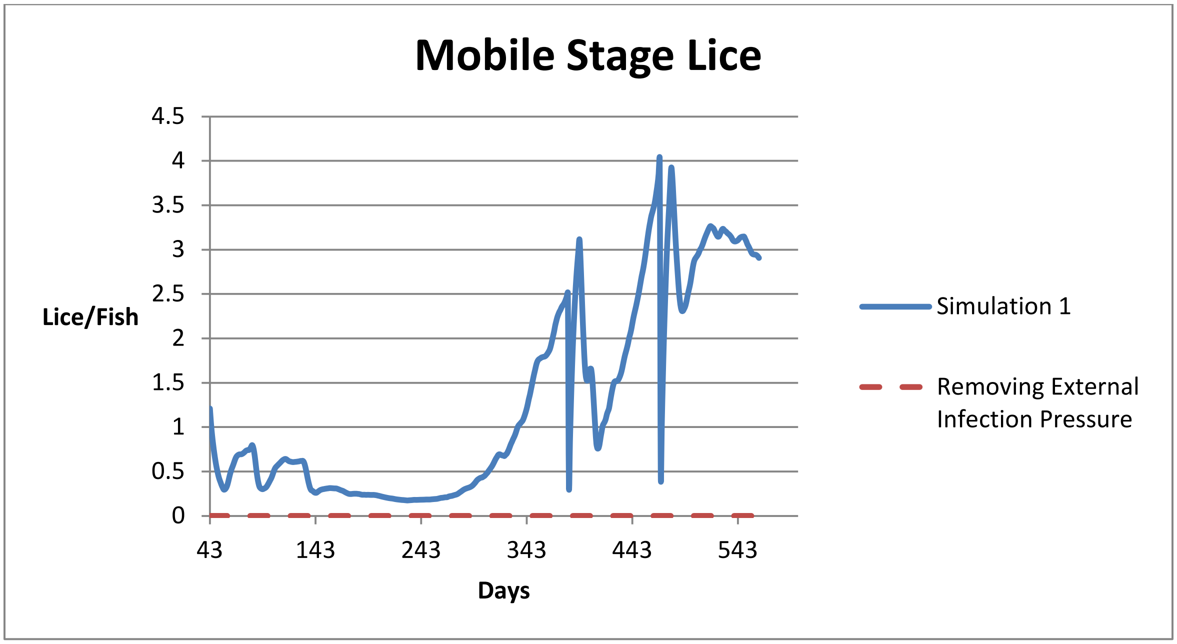


Figure 36: mobile stage lice dynamics (removing external infection pressure) comparing to simulation 1

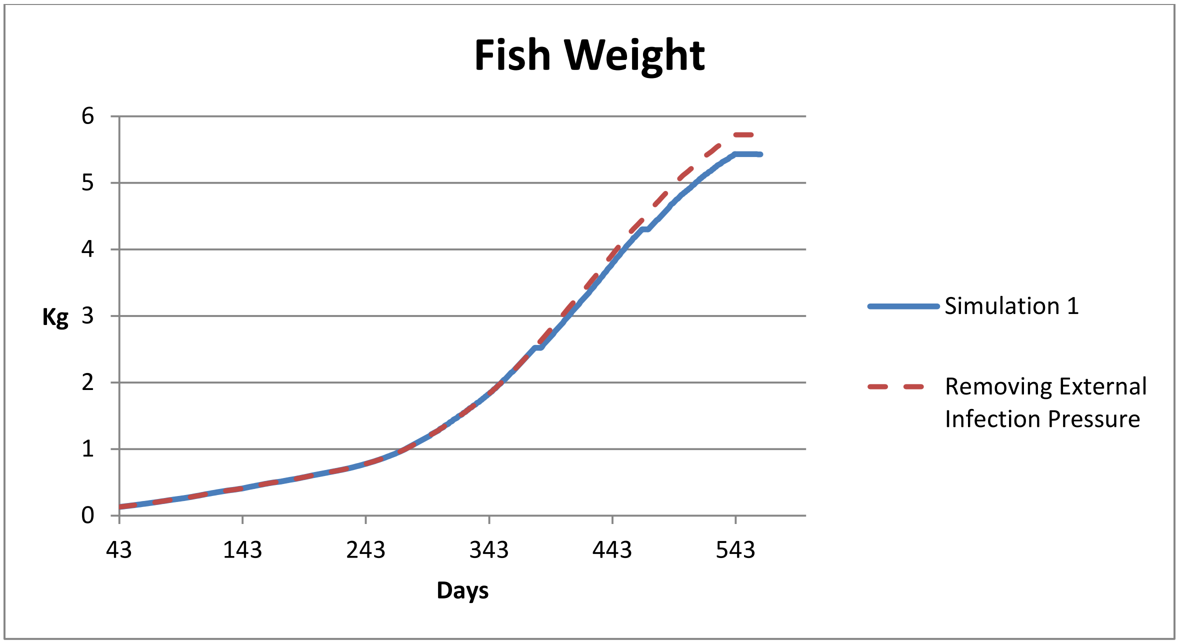


Figure 37: fish growth in case of removing external infection pressure comparing to simulation 1

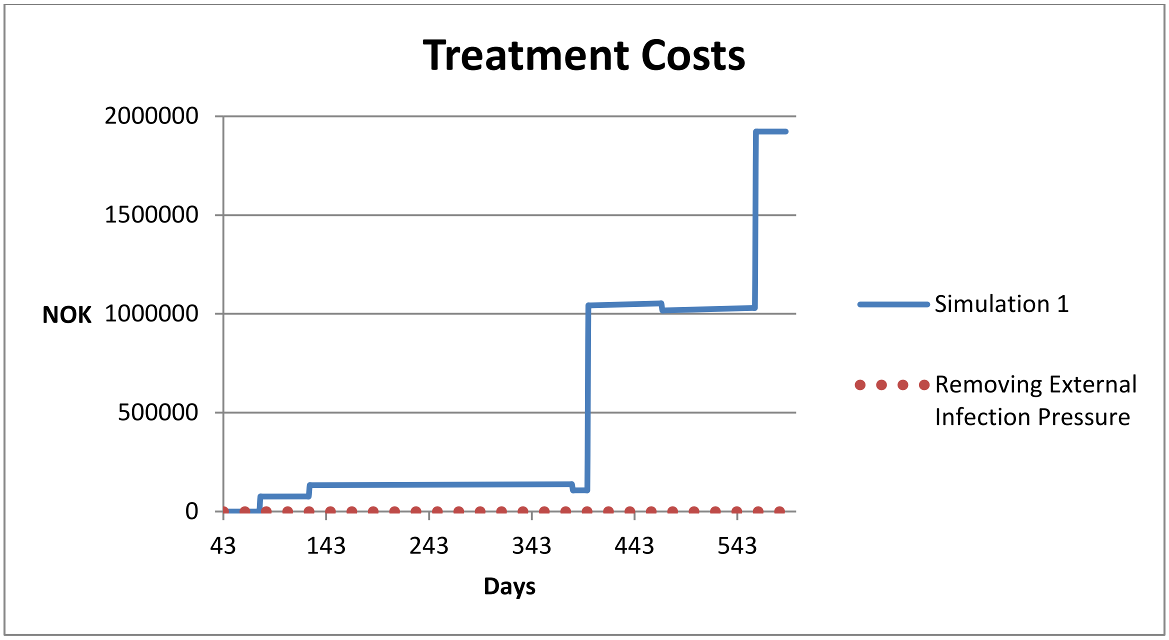


Figure 38: treatment costs in case of removing external infection pressure

2- Cutting Lice Egg Production Loop

The purpose of this test is to check whether the exogenous source of infection (i.e. *external infection pressure*) is responsible for the model behavior or the model behavior generated endogenously. To conduct this test, we cut lice egg production feedback loop. That is, the feedback from gravid female lice to lice egg production is deactivated by multiplying egg production by zero. Based on this test, both adult female lice and mobile stage lice should remain low and would not reach any peaks because lice population peaks are generated endogenously via lice egg production loop. Though, there will be slight increase and decrease of lice population overtime due to changes in *external infection pressure*.

It is important to set policy setting to “no policy” from the interface to ensure that there would not be any external influence that declines lice population. By cutting the main feedback loop in the model (i.e. lice egg production), fish grows normally (i.e. no starvation because of chemical treatments) and treatment costs will be zero because there is no need for treatments. Figures 39, 40, 41 and 42 show the model outputs when lice egg production loop is deactivated.

