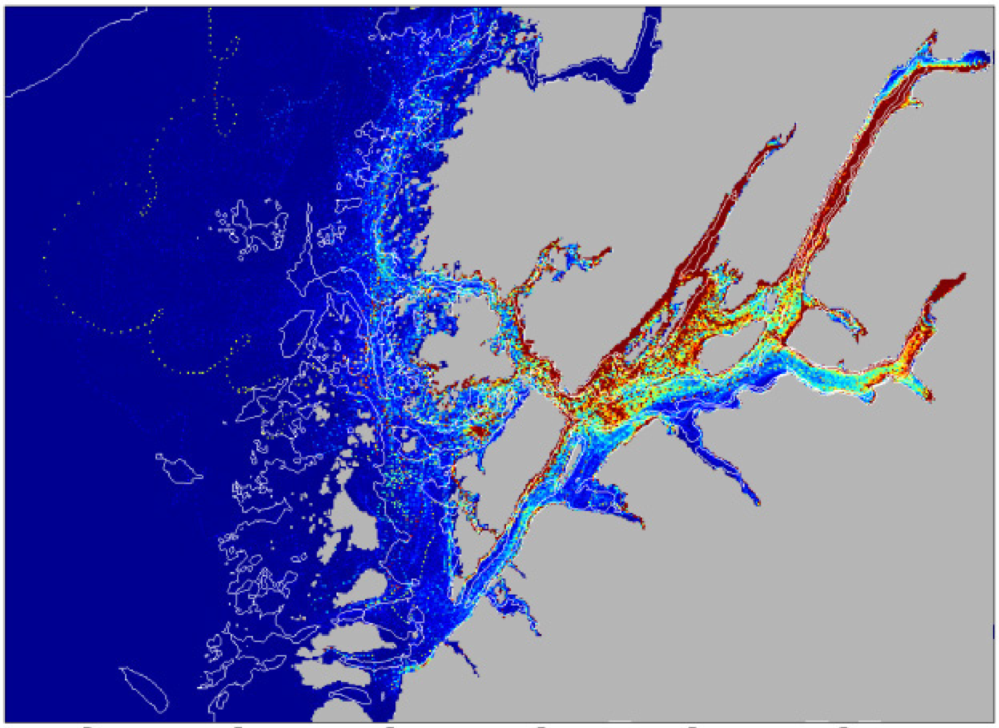
A26093 - Unrestricted

Report

Summary of results from the SALMODIS project

Author(s)
Hans Vanhauwaert Bjelland
Project partners



SINTEF Fisheries and Aquaculture Ltd.
Havbruksteknologi
2014-05-12

SINTEF Fiskeri og havbruk AS
SINTEF Fisheries and Aquaculture Ltd.
Postboks 4762 Sluppen
NO-7468 Trondheim
Norway
Telephone: +47 40 00 53 52
Telefax: +47 932 70 703
fish@sintef.no
sintef.no/fish
NO 980 478 270 MVA

Report

Summary of results from the SALMODIS project

KEYWORDS:
Disease control; Disease modelling; Decision Support Tool; Multi-disciplinary projects; Sea lice

VERSION
1.0

DATE
2014-05-12

AUTHOR(S)
Hans Vanhauwaert Bjelland
Project partners

CLIENT(S)
Norges forskningsråd

CLIENT'S REF.
207570/S40

PROJECT NO.
6020229

NUMBER OF PAGES/APPENDICES:
16

ABSTRACT

This report summarises the results from the SALMODIS project. Through a multidisciplinary approach, the project has addressed the needs for improved knowledge and tools for decision support related to disease management in salmon farming. The project group has studied the constraints of control strategies and the dynamics and varying effects of diseases on a local pen and farm level, and on a regional level between farms and wild populations.

PREPARED BY
Hans Vanhauwaert Bjelland

SIGNATURE

CHECKED BY
Ulf Winther

SIGNATURE

APPROVED BY
Arne Fredheim

SIGNATURE

REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
A26093	978-82-14-05719-5	Unrestricted	Unrestricted

SINTEF

Table of contents

1 Introduction

The objective of the SALMODIS research project was to improve the scientific basis for decision-making related to regulations and intervention strategies for disease control in the salmon farming industry. It aimed at supporting government and industry in evaluating constraints and cost-effectiveness of strategies with regard to their effects on economic, environmental and social dimensions.

Secondary objectives:

- Develop knowledge and methods to evaluate and compare constraints and cost-effectiveness of disease control strategies in terms of diverse sustainability dimensions and stakeholder interests.
- Develop tools and methods to integrate multidisciplinary knowledge to model viral and parasitic disease epidemiology and direct and indirect socio-economic effects.
- Develop tools and methods to make results from integrated models and other knowledge available to the decision makers, assisting both tactical response to an existing situation, and strategic, preventive disease control.

These objectives have required a broad, multidisciplinary approach to integrate perspectives and disciplines, covering social sciences, epidemiology, biology and economics.

2 Organisation

The SALMODIS- project has been carried out through collaboration between national research institutions, salmon farming companies, and selected international colleagues.

SINTEF Fisheries and aquaculture (SFH) and project manager Dr. Hans Bjelland has coordinated the project and has been involved in a number of research activities. Dr. Ingrid Ellingsen, Dr. Øyvind Knutsen and Dr. Lionel Eisenhauer have worked on an integrated model system to link farm populations of sea lice with their parasitic, free living life cycle phases and wild salmon migration patterns. Dr. Brad Schofield, Dr. Morten Alver Omholt and Eisenhauer have studied sea lice population modelling and estimation. Dr. Yajie Liu has studied the economics of site specific treatment strategies.

The Norwegian School of Veterinary Science (NVH) has been involved in various work tasks within the SALMODIS project. Prof. Eystein Skjerve, Dr. Arnfinn Aunsmo and Dr. Marit Stormoen have participated in the project from NVH. A large part of Stormoen's Ph.D. thesis has been written within the project.

University of Prince Edward Island (UPEI) and University of Strathclyde (UoS) have focused their activities on the documentation of key mathematical modelling research and approaches so that these are readily available for their implementation as decision support tools. In addition, development of pilot models to demonstrate these principles has been on-going and has included interactions with, and visits by, researchers from other SALMODIS partners. In addition to the funds supported by the project, additional resources were obtained in 2013 (from various projects funded by Canadian research agencies) to enable both Dr. Groner and Dr. Ruth Cox to continue to make significant contributions to the deliverables of SALMODIS. The work was coordinated by Dr. Revie, strongly supported by Prof. Gettinby at the University of Strathclyde.

Norwegian Institute of International Affairs (NUPI) contributions to SALMODIS have revolved around the development of an epidemiological-economic model of sea lice spread and control. Kanar Hamza, a research assistant at NUPI who will soon be starting a Ph.D. at the University of New England in Australia, worked with Dr. Karl M. Rich of NUPI to develop a system dynamics (SD) model of sea lice and salmon production for his M.Sc. at the University of Bergen.

Norwegian Institute for Nature Research (NINA) and Dr. Bengt Finstad has contributed with research on the effect and impacts of salmon lice infestations on wild salmonids. Finstad has had a central rle in coordinating the collection of data on aquaculture production, wild salmonids and infestations between industry, researchers and other programmes, such as the National salmon lice monitoring programme.

NTNU Social Research, Studio Apertura (NTNU-SR) have studied sustainability issues and stakeholders' interest related to diseases and disease control, as well as the challenges of decision makers to handle uncertainty. This work has been carried out by Dr. Tonje Osmundsen, Dr. Petter Almklov, Silje Skaug, Jørn Fenstad and Kristine Vedal Størkersen.

The industry partners, Salmar ASA , Marine Harvest Norway AS, Lerøy Seafood ASA, and their representatives have primarily participated through meetings, seminars and by sharing production data. Similarly, representatives from The Norwegian Seafood Research Fund (FHF) have participated in meetings and seminars.

Joint project meetings for all participants have been prioritized to support collaboration between the various groups. There have been six two-day meetings taking place in Trondheim or Oslo. In addition, smaller, more focused meetings and workshops have been held in between. Researchers have visited collaborating institutions (Stormoen visited both UPEI and SFH, Hamza visited UPEI and Cox visited farms in Norway).

3 Goal achievements

The project was originally organized in three work packages with sub-tasks that in different ways aimed at integrating sustainability dimensions and stakeholder interests with enabling technologies that integrate models and knowledge (see Figure 1).

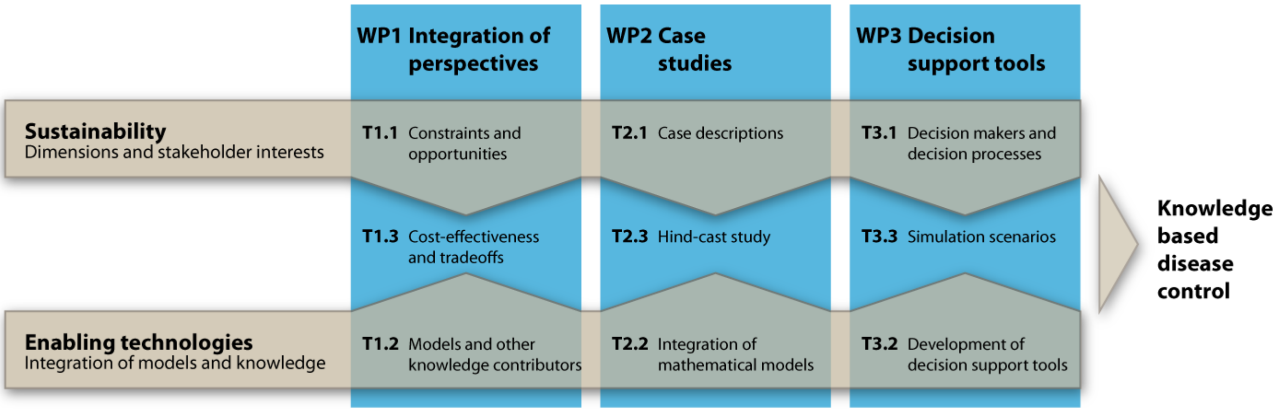


Figure 1 Work packages and sub-tasks

Although these work packages and tasks still cover the research carried out in the project, the multidisciplinary nature of the project has fostered some additional levels of perspectives:

- Diseases on a local, fish, pen or farm level
- Diseases on a regional level
- Diseases on a strategic and decision maker level

These are the levels that will be used in *Results* below. There is a strong relation between the approach of the original work packages and tasks, and the levels. Comments to the degree of goal achievement and deliverables (detailed in *Results*):

Task 1.1 Constraints and opportunities: Highly related to *Sustainability issues and stakeholders' interest*. Two workshops/seminars have been held to present the project results and get feedback from a wider audience. A paper has been presented and another is in preparation.

Task 1.2 Models and other knowledge contributors: Carried out in the initial stages of the project and documented in a report (Schofield et al., 2012). Papers that have partly been written in the project and are related to this task is Heuch et al. (2011) and Gettinby et al. (2011).

Task 1.3 Cost-effectiveness and tradeoffs: Highly related to *Epidemiological-economic model of sea lice spread and control* and *Economic model of control strategies at a farm level* where several papers have been published and are in preparation. Rich and Liu co-chaired a special section on the IIFET conference, held in Des Salaam, Tanzania, July 16-20, 2012. Three presentations were given from the group (Hamza, Karl Rich, & David Wheat, 2012a; Hamza, Karl Rich, Marit Stormoen, Arnfinn Aunsmo, & Eystein Skjerve, 2012; Liu, 2012).

Task 2.1 Case descriptions: Data has been collected primarily through the work in *Impact of lice from farmed salmonids on wild populations*, and to support research in other tasks. Two historic cases have been documented in terms of their sustainability issues, stakeholder interests, and available data:

1. The sea-lice situation in Mid-Norway, which has utilized historic and ongoing data sampled from farmed and wild fish over several years in the Romsdalsfjord (Bjørn et al. 2013).
2. Outbreaks of PD in the region of Romsdalsfjorden, the county of Sør-Trøndelag, and its potential spread further north.

Data on sea lice abundance and PD prevalence in wild and farmed fish in specific areas has been collected from the industry, research and monitoring programs, and national databases. Sustainability issues has been described with a focus on the potential interaction between disease in aquaculture and its environmental and social effects. The chosen areas have further been subject to disease intervention programs in the salmon industry. Cost data and potential effects on sustainability issues collected and described. Several reports have been published.

Task 2.2 Integration of mathematical models: This is intrinsic to most of the research carried out in the project. Instead of a single integration of models, several approaches to development and integration have been studied. Numerous numerical models and demonstrators have been developed, and scientific papers have been published and are in preparation.

Task 2.3 Hind-cast study: The utilisation of data to test the data has been essential to much of the modelling work in the project. Scientific papers have been prioritized ahead of technical report.

Task 3.1 Decision makers and decision processes: Related to *Sustainability issues and stakeholders' interest* where a paper has been presented and another is in preparation. Some associated projects and initiatives are influenced by project studies (see Task 3.2).

Task 3.2 Development of decision support tools: As focus has shifted from a single integration of models towards individual models with more specific scopes, this task has been given lower priority in the project. There are therefore no project deliverables directly related to this. However, the project has spawned and supported a number of associated projects (e.g. http://chile.sinmod.com/ and http://nordland.sinmod.com/) and future initiatives.