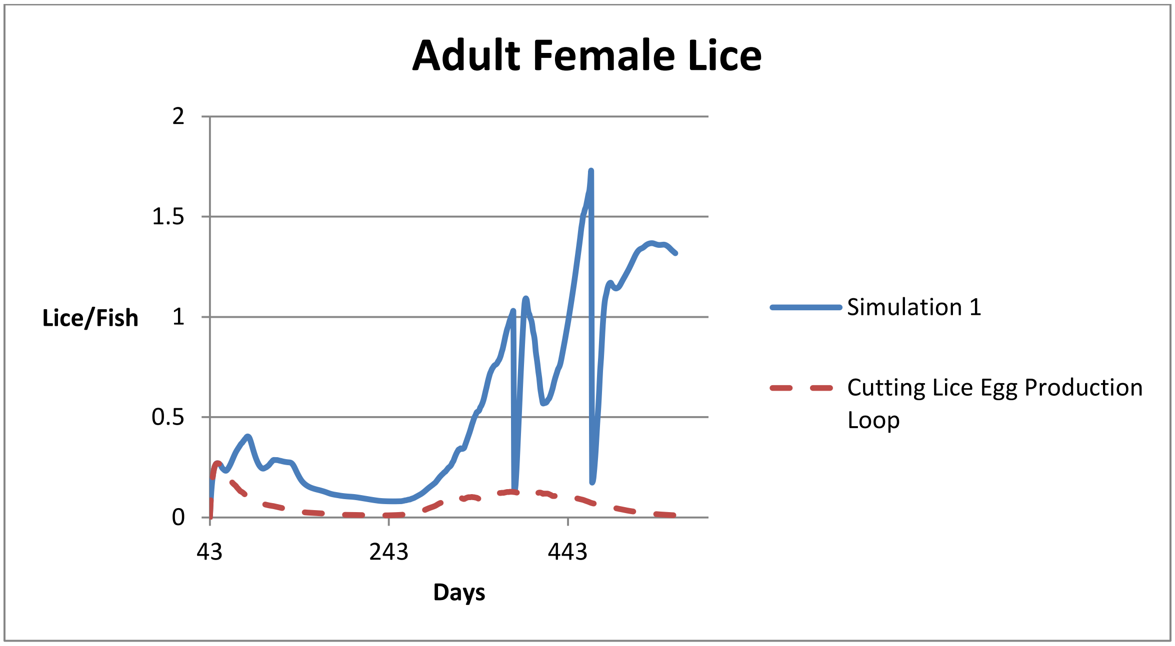


Figure 39: comparing adult female lice population dynamics (cutting lice egg production loop) with simulation 1

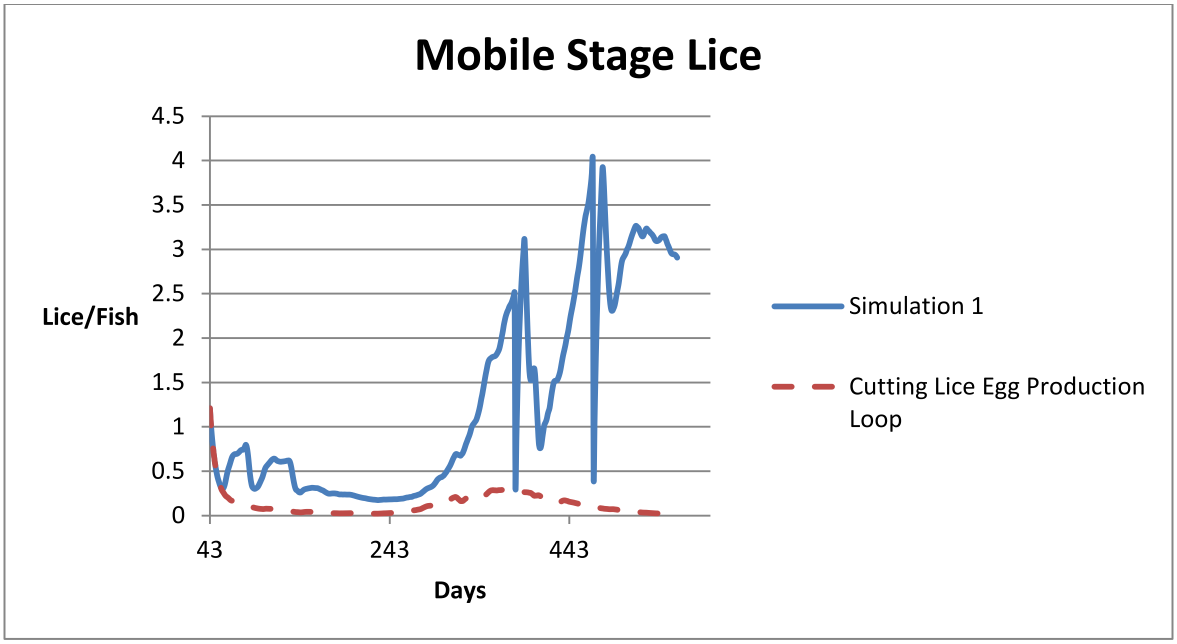


Figure 40: comparing mobile stage lice population dynamics (cutting lice egg production loop) with simulation 1

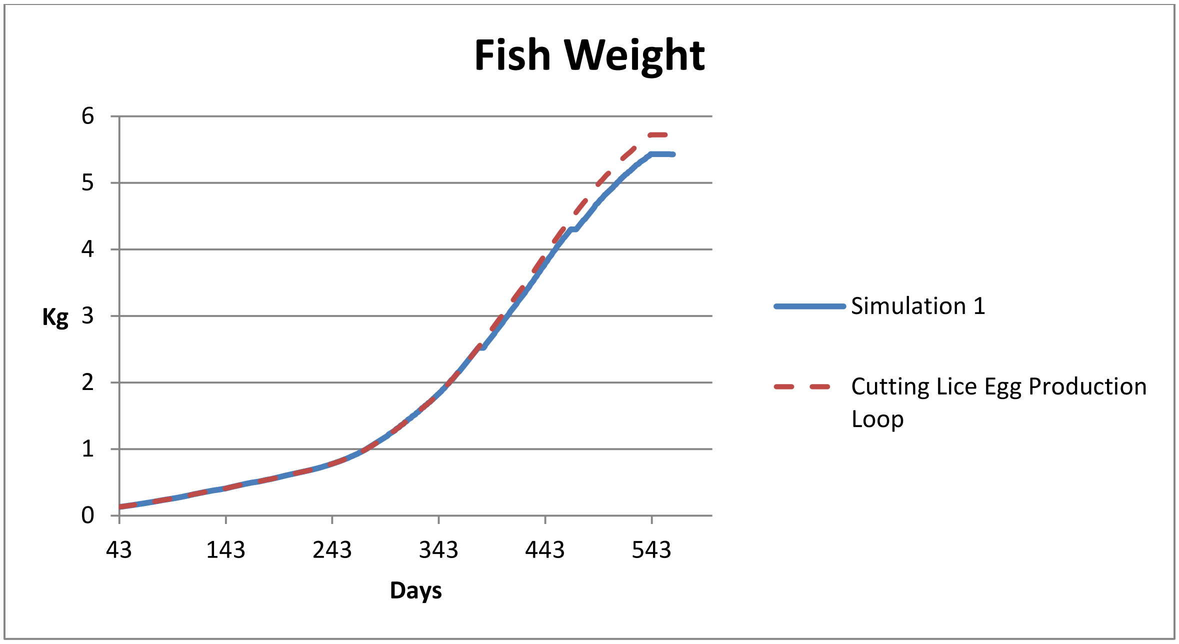


Figure 41: fish growth in case of cutting lice egg production loop comparing to simulation 1