Task 3.3 Simulation scenarios: Again, this task has been intrinsic in much of the modelling work, but without aiming at a single integration of models. Scientific papers have been prioritized ahead of technical report.

Meetings with various stakeholders have been held in a number of contexts. Individual project results have been disseminated through scientific journals, trade press articles (Research Media, 2012; Tønset, 2011) and presentations at conferences and workshops to reach various audiences (see *Results*). General presentations of the project or parts of the project have also been presented to national and international audiences through presentations, trade press articles and home page (Bjelland, 2011a, 2011b, 2013a, 2013b). Two workshops/seminars have been held to present the project results and get feedback from a wider audience.

With regard to its objectives, the project has contributed to knowledge about and relevant to decision-making related to regulations and intervention strategies for disease control in the salmon farming industry. The project has joined diverse research groups and initiated integration of knowledge. This is demonstrated by a number of publications collaboratively written by researchers from two or more partner institutions. However, there are still a number of research tasks remaining that need to be addressed to fully provide decision makers with tools, rather than models and other knowledge components, to assisting both tactical response to an existing situation, and strategic, preventive disease control. While both viral and parasitic disease epidemiology was targeted, there has been a focus on sea lice. This is partly because of the acuteness and industry attention to this problem in the project period. Sea lice also represent a much richer and available data source for model development.

The project has addressed highly acute challenges facing the salmon farming industry. The project group will continue research within the field and utilise knowledge gained to support the industry and the authorities to improve disease management.

4 Results

4.1 Diseases on a local, fish, pen or farm level

Various modelling approaches have been carried out to improve the understanding of disease dynamics, and thereby effects of various interventions and strategies, and data sampling and estimation.

4.1.1 Stochastic model for lice reproduction

A stochastic model for lice reproduction to estimate the number of adult female lice that reproduces at different abundance levels has been developed. This was done by generating a model in @Risk and calibrated by data collected from 13 fish farms. The model showed that the number of fertilized female lice is not linearly related to the number of adult females at the farm, but that the reproduction is slower at low levels due to mate limitations. The results have been presented (Stormoen, Skjerve, & Aunsmo, 2012) and were published in Journal of Fish diseases and are part of Stormoen's PH.D. thesis (Stormoen, Skjerve, & Aunsmo, 2013; Stormoen, 2013).

4.1.2 A dynamic model of lice production

A dynamic model of lice production has been made in Anylogic through a collaboration between NVH and UPEI. The output from the stochastic model has been utilized in this model to estimate the optimal treatment threshold for limiting population growth at low levels. The model, and the paper, was part of Stormoen's PhD thesis (Stormoen, 2013) and a reworked version is planned to be submitted during spring 2014 (Stormoen, Maya L. Groner, Ruth Cox, Crawford W. Revie, & Arnfinn Aunsmo, in prep.). The model has been presented at the SeaLice 2012 and the NRC-conference (Stormoen & Schofield, 2012; Stormoen, 2012).

4.1.3 Agent-based modelling

Dr. Groner's foci have continued to be around novel modelling approaches to sea lice and their responses to medicinal treatments / alternative interventions. She led the development of an agent-based model to help explore the interactions between sea lice population dynamics and cleaner fish (wrasse) under different infestation conditions and temperature regimes. Results from this work, together with an alternative individual-based model resulting from research led by Dr. Cox, were presented in draft form to scientists at a number of conferences (Cox, Groner, Gettinby, & Revie, 2012; Groner, Cox, Gettinby, & Revie, 2012) to aid in finalising a peer-reviewed manuscript, the first that we know of to document a mathematic model for this type of biological control in salmon aquaculture (Groner, Ruth Cox, George Gettinby, & Crawford W. Revie, 2013).

Dr. Groner then led some exploration by the UPEI/UofS team members around the use of population projection matrices (PPMs) as an alternative approach to understanding the importance of the different stages in the sea lice life cycle. The sensitivity and elasticity characteristics that can be derived from such PPMs can be useful in identifying, for example, the important of parameter accuracy as various stages in the sea lice life cycle, or the likely significance of treatment failures that occur due to different modalities of intervention (e.g. inhibition of moulting versus mortality of adult lice). Again the potential of this approach was explored with scientific colleagues through active engagement at scientific conferences (Groner, Cox, Gettinby, Stormoen, & Revie, 2013; Groner & Revie, 2012) and was then published in the form of a full peer-reviewed journal article (Groner, Gettinby, Stormoen, Revie, & Cox, 2014).

An important and growing element of Dr. Groner's research over the final year of the project involved the exploration of appropriate modelling structures to allow for a better understanding, and investigation of the emergence of resistance to chemotherapeutants within sea lice populations. The influence of sea lice population structure, genetic mechanisms of resistance and treatment strategies on mechanisms in the evolution of resistance within sea lice populations are poorly understood, and few models (other than purely theoretical/generic) exist to explore these topics. Dr. Groner has extended the agent-based modelling approach which she piloted to study the impacts of cleaner fish on sea lice populations so that it can now be used to explore how molecular, population and environmental variation influence the evolution of resistance to chemotherapeutants. Once again she has solicited initial feedback from a broader set of research colleagues through a presentation at a conference on Evolutionary Biology (Gettinby, Maya L. Groner, Ruth Cox, C. Robbins, & Crawford W. Revie, 2013; Groner, Ruth Cox, Crawford W. Revie, & George Gettinby, 2013) and has followed this up with a manuscript which will be submitted to Evolutionary Applications for peer-review in spring 2014 (Groner, Gettinby, Cox, & Revie, in prep.).

4.1.4 Impact of gender ratios

Dr. Cox coordinated those modelling research activities which related to the issue of the impact of gender ratios and parasite aggregation on population dynamics, with strong linkage to the work on Allee effects that Dr. Stormoen was carrying out as part of her PhD at the Norwegian College of Veterinary Medicine. It has been pointed out that all mathematical models have made assumptions about sea lice life history and sexual reproduction. However, many of these assumptions are based on parameters that are difficult to estimate where data are sparse or unavailable, yet they can have considerable influence on parasite population dynamics. This research has therefore had two main foci; (i) assessing historical data sets to find evidence for the best parameter estimates or looking to generate such where no data sets are available, and, (ii) the continued exploration of how different assumptions around reproductive success impact of sea lice population dynamics in both DDE and agent-based models.

An assessment of historical data sets included the analysis of data from both farmed and wild salmon populations as it was felt that a clearer understanding of the range of sex ratios, and the circumstances in which they arise, would be helpful in any modelling efforts. This has led to the development of two papers (Ruth Cox, Maya L. Groner, George Gettinby, & Crawford W. Revie, in prep.b; Ruth Cox, Maya L. Groner, George Gettinby, T. Patanasatienkul, et al., in prep.) which also includes scientists from outside of the SALMODIS 'team' with expertise in wild Pacific and returning Atlantic salmonids. In addition Dr. Cox obtained funding through the CERC programme to spend some time looking at empirical data sets from Atlantic salmon farms, which included the opportunity to visit Norway and carry out some project-specific sea lice monitoring together with Dr. Stormoen in September, 2013 (see below for details).