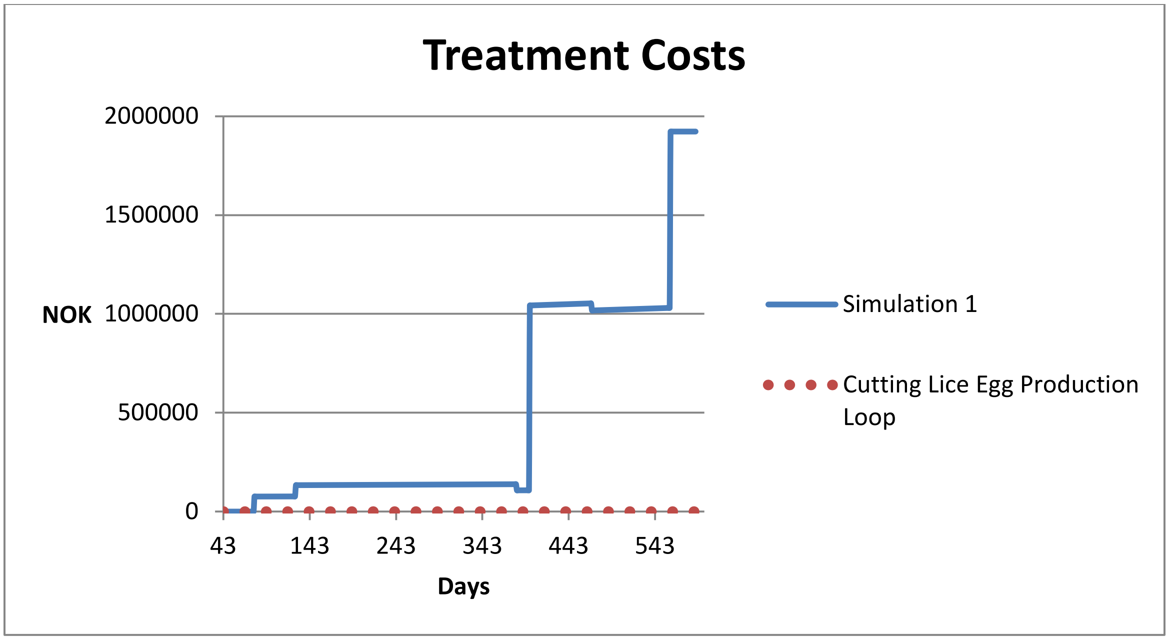


Figure 42: treatment costs in case of cutting lice egg production loop

3- Cutting Female Population Loop

The purpose of this test is to evaluate the model structure in terms of real system. In real system, there must be male and female lice in order to produce eggs and complete lice population cycle. In this test, we cut female population loop by multiplying the flow between *Chalimus L. Salmonis* and *Preadult Female L. Salmonis*. Thus, the model prevents developing of female lice which means the egg production process is deactivated. It should be noted that the behavior of adult female lice in figure 43 shows a slight increase before approaching zero because of initial value of stocks. The simulation outputs of this test should generate a very low mobile stage lice population and the population of adult female lice is mostly zero.

It is important to set policy setting to “no policy” from the interface to ensure that there would not be any external influence that declines lice population. By cutting female population loop, fish grows normally (i.e. no starvation because of chemical treatments) and treatment costs will be zero because there is no need for treatments. Figures 43, 44, 45 and 46 show the model outputs when female lice population loop is deactivated.

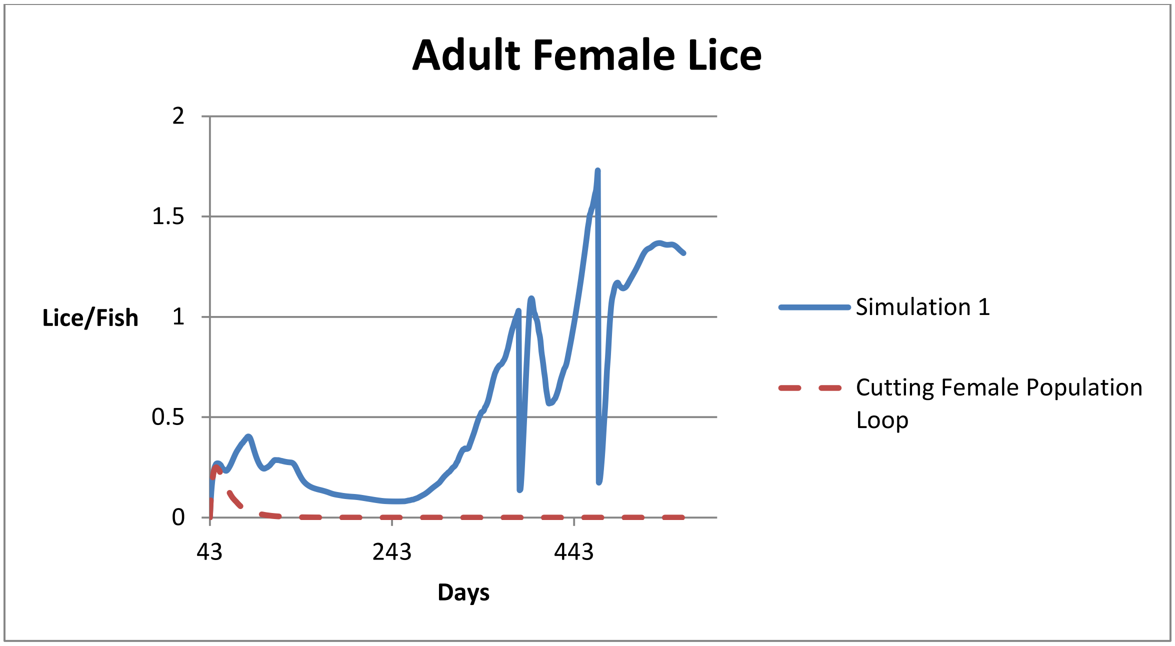


Figure 43: comparing adult female lice population dynamics (cutting female population loop) with simulation 1

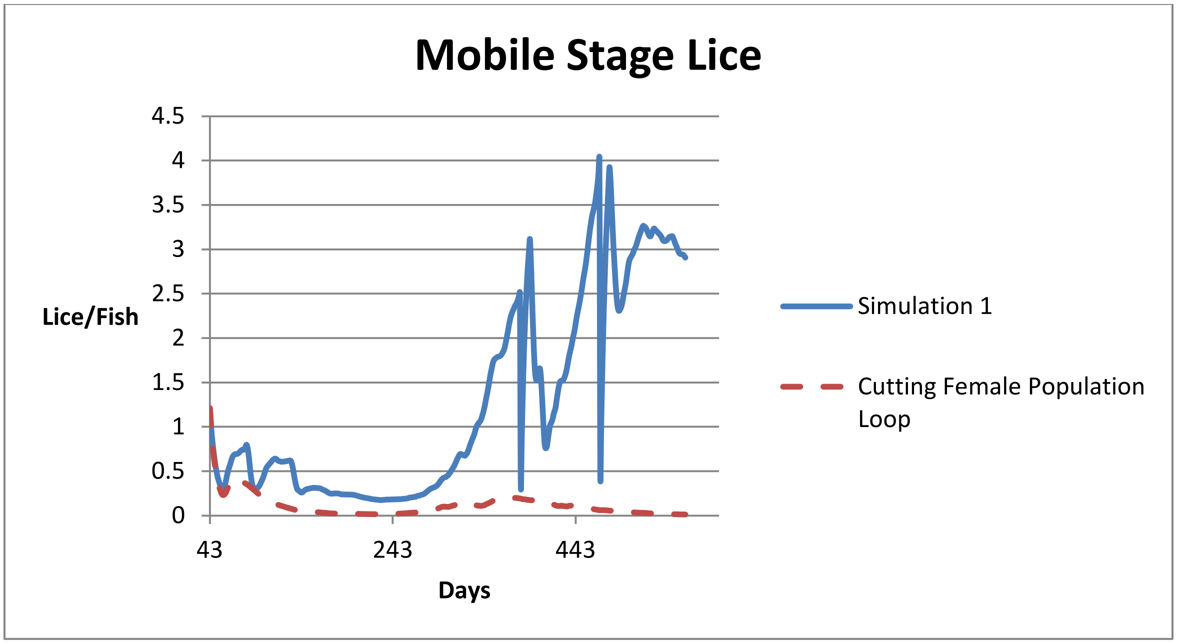


Figure 44: comparing mobile stage lice population dynamics (cutting female loop) with simulation 1