Research on creating models of population dynamics that are suited to exploring these types of issues has also continued. A stochastic individual-based model has been created by Dr. Cox, which simulates individual Atlantic salmon infected with sea lice within a cage during a two-year production cycle. As this model simulates the salmon as the individual; individual salmon lice levels can be recorded. The model has been used to assess issues such as: How does the ratio of male and female lice change according to assumptions about aggregation of male and female lice? Does the ratio of male and female lice change according to external lice infection pressure? Furthermore, additional work is being done to, explore inter alia the fact that these simulations appeared to demonstrate a ‘tipping point’ within the parameter space – a point at which the lice population increases exponentially (Ruth Cox, Maya L. Groner, George Gettinby, & Crawford W. Revie, in prep.a).

Additional research that links with the work of Dr Cox is in the development of DDE models led by Dr Stormoen. The work, which focuses on the influence of the Allee effect and on the effects of treatment thresholds on salmon lice on farmed Atlantic salmon, were explored during a visit that Dr. Stormoen made to UPEI in September/October of 2012 and resulted in the preparation of a scientific manuscript (see *A dynamic model of lice production*).

4.1.5 Recursive bayesian estimation

Beside the various knowledge based modelling approaches, recursive bayesian estimation has been applied in order to improve model predictions from current data available from the national sea lice monitoring programme. This is of particular importance to ensure the accuracy of model predictions which relies on the degree of information available which determines the level of realism that knowledge based models can reproduce according to the different source of variability found in the real system they describe. In addition, the data used for model predictions is sometimes very difficult to provide and include inherent biases due to current limitations in the methodological approaches, technical or economic constraints. A review on current available population models for *L. salmonis* has been performed and a state estimator based on a state space model formulation for the parasitic stages has been built. The state estimator has been applied to a case study on farmed Atlantic salmon from mid-Norway. The results show a systematic underestimation of the chalimus counts on the farmed fishes. This has strong implications for the ability to predict sea lice population levels based on non-filtered data. Subsequently, model predictions based on filtered data have been performed. This investigation shows that further information has to be included in knowledge based models. Among those, data on treatments and treatment effectiveness linked to the treatment types is crucial, the effect of temperature is an important environmental parameter to take into account at the seasonal time scale and that external infection pressure might be relevant to explain an important fraction of the population's variability which remains unexplained. This work is submitted as a scientific paper (Schofield, Eisenhauer, Alver, & Bjelland, submitted).

4.2 Diseases on a regional level

4.2.1 Impact of lice from farmed salmonids on wild populations

Through the project and other related activities, Finstad has participated in monitoring activities of wild salmonid populations. Infectious and parasitic diseases naturally have a direct effect on the welfare of farmed fish. In addition, a serious concern has arisen about the impact of lice from farmed salmonids on wild populations. At any time, the Norwegian salmon industry has more than 350 million fish in open seawater cages. With between 8 to 12 million wild smolts going to sea every year and less than a million returning to coastal waters for spawning, wild populations will thus live in constant threat from exposure to sea lice from farmed salmonids. Atlantic salmon (Salmo salar L.) and wild sea trout (Salmo trutta L.) have a different infection pattern for sea lice because of the strategies employed during the sea phase. Atlantic salmon migrate to the open ocean, whereas sea trout remain in the inner fjord systems. Besides, of the lice problem, a recurrent health problem in salmonid farming is the occurrence of a range of viral infections. Historic cases The field studies have been performed in the Romsdalsfjord area. The field period has been from May to October 2011 (Berg et al., 2012) and from May to August 2012 (Berg et al., 2013; Bjørn et al., 2013; Taranger, Terje Svåsand, Bjørn Olav Kvamme, Tore S. Kristiansen, & Karin K. Boxaspen, 2013). The fieldwork has been demanding and involved personnel from both the science branch and from the industry. Five bag nets for sampling sea trout have been placed at fixed locations in this fjord system in the mentioned field period. At each sampling, the fish has been anaesthetized, sea lice have been counted on the fish, the fish has been tagged (streamer tags) and thereafter been released after a period of recovery (Bjørn et al., 2011). At the same period, lice data on fish in fish farms (13-16 farms in total each year) has been monitored together with biomass data and number of fish in each fish farm making us able to estimate lice production from farms related to infestation of lice on wild fish. These data have thereafter been used for further modelling in other modelling activities. As a general view, we see that the lice load on wild sea trout varies but increases at the outhermost sampling stations in the Romsdalsfjord system. Input of data from lice on wild fish and farmed fish has given us a great opportunity to estimate the realistic lice load on wild fish related to production in farms and enabled the Romsdalsfjord system as an important national modelling area in the same manner as for the Hardangerfjord system. In additions to published reports, and presentations (Finstad, 2011a, 2011b, 2011c, 2012a, 2012a, 2012b, 2012b, 2012c, 2013a, 2013b), the research is planned for publication in scientific papers (Finstad & et al., in prep.a, in prep.b, in prep.c).

4.2.2 Integrated modelling of regional effects and dispersion

Several implementation steps were required to achieve a fully integrated model system able to link the parasitic, free living life cycle phases of sea lice accounting for host density, temperature and wild salmon migration patterns.

The integration of the 3D SINMOD ocean model and a detailed model on the pelagic larval phase has been achieved. The coupled model setup simulates successfully realistic dynamic 3D distribution fields of larval sea lice stages. Model tests have been performed to investigate the vertical distribution of sea lice resulting from the interplay between the potential maximal swimming speed of the sea lice larvae and vertical mixing intensities encountered in the water column for fjord and coastal areas. Model results show that the sea lice are able, at the infectious copepodite stage level at least, to maintain themselves in the upper 10-20 meters. Nevertheless further investigations on the behavioral traits of the sea lice larvae need to be implemented in particular with regard to dial cycles and escape-aggregation behavior along strong haloclines. The model setup also reveals that characteristic topographical features of the landscape such as fjord arms might play an important role in the enhancement and propagation of sea lice larvae. Indeed, the conjunction of the flushing time and the development time of the larvae can display a synergetic effect by acting as a reservoir for development of the larvae in the first instance and to flush out an up concentrated amount of infectious individuals along the front created by the current flowing along the openings of fjordarms creating pulse events.