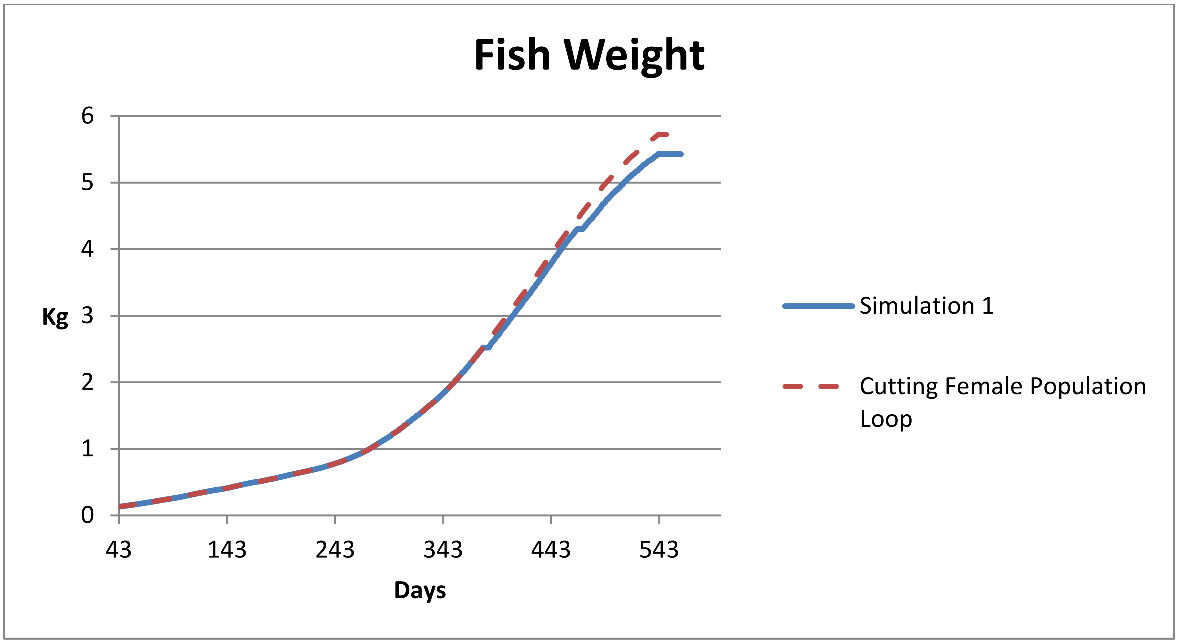


Figure 45: fish growth in case of cutting female population loop comparing to simulation 1

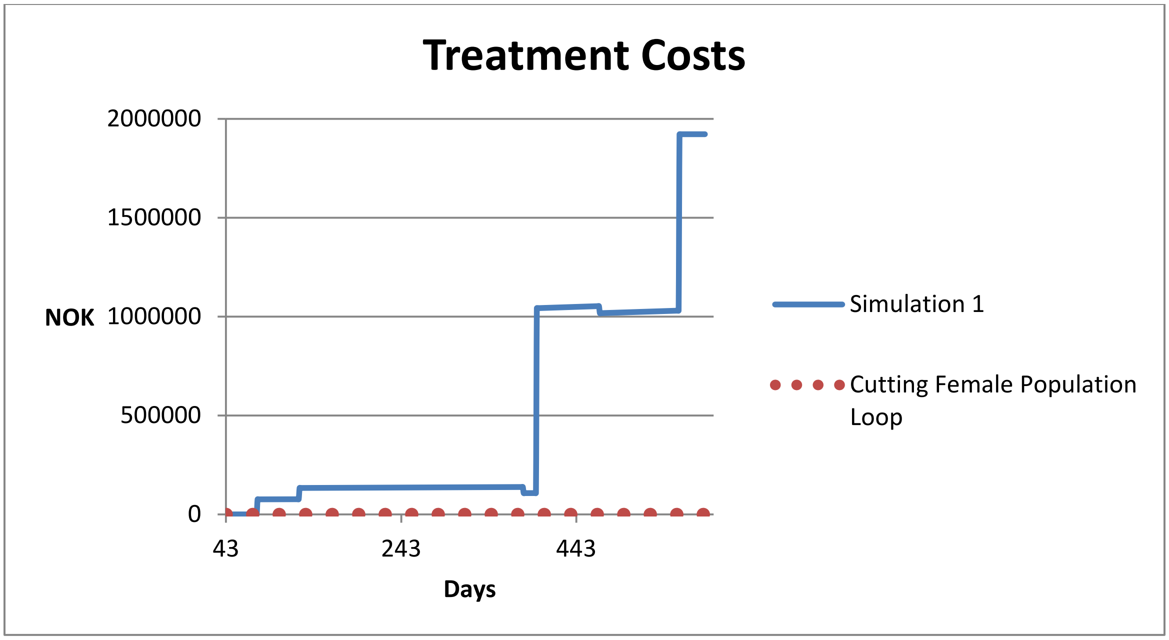


Figure 46: treatment costs in case of cutting female population loop

4- Cutting Male Population Loop

The purpose of this test is to evaluate the model structure in terms of real system. In real system, there must be male and female lice in order to produce eggs and complete lice population cycle. In this test, we cut male population loop by multiplying the flow between *Chalimus L. Salmonis* and *Preadult male L. Salmonis*. Thus, the model prevents developing of male lice which means the egg production process is deactivated. It should be noted that the behavior of mobile stage lice[12] in figure 47 shows a slight increase and decrease overtime because of initial value of stocks and the population of preadult female lice. The simulation outputs of this test should generate a very low mobile stage lice (in this case mainly preadult female because the model prevents evolving male lice) population and the population of adult female lice is low.

It is important to set policy setting to "no policy" from the interface to ensure that there would not be any external influence that declines lice population. By cutting male population loop, fish grows normally (i.e. no starvation because of chemical treatments) and treatment costs will be zero because there is no need for treatments. Figures 47, 48, 49 and 50 show the model outputs when female lice population loop is deactivated.

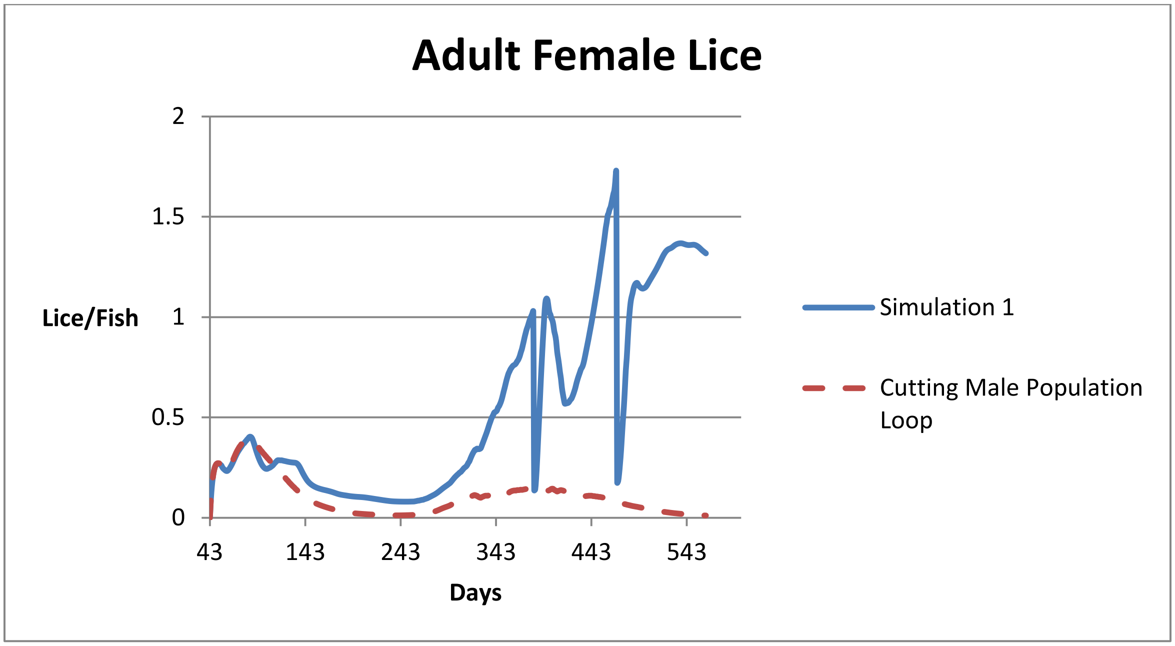


Figure 47: comparing adult female lice population dynamics (cutting male population loop) with simulation 1

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[12] Mobile stage lice include all males and preadult female

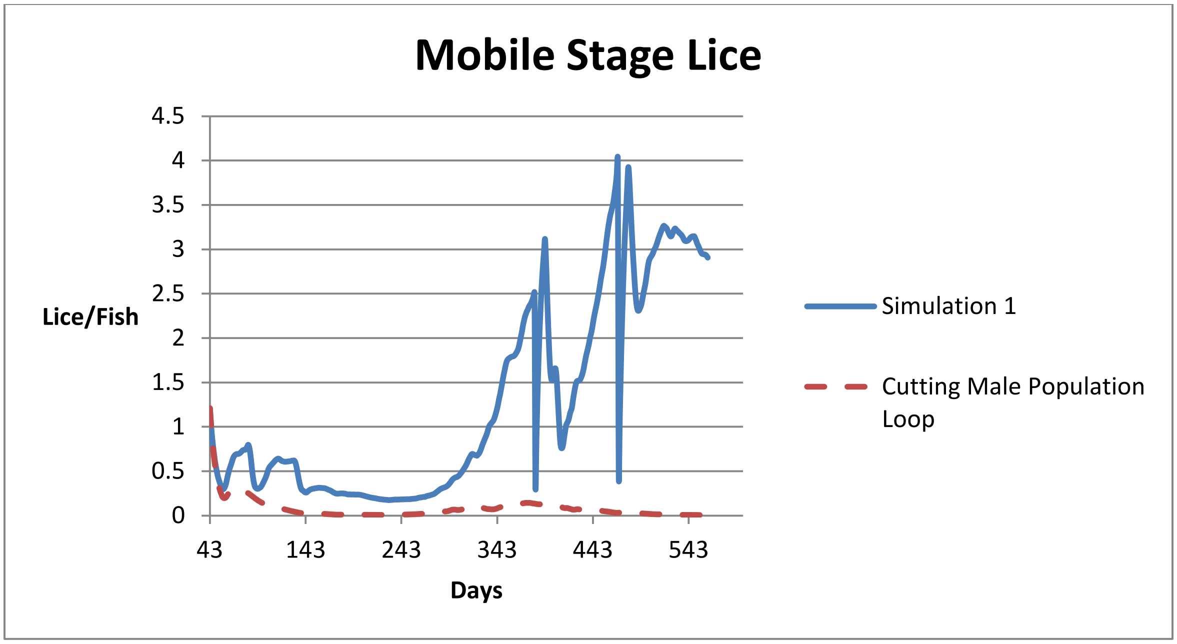

Figure 48: comparing mobile stage lice population dynamics (cutting male population loop) with simulation 1

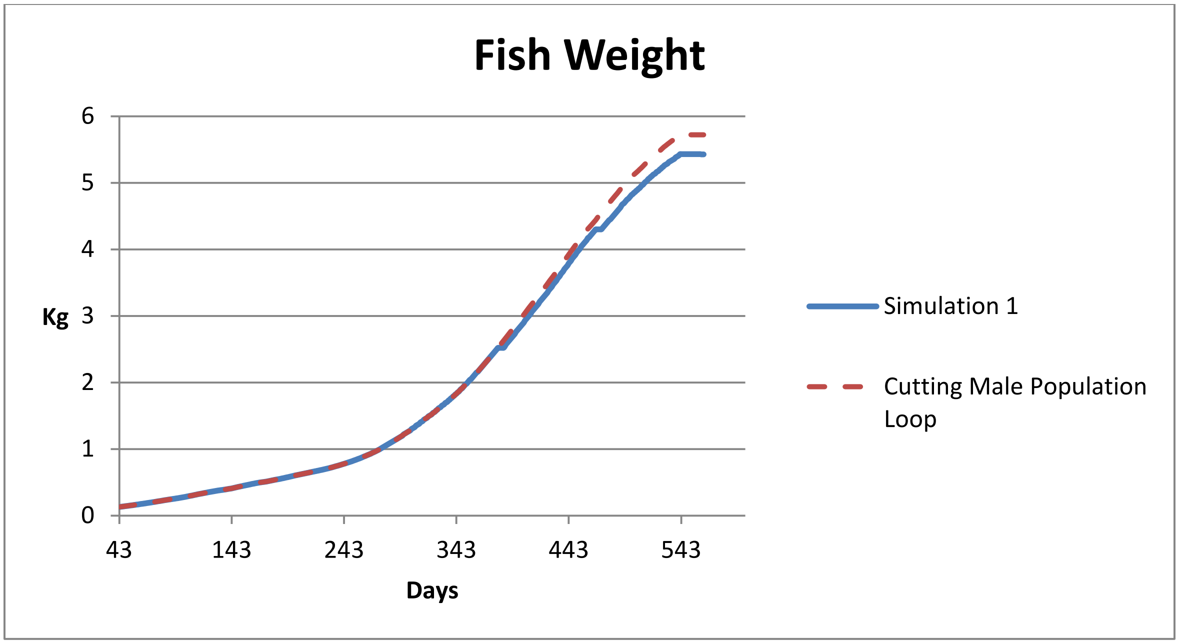

Figure 49: fish growth in case of cutting male population loop comparing to simulation 1

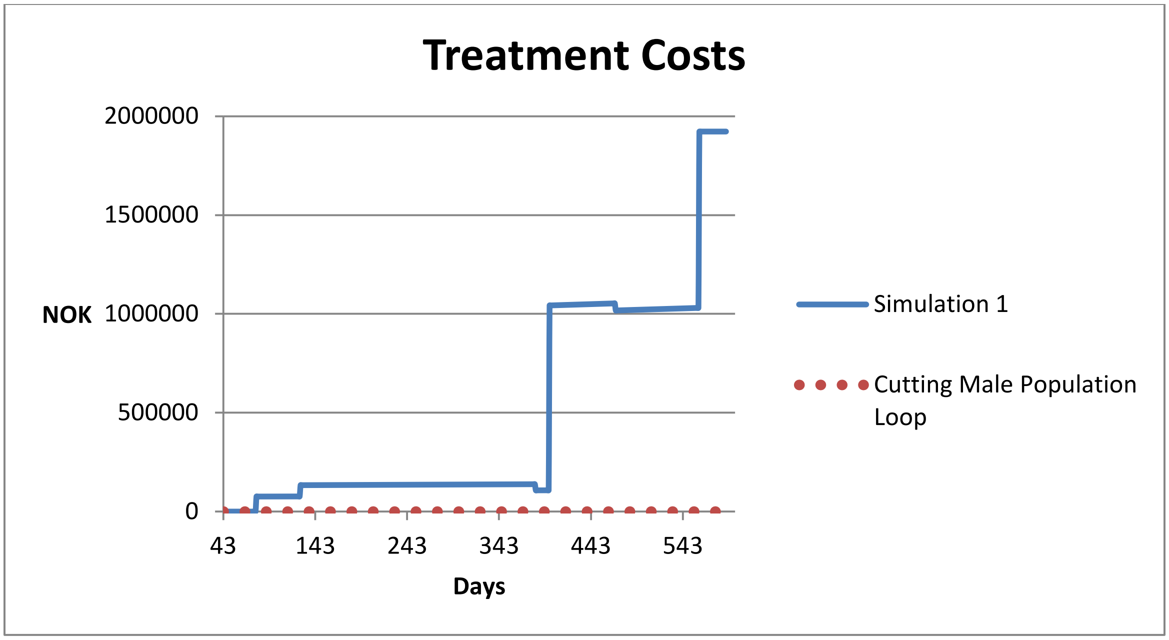

Figure 50: treatment costs in case of cutting male population loop

As we indicated in the main part of this report that lice initially introduced to a fish in a cage from outside sources (i.e. *external infection pressure*). But external infection alone is not sufficient to cause problems to salmon farms. The problem arises when internal reproduction process starts to dominate the lice production cycle. The conducted structure-behavior tests show that the model outputs are generated endogenously, which in turn improves the robustness of the model.

- ***Extreme Condition Test***

In this test, we examine model reaction under extreme conditions. That is, testing model under sever condition that is possible to occur in real system. The purpose of this test is to evaluate model reaction and compare it with the case in real system. For this purpose, we analyze to sever conditions: (1) assuming that there is no lice infection, and (2) allowing lice to grow without control (in this case, we assume that lice can grow with no limitations including fish death).

The first test, assuming that there is no lice infection, we set the value of sea lice life stages to zero and assume that there is no infection. The model outputs should show no grows in sea lice population, no lice treatment costs, and fish should grow smoothly (without starvation because there is no need to implement sea lice control treatments). It should be noted that this test is similar to removing external infection pressure test (refer to structure-behavior test section) and the results are reported there.

The second test, allowing lice to grow without control; we run the model without implementing any lice control treatments. The purpose of this test is to evaluate model behavior comparing to real system. However, we assume that lice population can grow on fish infinitely. The aim of this test is to evaluate lice growth pattern and not to check its influence on fish. Under the condition of allowing lice growing without control, the number of lice should increase dramatically. The only limitation that prevents lice population growth is related to water temperature. In a very low water temperature (3 to 6 Celsius degree) lice will have no or very limited growth in population. The lice population under this test is shown in figures 51 and 52.