Furthermore, integration of the oceanographic model setup and the parasitic models describing population dynamics, ontogenetic development and reproduction dynamics at the fish farms (Stormoen et al., 2013) has been achieved. Test runs have been performed to provide model estimates of larval sea lice concentrations in the water mass, which is critical information to obtain for predicting infection pressure and very difficult to access by means of direct measurements. Indeed, estimates from realistic model scenarios confirm that the relatively high amount of sea lice eggs released per site lead to concentrations below 1 ind. m^{-3} throughout the water column most of the time. Particular pulse events of higher larval concentrations resulting from the interplay between larval migratory behavioral processes and particular patterns of the ocean current field are key in predicting external infection events which play a crucial role in the initial infection processes and infection dynamics at larger geographic scales, i.e. coastal areas.

A langrangian (particle based) smolt migration model for the wild salmon (*S. salar*) has been implemented to the model setup described above in order to evaluate the impact of the infection pressure generated by the farming activity onto the wild salmon migrating trough fjords in the spring timesurrounding water masses. Model tuning has been performed on the swimming behavior to optimize the modeled swimming behaviormigration pattern of the fish in near shore areas in order to prevent an overestimation of the exposure times to sea lice concentrations and a potential bias in the encounter rates between the salmon smolts and the sea lice infectious stage. Moreover, test runs have been carried out to quantify the impact of the known variability in the average swimming speed of salmon smolts (between 0.5 and 1 body length per second) during the spring run across areas featuring salmon farming activity to sea lice exposure. Results show that the sensitivity to the swimming speed plays a major role in the encounter rates related to very localized higher sea lice concentration fields which might be found along the salinity fronts or in relatively steady eddy structures.

A fully integrated model setup has been applied to a case study for the Romsdal fjord (midt-Norway) based on data delivered by the National Plan on Salmon Lice Survey combined with data on salmon smolt migration time windows from the major rivers systems provided by the National Institute for Nature Research (NINA) in collaboration with Dr. Bengt Finnstad. A series of test runs have been performed to explore the sensitivity of the Cultured Salmon – Sea Lice – Wild Salmon interactions with focus on the oceanographic features likely to enhance the propagation of the infectious agent in conjunction with the larval development time of the sea lice. In addition to presentations (Eisenhauer, 2013; Knudsen, Ingrid Ellingsen, Brad Schofield, & Hans Vanhauwaert Bjelland, 2011, 2012; Knudsen, Ingrid Ellingsen, Lionel Eisenhauer, & Hans Vanhauwaert Bjelland, 2012), the results of the integrated model system will be published in a scientific paper (Eisenhauer, Ellingsen, Knudsen, Bjelland, & Finstad, in prep.).

4.3 Diseases on a strategic and decision maker level

4.3.1 Sustainability issues and stakeholders' interest

NTNU Samfunnsforskning carried out an empirical study based on qualitative interviews and document studies during 2011. The objective of the study was to study sustainability issues and stakeholders' interest related to diseases and disease control. A literary review on disease control encompassing both public regulation and laws as well as earlier research was conducted. Thereafter 20 key respondents were interviewed, representing both the industry and governmental agencies. Also, a workshop was held allowing a larger group of stakeholders to respond to preliminary findings. Their views and opinions were included as part of the data material. This work resulted in a report on disease control strategies and decision making in salmon farming (Osmundsen, Silje Skaug, Petter G. Almklov, Jørn Fenstad, & Kristine Vedal Størkersen, 2012).

The report deviates from earlier research by taking a social science perspective on the challenges of disease control in salmon farming. Controlling and preventing diseases and lice in aquaculture is an important issue for the industry and society at large. Diseases infect between farmed and wild fish, and may cause severe consequences in both groups. While there are many effective measures in place, both through the daily routines at the individual fish farm, and in the work done by various authorities, there are still improvements that can be made. There is much we do not know about diseases in aquaculture in regards to infection and possible treatments; decision making is therefore often based on guess-work, hearsay and former experience. In some cases, these sources of knowledge are invaluable, but in others they cause erroneous inference. A relevant example is when knowledge is not transferable between two apparently similar situations. We find that the industry applies a wide range of measures to combat and prevent diseases, but few of these have a proactive long-term perspective.

The main points of the report were in 2012 developed into a paper applying these findings to a safety perspective focusing on decision-making issues. The paper was presented at the Working on Safety conference in Gdansk, Poland in September 2012 (Osmundsen, Petter G. Almklov, & Hans Vanhauwaert Bjelland, 2012c). Our findings show that constraints on decision making in aquaculture is in particular related to what many see as a lack of knowledge on basic and fundamental issues related to disease control. Respondents emphasized that they found it difficult to evaluate research results and to make use of such results in the daily running of the farm. They, therefore, emphasized their reliance on prior experience as a main source for information. Experience has the advantage that it is actionable knowledge: it contains the definition of the problem, possible solutions, and description of how to take actions. Research results on the other hand may appear abstract and removed from real problems at the farm. It is fruitful to understand decision making in fish farming through a perspective emphasizing the interdependencies and complexities of the decision context. Irrespective of who makes a decision there will always be an element of uncertainty and a network of actors involved in the process. These will weigh the multitude of conflicting considerations, like economic profit, fish welfare and wild fish survival, differently. In addition, the decision process plays out on a political field where the reputation of the industry is at stake. Fish farming companies often involuntary have to share the blame, supporting communal efforts to control diseases. Herein also lay the fundamental dilemma fish farmers face. In order to progress with articulation work, and continuously improve their ability to handle diseases and parasites they are dependent on transparency. Improved access to data and information from nearby farms is a necessity for knowledge growth and integrated decisions. On the other hand, such information may also be used in a negative manner by media, environmentalists, and at times by the authorities. There is therefore resistance towards transparency even though they may also benefit by sharing more information. Increasingly groups of fish farmers have established their own closed databases accessible to only themselves.

While the paper was presented at WOS conference (Osmundsen, Petter G. Almklov, & Hans Vanhauwaert Bjelland, 2012b; Osmundsen, Petter G. Almklov, et al., 2012c) and later developed to a Norwegian article in Norsk Fiskeoppdrett (Osmundsen, Petter G. Almklov, & Hans Vanhauwaert Bjelland, 2012a), it is now under revision to be sent in for review to an international journal (Osmundsen, Almklov, & Bjelland, in prep.).

4.3.2 Economic model of control strategies at a farm level

The economics of control strategies at a farm level have been explored with a focus on sea lice problem. Diseases can cause reduction in growth, low feed efficiency and market prices, increasing mortality rates, and expenditures on prevention and treatment measures. Aquaculture farms suffer the most direct and immediate economic losses from diseases. Prevention and treatment strategies are at the core in eliminating or minimizing the disease, while cost-effective disease control strategies at the fish farm level are needed to enhance productivity and profitability. The goal of a control strategy is to minimize total disease costs including biological losses and treatment costs while to maximize overall profit. Achieving this goal depends on the integration between fish growth, sea lice dynamics and economic factors. A production function has been constructed to incorporate the effects on production at a farm level, followed by cost-benefit analysis to take into account several prevention and treatment strategies. The model has been applied to case studies in Norway with a focus on sea lice. The results that have been submitted to a scientific journal (Liu & Bjelland, submitted) and reveal that treatments are very costly and treatment costs are very sensitive to treatment types used and timing of treatment conducted.