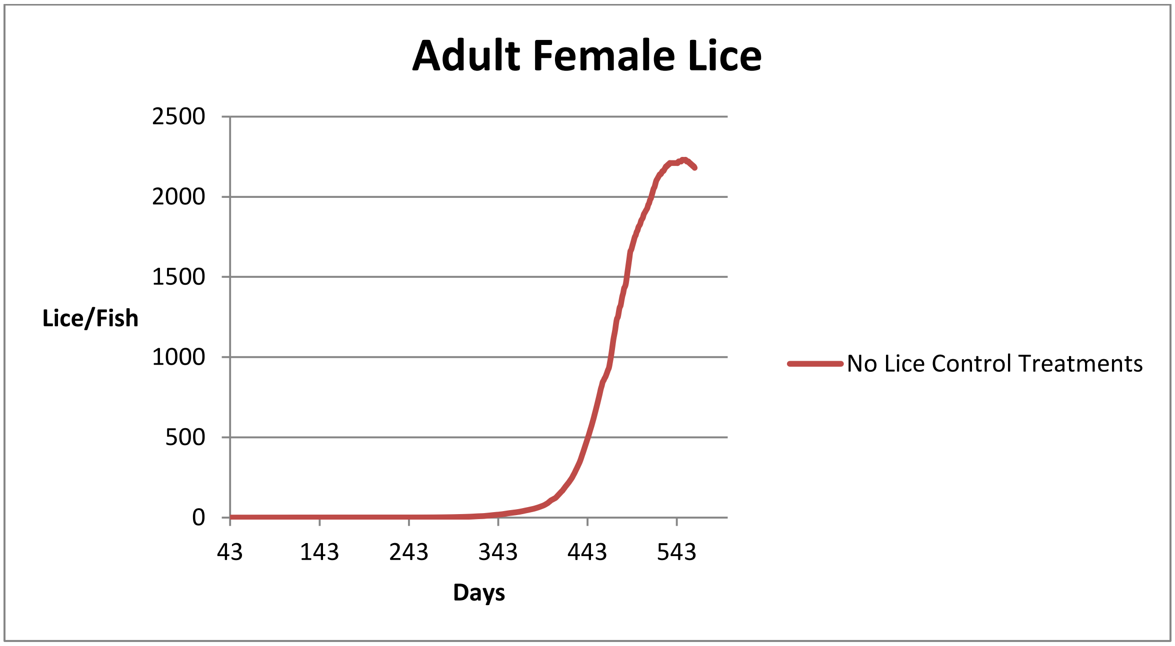

Figure 51: adult female lice population in case of allowing lice to grow without control

Adult female lice population grow slowly at the beginning of simulation because lice population is small and water temperature[13] gets lower overtime which leads to a slow growth of lice population. However, as winter passes, water temperature starts to increase and sea lice population already grown and accumulated during winter time and is ready to boom because lice grow extremely fast with high water temperature (10 to 15 Celsius degree). Thus, adult female lice population starts to grow rapidly from day 343 and on. However, as summer passes and water temperature declines, the lice population grows at a slower rate. But because the lice population already grown to large and therefore the impact of low temperature only appears at the very end of simulation.

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[13] As it was mentioned in the main part of this report, the time horizon starts in of X-axis starts in September 2008 and ends in April 2010.

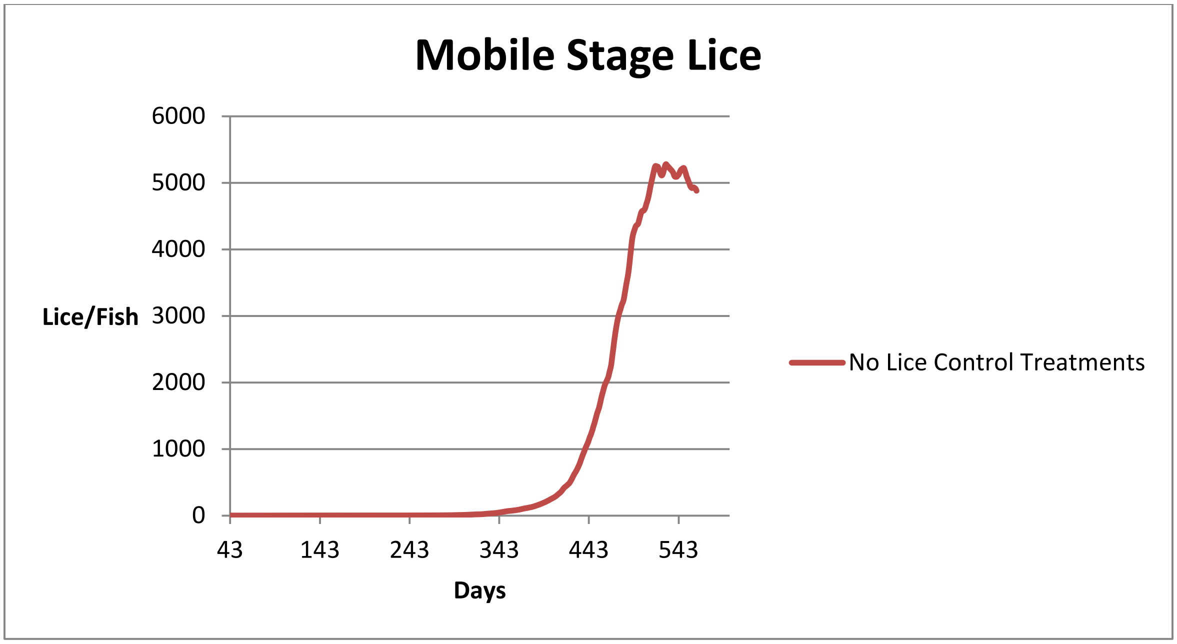

Figure 52: male stage lice population in case of allowing lice to grow without control

Mobile stage lice population shows the same growth pattern as in adult female lice. But the growth pattern of mobile stage lice is slightly different than adult male lice at the end of simulation. That is, it shows an oscillatory behavior. The reason for that is change in temperature is gradual and oscillatory, which is reflected on lice population. And since mobile stage lice include all males and preadult female lice (early stages of lice life stages), therefore, the change in water temperature and the lice population growth is reflected in mobile stage lice population.

The conducted validation tests in appendix 4 showed and analyzed model outputs through conducting different model validation tests (i.e. phase validity, unit consistency, reference mode comparison, structure behavior test, and extreme condition test). The model output in all of these validation tests behaved logically and showed reasonable pattern. It also showed a logical response among model sectors. Therefore, the conducted validation tests enhance the reliability of the model behavior and improve the robustness of the model.

Appendix 6: Interface Description

In this appendix, we describe the model interface. The model interface includes four major parts: (1) control page, (2) fish pen and growth model, (3) sea lice population model, and policy and economic model, and (4) validation tests. At each page, there is instruction button that instructs the user to use the interface and explain its contents.

Control Page

The control page includes navigation buttons that take you to other section of the interface and allows you to open the report. Figure 53 shows the control page of the interface.