4.3.3 Epidemiological-economic model of sea lice spread and control

NUPI contributions to SALMODIS have revolved around the development of an epidemiological-economic model of sea lice spread and control. Kanar Hamza, a research assistant at NUPI who will soon be starting a Ph.D. at the University of New England in Australia, worked with Dr. Karl M. Rich of NUPI to develop a system dynamics (SD) model of sea lice and salmon production for his M.Sc. at the University of Bergen. His model contained separate models of sea lice, salmon growth, and their interaction, combined with a module that simulated the costs associated with different control strategies. Model results indicated that sea lice infection pressure was markedly reduced by changing the timing and type of treatment vis-à-vis current practices. This was also more cost effective than current practices. An innovation of this model was to directly incorporate the role that delays and feedbacks play in disease control protocols and the role that systems models can play in aquatic health, which represents an important contribution to the literature. The main paper from the thesis was submitted for publication (Hamza, Rich, & Wheat, Submitted), while a synthesis paper was published (in Norwegian) in *Norsk Fiskeoppdrett* (Hamza & Aunsmo, 2013). Presentations has been made at international conferences (Hamza, Karl Rich, & David Wheat, 2012a, 2012b; Hamza, Karl Rich, Marit Stormoen, et al., 2012; Hamza, 2012; Rich, Stormoen, Aunsmo, Hamza, & Skjerve, 2011).

A final contribution to SALMODIS is an extension of Mr. Hamza's SD model to incorporate sea wrasse as a more sustainable means of sea lice control. This paper will be submitted to the International Institute for Fisheries Economics and Trade meetings in Australia in 2014 (Hamza & Rich, 2014) and for later submission for publication in 2014. Tentative model results showed that using sea wrasse is extremely efficient in controlling sea lice at low levels in salmon farms, significantly reducing the need of using multiple chemical treatments to control lice population. The reduced use of chemical treatments leads to a significant reduction in costs to control sea lice relative to the case of not using sea wrasse. Reducing dependency on chemicals to control lice population further benefits the salmon industry through reducing its environmental footprint and enhancing the social responsibility of the industry.

4.3.4 Controlling emerging infectious diseases in salmon aquaculture

The epidemiology, economic and social science groups in the project cooperated on a paper to the OIE Scientific and Technical Review, *Controlling emerging infectious diseases in salmon aquaculture* (Aunsmo, Tonje C. Osmundsen, T. M. Pettersen, F.O. Mardones, & Karl Rich, submitted). The impact of disease incursions facing salmon aquaculture, drawing lessons between terrestrial animal diseases and those facing aquaculture has been reviewed. Different types of control strategies implemented against emerging diseases in aquaculture are discussed, and further how the properties of different infectious agents may induce decisions towards different control strategies. Furthermore, the institutional organization of control strategies are discussed, with particular emphasis on the roles and responsibilities of regulatory authorities and the private sector, both in aggregate and among individual companies. As case studies, the emergence and control of ISA worldwide and PD in Norway are compared and contrasted, this to enlighten some of the controversies that may evolve.

5 Dissemination

5.1 Peer reviewed

Gettinby, G., Robbins, C., Lees, F., Heuch, P. A., Finstad, B., Malkenes, R., & Revie, C. W. (2011). Use of a mathematical model to describe the epidemiology of Lepeophtheirus salmonis on farmed Atlantic salmon Salmo salar in the Hardangerfjord, Norway. Aquaculture, 320(3-4), 164–170. doi:10.1016/j.aquaculture.2011.03.017

Groner, M. L., Cox, R., Gettinby, G., & Revie, C. W. (2013). Use of agent-based modelling to predict benefits of cleaner fish in controlling sea lice (Lepeophtheirus salmonis) infestations on farmed Atlantic salmon. Journal of Fish Diseases, 36, 195–208.

Groner, M. L., Gettinby, G., Stormoen, M., Revie, C. W., & Cox, R. (2014). Modelling the impact of temperature-induced life history plasticity and mate limitation on the epidemic potential of a marine ectoparasite. PlosOne.

Heuch, P. A., Gettinby, G., & Revie, C. W. (2011). Counting sea lice on Atlantic salmon farms-empirical and theoretical observations. Aquaculture.

Stormoen, M., Skjerve, E., & Aunsmo, A. (2013). Modelling Salmon lice (Lepeophtheirus salmonis, Krøyer) reproduction on farmed Atlantic salmon (Salmo salar L). Journal of Fish Diseases, (1), 25–33.

5.2 Submitted or in preparation

Aunsmo, A., Osmundsen, T. C., Pettersen, T. M., Mardones, F. O., & Rich, K. (submitted). Controlling emerging infectious diseases in salmon aquaculture. *OIE Scientific and Technical Review*.

Cox, R., Groner, M. L., Gettinby, G., Patanasatienkul, T., Todd, C. D., & Revie, C. W. (in prep.). Sex ratios and aggregation of male and female sea lice Lepeophtheirus salmonis and Caligus. clemensi on wild salmon hosts. *Target Journal: American Naturalist*, *Anticipated submission: Spring 2014*.

Cox, R., Groner, M. L., Gettinby, G., & Revie, C. W. (in prep.a). Individual-based modelling to investigate the influence of parasite aggregation and sex ratio on the population dynamics of the salmon louse Lepeophtheirus salmonis, *Anticipated submission: Summer 2014*.

Cox, R., Groner, M. L., Gettinby, G., & Revie, C. W. (in prep.b). Infestation of the ectoparasitic sea louse, Lepeophtheirus salmonis, on farmed Atlantic Salmon, Salmo salar L: intensity, distribution and gender ratio, *Anticipated submission: Spring 2014*.

Eisenhauer, L., Ellingsen, I., Knudsen, Ø., Bjelland, H. V., & Finstad, B. (in prep.). Modeling the complete sea lice (L. salmonis) life-cycle: a tool for evaluating the impact on cultured and wild salmon. *Rine Ecology Progress Series*.

Finstad, B., & et al. (in prep.a). Fishing coastal fish with bag-nets in Norwegian fjords: relationships among captured fish species and environmental parameters. *Journal Not Decided*.

Finstad, B., & et al. (in prep.b). From farms to wild: salmon lice (Lepeophtheirus salmonis) infection on sea trout (Salmon trutta) populations in Norwegian fjord systems. *Journal Not Decided*.

Finstad, B., & et al. (in prep.c). Low recaptures of tagged sea trout (Salmo trutta) infected with sea lice (Lepeophtheirus salmonis) in Romsdalfjord, Norway. *Journal Not Decided*.

Groner, M. L., Gettinby, G., Cox, R., & Revie, C. W. (in prep.). Modelling the influence of refugia on the evolution of resistance to chemotherapeutants in Lepeophtheirus salmonis. *Target Journal: Evolutionary Applications*, *Anticipated submission: March 2014*.
Hamza, K., Rich, K., & Wheat, D. (submitted). A system dynamics approach to sea lice control in Norway. *Submitted to the Journal of Aquaculture Economics & Management*.
Liu, Y., & Bjelland, H. V. (submitted). Economics of Disease Control Strategy in Salmon Aquaculture. *Preventive Veterinary Medicine*.
Osmundsen, T. C., Almklov, P. G., & Bjelland, H. V. (in prep.). Decision making as articulation work in fish farming disease control. *Working on Safety*.
Schofield, B., Eisenhauer, L., Alver, M. O., & Bjelland, H. V. (submitted). Population dynamics modeling and recursive Bayesian estimation for tracking Salmon lice (Lepeophtheirus salmonis) abundance on farmed Atlantic salmon (Salmo salar). *Aquaculture*.
Stormoen, M., Maya L. Groner, Ruth Cox, Crawford W. Revie, & Arnfinn Aunsmo. (in prep.). Effects of treatment thresholds on salmon lice (Lepeophtheirus salmonis) populations on farmed Atlantic salmon (Salmo salar, L.), a system dynamics approach, *[A version of this has been presented as part of Dr. Stormoen's PhD thesis but the co-authors will continue to collaborate to have it submitted as a full scientific paper.]*.

5.3 Thesis and reports

Berg, M., Bengt Finstad, Arne Kvalvik, Ingebrigt Uglem, Pål Arne Bjørn, & Rune Nilsen. (2013). *Laksefisk og luseovervåking i Romsdalsfjorden - Del 2.* (NINA Rapport No. 919) (pp. 1–42). Trondheim, Norway: Norsk institutt for naturforskning.
Berg, M., Finstad, B., Kvalvik, A., Uglem, I., Bjørn, P. A., & Nilsen, R. (2012). *Laksefisk og luseovervåking i Romsdalsfjorden* (NINA Rapport No. 779). Trondheim, Norway: Norsk institutt for naturforskning.
Bjørn, P. A., Finstad, B., Asplin, L., Skilbrei, O., Nilsen, R., Llinares, R. M. S., & Boxaspen, K. K. (2011). *Metodeutvikling for overvåkning og telling av lakselus på viltlevende laksefisk* (No. 8-2011). Tromsø/Bergen, Norway: Havforskningsinstituttet.
Bjørn, P. A., Nilsen, R., Serra Llinares, R. M., Asplin, L., Boxaspen, K. K., Finstad, B., … Wiik Vollset, K. (2013). *Lakselusinfeksjonen på vill laksefisk langs Norskekysten i 2013* (Sluttrapport til Mattilsynet No. 32-2013) (pp. 1–34). Bergen, Norway: Havforskningsinstituttet.
Hamza, K. (2012, June 29). *The Role of System Dynamics Approaches in Aquatic Disease Management: An Application to Sea Lice Control in Norway* (Master of Philosophy). University of Bergen, Bergen, Norway.
Osmundsen, T. C., Skaug, S., Almklov, P. G., Fenstad, J., & Størkersen, K. V. (2012). *Disease control strategies and decision making in salmon farming - Perspectives from the social sciences*. Studio Apertura, NTNU Samfunnsforskning AS.
Schofield, B., Bjelland, H. V., Ellingsen, I., Knudsen, Ø., Thakur, M., & Liu, Y. (2012). *SALMODIS Task 1.2 - Models and other knowledge contributors*. SINTEF Fiskeri og havbruk AS.
Stormoen, M. (2013). *Disease control in Norwegian marine salmon aquaculture. Contrasting pathogens, diseases and control.* (PhD Thesis). Norwegian University of Science and Technology, Oslo, Norway.
Taranger, G. L., Svåsand, T., Kvamme, B. O., Kristiansen, T. S., & Boxaspen, K. K. (2013). *Risikovurdering norsk fiskeoppdrett 2012* (Fisken og havet No. særnummer 2) (p. 164s).

5.4 Trade press

Hamza, K., & Aunsmo, A. (2013). Bruk av system-dynamiske modellering ved beslutninger i håndtering av sykdom i akvakultur. *Norsk Fiskeoppdrett*, (4), 54–57.
Osmundsen, T. C., Almklov, P. G., & Bjelland, H. V. (2012a). Bevisfellen. *Norsk Fiskeoppdrett*, *2012*(7).
Research Media. (2012, July). Saving salmon – and money/Facing fish farm challenges. *International Innovation*, 25–27.
Tønset, S. (2011, mai). Vil bekjempe sykdom med helhetsblikk. *Fish.no*. Retrieved from http://www.fish.no/oppdrett/4528-vil-bekjempe-sykdom-med-helhetsblikk.html

5.5 Presentations

Bjelland, H. V. (2011a, September 10). *SALMODIS*. Presented at the Lakselusworkshop i regi av forskningsprosjektet PrevenT, Ålesund, Norway.
Bjelland, H. V. (2011b, November 21). *Bærekraftige kontrollstrategier mot sykdom i lakseoppdrett*. Presented at the Arbeidsmøte i FHF Verdikjede havbruk, Gardermoen.

Bjelland, H. V. (2013a). SALMODIS project: Getting an overall view to get salmon diseases under control. Presented at the Science Week, Puerto Varas, Chile.

Bjelland, H. V. (2013b). Tools and methodologies for _strategic control of diseases. Presented at the Science Week, Puerto Varas, Chile.

Cox, R., Groner, M. L., Gettinby, G., & Revie, C. W. (2012, August 20). *Modelling the effectiveness of cleaner fish for the biological control of sea lice in farmed salmon*. Poster presented at the The 13th conference of the International Society for Veterinary Epidemiology and Economics, Maastrich, The Nederlands. Retrieved from http://www.isvee13.org/

Eisenhauer, L. (2013, August 15). *Modeller for lakselus på og mellom lokaliteter*. Presented at the Varslingstjenester for havbruksnæringen, Seminar under AquaNor 2013, Trondheim, Norway.

Finstad, B. (2011a, March 2). *Lakselusfaren og situasjonen for villaksen*. Presented at the Årsmøte for Vefsn jeger og fiskerforening, Fru Haugans Hotell, Mosjøen.

Finstad, B. (2011b, November 16). *Miljøvirkninger av havbruk*. Presented at the Havforskermøtet 2011, Royal Garden, Trondheim.