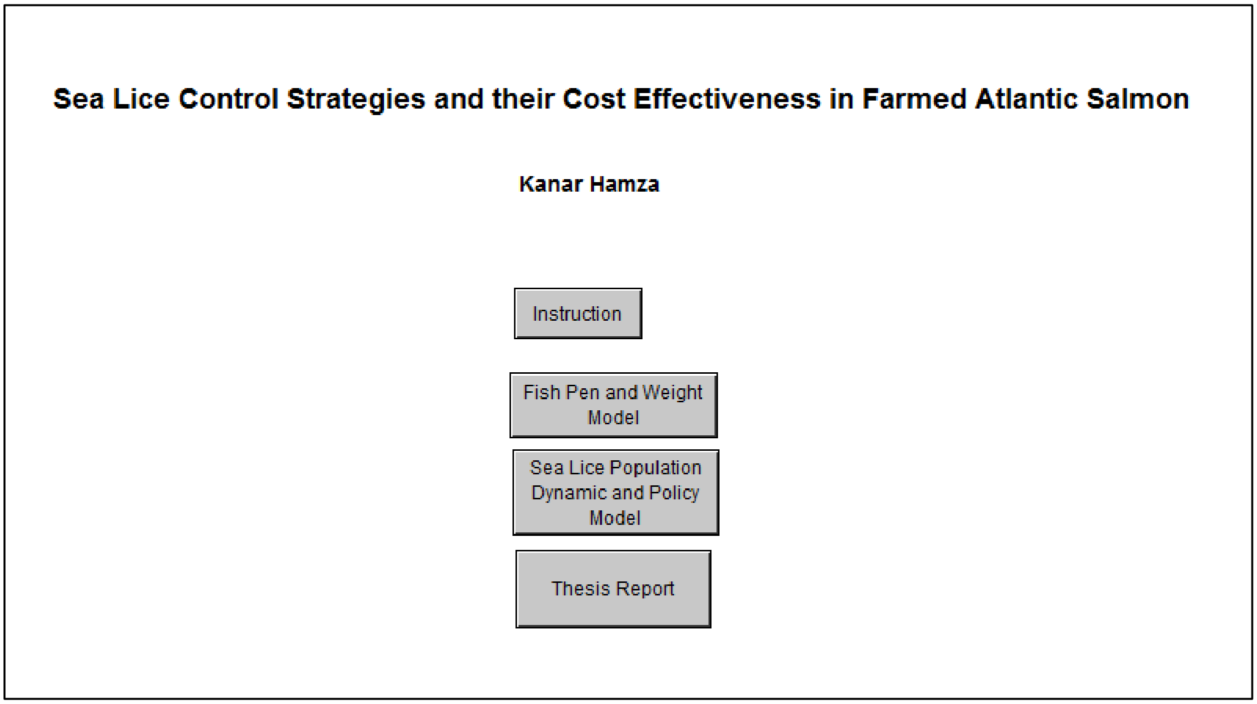

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Figure 53: control page of the interface

Instruction:

To view the structure of fish aging model, please click on Fish Pen and Weight Model and then follow the instruction on that page.

To view the structure of sea lice population dynamic and policy model, please click on Sea Lice Population Dynamic and Policy Model and then follow the instruction on that page.

Fish Pen and Weight page

Fish pen and growth page includes graphs that show fish growth and number in the cage. The “instruction” button instructs the user to use the page. The page includes “run” and “restore” buttons that allows the user to run and restore the model. The button “Pen and Fish Weight” takes you through the structure of this sector of the model and shows a step by step description of the model. The “exogenous feeding data” and “endogenous feeding” switches allow the user to run the model under both conditions and compare the results on the graph. Figure 54 shows fish growth and pen model.

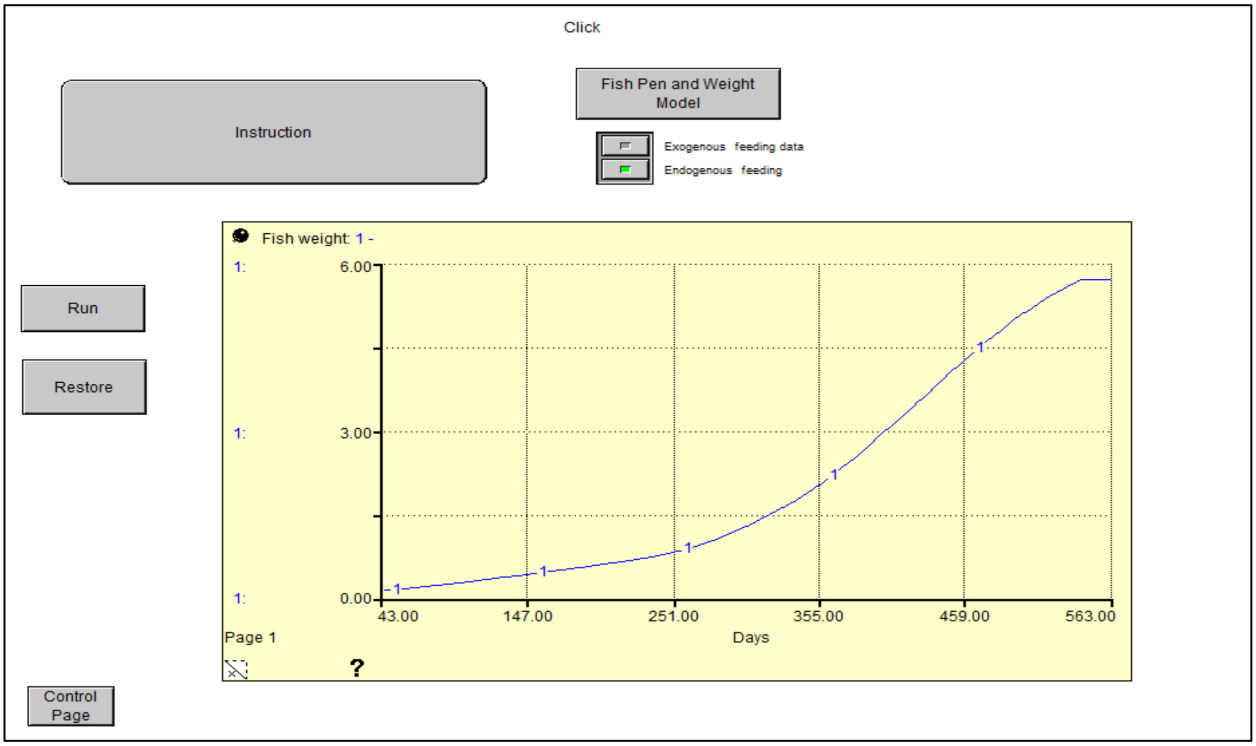


Figure 54: fish pen and weight model page of the interface

Instruction:

1- The button "Pen and Fish Weight" takes you through the structure of the model.
2- The button "Run" allows you to run the model.
3- The button "Restore" allows you to restore graphics and tables.
4- The graph in the middle of the page shows the growth of fish weight. Click on the small triangle on the bottom left side of the graph to see the graph that shows number of fish in a pen.
5- Exogenous and endogenous switches under the button "Pen and Fish Weight" are working as follow:

When the switch "Exogenous Feeding data" is activated (green), it means we are running the model by using the feeding data provided by the client (real feeding data from past production cycle inserted to the model exogenously). That means "Endogenous Feeding" is not activated (gray).

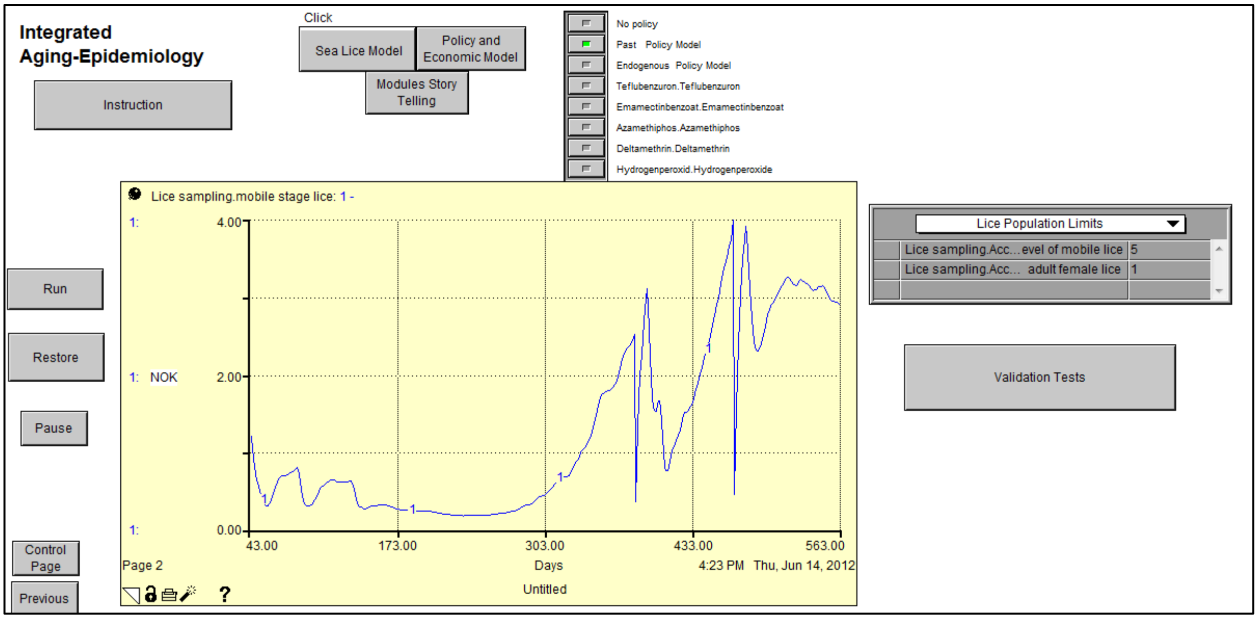
To activate endogenous feeding and deactivate exogenous feeding data, please click on "Endogenous feeding" switch." Endogenous feeding lets the model decide to feed fish based on fish weight and water temperature.