Finstad, B. (2011c, November 22). *Resultater fra den nasjonale lakselusovervåkningen og Resultater fra andre prosjekter i Romsdalen (telemetri og vandringsstudier)*. Presented at the Fagseminar om lakselus og luseovervåkning i Romsdalsfjorden, Rica Seilet Hotell, Molde, Norway.

Finstad, B. (2012a, March 14). *Lakselus – villfisk*. Presented at the Helsetjenesten for kultiveringsanlegg, Quality Airport Hotell, Værnes, Norway.

Finstad, B. (2012b, May 7). *Ecological behavior of salmonids in their changing environments in Norway*. Presented at the The 6th World Fisheries Congress, Edinburgh, UK.

Finstad, B. (2012c, September 28). *Resultat av lusekartlegging på sjøørret i Romsdalsfjorden*. Presented at the Akva Møre-konferansen 2012, Quality Waterfront Hotel, Ålesund, Norway.

Finstad, B. (2013a, February 21). *Sea lice studies at NINA – Interactions between wild- and farmed fish*. Presented at the Direktoratet for naturforvaltning – møte mellom Irske og Norske lakseforvaltere, Trondheim, Norway.

Finstad, B. (2013b, November 6). *Lus og villfisk – effekter på individ og populasjoner i små og store fjordsystem*. Presented at the KLV-seminar - Lakselus – kunnskapsstatus og tiltak i Namdalen, Juvika, Høgskolen i Nord-Trøndelag, Campus Namsos, Norway.

Gettinby, G., Groner, M. L., Cox, R., Robbins, C., & Revie, C. W. (2013). Two models for the control of sea lice infections using chemical treatments and biological control on farmed salmon populations. Presented at the Proceedings of the 22nd Meeting of the Population Approach Group in Europe (PAGE), Glasgow, Scotland.

Groner, M. L., Cox, R., Gettinby, G., & Revie, C. W. (2012, May 20). *Understanding the role of wrasse in controlling sea lice using individual-based models*. Presented at the Sea Lice 2012, Bergen.

Groner, M. L., Cox, R., Gettinby, G., Stormoen, M., & Revie, C. W. (2013). *Influence of temperature on the life history and epidemic potential of a marine ectoparasite of salmon*. Presented at the Ecology and Evolution of Infectious Diseases 2013, State College, PA, USA.

Groner, M. L., Cox, R., Revie, C. W., & Gettinby, G. (2013). *Modeling resistance to chemotherapeutants in salmon ectoparasites: the influence of treatment regimens and temperature*. Presented at the European Society of Evolutionary Biology 2013, Lisboa, Portugal.

Groner, M. L., & Revie, C. W. (2012, July 6). *Elastograms and Individual-based models: comparing approaches to understanding effects of life history variation on the evolution of resistance to insecticides in sea lice (Lepeophtheirus salmonis)*. Poster presented at the Poster at Evolution 2012, Ottawa, Canada. Retrieved from http://www.confersense.ca/Evolution2012

Hamza, K., Karl Rich, Marit Stormoen, Arnfinn Aunsmo, & Eystein Skjerve. (2012, July 16). *An integrated epidemiological-economic model of sea lice control in aquaculture: A system dynamics approach*. Presented at the 16th biennial conference of the International Institute for Fisheries Economics and Trade (IIFET), Dar es Salaam, Tanzania.

Hamza, K., & Rich, K. (2014, July 7). *Sustainable biological control of sea lice in Norwegian Atlantic salmon farms: a system dynamics approach*. Presented at the Submitted to the 17th biennial conference of the International Institute for Fisheries Economics and Trade, Queensland University of Technology (QUT), Brisbane, Australia.

Hamza, K., Rich, K., & Wheat, D. (2012a, July 16). *The Role of System Dynamics Approaches in Aquatic Disease Management: An Application to Sea Lice Control in Norway*. Presented at the Conference of the International Institute of Fisheries Economics & Trade (IIFET), Dar es Salaam, Tanzania.

Hamza, K., Rich, K., & Wheat, D. (2012b, July 22). *The Role of System Dynamics Approaches in Aquatic Disease Management: An Application to Sea Lice Control in Norway*. Presented at the Proceedings of the 30th International Conference of the System Dynamics Society, St. Gallen, Switzerland.

Knudsen, Ø., Ellingsen, I., Eisenhauer, L., & Bjelland, H. V. (2012, May 20). *Modelling dispersion of sea lice (L. salmonis) in Romsdalsfjorden –implications for wild and farmed salmon*. Presented at the Sea Lice 2012, Bergen.

Knudsen, Ø., Ellingsen, I., Schofield, B., & Bjelland, H. V. (2011, November 16). *Modelling of sea lice in SALMODIS*. Presented at the Havforskermøtet 2011, Royal Garden, Trondheim.

Knudsen, Ø., Ellingsen, I., Schofield, B., & Bjelland, H. V. (2012, April 16). *Modellering av populasjonsvekst og spredning av lakselus i Romsdalsfjorden - konsekvenser for vill og oppdrettsfisk*. Presented at the Programkonferansen Havbruk 2012, Stavanger.

Liu, Y. (2012, July 16). *The Economics of Controlling Diseases on Fish Farms*. Presented at the Conference of the International Institute of Fisheries Economics & Trade (IIFET), Dar es Salaam, Tanzania.

Osmundsen, T. C., Almklov, P. G., & Bjelland, H. V. (2012b, August 23). *Decision making as articulation work in fish farming disease control*. Presented at the Samfunnsdagen 2012, Trondheim, Norway.

Osmundsen, T. C., Almklov, P. G., & Bjelland, H. V. (2012c, September 14). *Decision making as articulation work in fish farming disease control*. Presented at the Working on safety, Sopot, Poland. Retrieved from http://www.wos2012.pl/

Rich, K., Stormoen, M., Aunsmo, A., Hamza, K., & Skjerve, E. (2011). Economic impacts of aquatic diseases: methodological issues and applications to sea lice control in farmed Norwegian salmon. Presented at the Forum for North American Association of Fisheries Economics, Honolulu.

Stormoen, M. (2012, April 16). *Fordeling av lus på laks og betydning for reproduksjon og kontroll*. Presented at the Programkonferansen Havbruk 2012, Stavanger, Norway.

Stormoen, M., & Schofield, B. (2012, May 20). *Salmon Lice Population Dynamics Modeling with Applications to Treatment Strategies*. Presented at the Sea Lice 2012, Bergen.

Stormoen, M., Skjerve, E., & Aunsmo, A. (2012, August 20). *Stochastic simulation model - proportions of pregnant salmon lice*. Poster presented at the The 13th conference of the International Society for Veterinary Epidemiology and Economics, Maastrich, The Nederlands. Retrieved from http://www.isvee13.org/