The growth of fish through endogenous feeding should be compared with the growth of fish through exogenous feeding to see whether the model replicates the growth of fish data (exogenous feeding) or not.

6- When you finish reviewing this page, please make sure that "endogenous feeding" switch is on and press the button "Control Page" on the bottom left of the screen to go back to the control page and then choose Sea Lice Population Dynamic and policy Model.

Sea Lice Population Dynamics and Policy Model

This page represents the most important part of the interface. Here, we report the results of different simulations to test various lice control treatment scenarios. The user can check the level of sea lice population and based on that decides which treatments to select. Figure 55 shows sea lice population dynamics and policy model page of the interface.



☐ No policy
☑ Past Policy Model
☐ Endogenous Policy Model
☐ Teflubenzuron.Teflubenzuron
☐ Emamectinbenzoat.Emamectinbenzoat
☐ Azamethiphos.Azamethiphos
☐ Deltamethrin.Deltamethrin
☐ Hydrogenperoxid.Hydrogenperoxide

Lice Population Limits	
Lice sampling.Acc...evel of mobile lice	5
Lice sampling.Acc... adult female lice	1

Figure 55: sea lice population dynamics and policy model page of the interface

Instruction:

1- The button "Sea Lice Model" takes you through the structure of the sea lice population dynamic model.
2- The button "Policy and Economic Model" takes you through the structure of the lice control and economic model.
3- The button "Modules Story Telling" takes you through the structure of modules used inside the buttons in point 1 and 2. When you click on the button "Modules Story Telling," please follow the instruction.
4- You should do points 1, 2 and 3 consecutively. Thus, go through Seal lice model, and then go through Policy and Economic model, and finally Modules Story Telling.
5- The button "Run" allows you to run the model.
6- The button "Restore" allows you to restore graphics and tables.
7- The button "pause" allows you to pause the model whenever you want.
8- The graph in the middle of the page shows number of mobile stage lice per fish (page 2). Click on the small triangle on the bottom left side of the graph to see the graph that shows number of adult female lice per fish (page 3) and cumulative costs of treatments (page 1).
9- The button "validation Tests" takes you to the page that allows you to conduct a few model validation tests.
10- The input table from the right side of the graph allows you to change the level of acceptable mobile lice and adult female lice per fish (thresholds). When a change of these thresholds needed, the model will pause and show a message, please follow the instruction of the message.
11- The list of switches on the top of the graph is treatment options. You can pause the model whenever you want to implement one of them and/or you can wait until the model pauses because sea lice population exceeds thresholds. When that happens, follow the instruction that shows.
12- Please, the Switch "No Policy" was created just to check how sea lice population behave if we assume that they can grow without limitations (assuming fish will not die and no treatment is implemented). Thus, in case you run the model with no policy, restore the model before conducting other runs because the growth of sea lice population is extremely high when "no policy" switch is on.
13- Past policy model switch introduces implemented treatments from past production cycle to the model. When this switch is on, the model will run without any pauses or messages because the past treatments are forced to the model. The purpose of this run is to see how our model replicated historic data about sea lice population (from past production cycle).

14- When you turn on endogenous policy model, you are responsible to control sea lice population through choosing treatment from the switches under it (when you turned on this switch, you cannot turn on "no policy" and/or "past treatment model" switches. In order to make a treatment active, pause the model (or the model automatically pause when sea lice population exceeds thresholds), click on a treatment, then click run. The model runs for one time unit and will pause again, then turn on endogenous policy model so the model will implement the treatment and keep running.

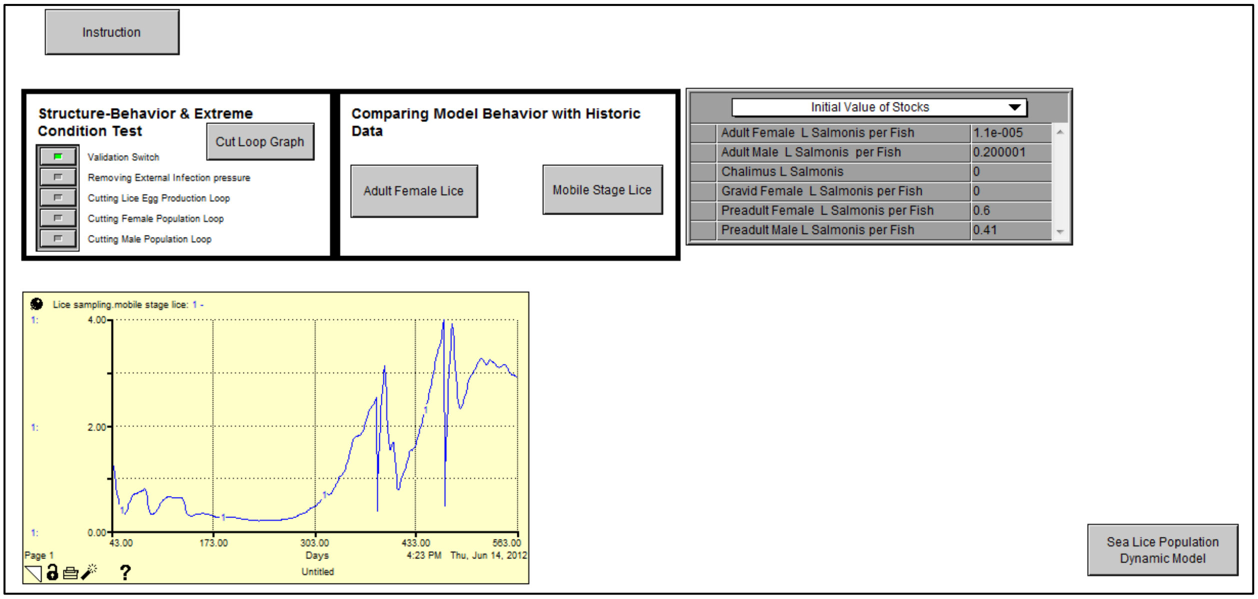
15- Until day 300, it is recommended only to use in-feed treatments (that is, Emamectinbenzoat and Teflubenzuron) because fish are small and cannot tolerate chemical treatments (that is, Deltamathrin, Azamethiphos, and Hydrogenperoxid). Afterwards, you can choose any treatment you want. However, as fish grow in size in-feed treatments get more expensive because larger quantity is required. The effectiveness of in-feed treatments continuous for a few weeks while chemical treatments is effective only for one day.

16- You can pause the model anytime you want while the model is running to check the population of mobile stage lice and adult female lice to decide when to launch a treatment and which type of treatment. Hint, (a) In-feed treatment will not kill adult stage lice, and (b) chemical treatment will only kill adult and preadult lice (no effect on Chalimus).

17- Please don't forget to turn “no policy” switch on when you go to validation page (That is, button of "validation tests on the right side of the graph).

Validation Tests

This page of the interface allows the user to make a few validation tests to evaluate the robustness of the model. The interface allows the user to do: (1) Structure-behavior test, (2) reference mode test, and (3) Extreme condition test. Figure 56 shows the validation test page of the interface.



Initial Value of Stocks	
Adult Female L Salmonis per Fish	1.1e-005
Adult Male L Salmonis per Fish	0.200001
Chalimus L Salmonis	0
Gravid Female L Salmonis per Fish	0
Preadult Female L Salmonis per Fish	0.6
Preadult Male L Salmonis per Fish	0.41

Figure 56: validation test page of the interface

Instruction:

This page shows a few validation tests. To do the tests:

1- In the Structure behavior box:

a) Switching validation switch on (green) means no validation test is operating. First, run with switch validation on and then run the other switches respectively to see how behavior changes on the graph.

b) To activate validation tests, simply click on the switches. Click on the button "Cut Loop Graph" to see which loops are tested.

c) Removing External Infection Pressure means not allowing sea lice to infect fish from outside sources. Initial values of stocks are set to zero.

d) Cutting Lice Egg Production Loop means canceling the most important loop in the model. By canceling this loop, sea lice are only introduced to fish from outside sources and sea lice population will stay at a very low level.

e) Cutting Female Population Loop means female sea lice will not develop and therefore lice level stays at a very low level because both female and male are needed for reproduction.

f) Cutting Male Population Loop means male sea lice will not develop and therefore lice level stays at a very low level since both female and male are needed for reproduction.

2- Comparing model behavior with historic data is reference model comparison. That is, we compare the model results with the sea lice data from past production cycle. Click on the buttons inside the box to see the graph.

3- When you finish, please make sure that "Validation Switch" is on and click on the button "Sea Lice Population Dynamic Model" to go back to that page.