Salmon Parasite Interactions in Linnhe, Lorn and Shuna (SPILLS) Final Project Report

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Salmon Parasite Interactions in Linnhe, Lorn and Shuna (SPILLS) Final Project Report

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Foreword

Sustainable use and management of the marine environment requires robust environmental monitoring and modelling to understand and mitigate against risks caused by human activities, including potential risks posed by sea lice originating from salmon farms in Scotland to wild and farmed salmonids.

Marine finfish farms are regulated by the Scottish Environmental Protection Agency. Modelling and environmental monitoring underpin SEPA's approach to regulating discharges from fish farms (SEPA 2019) and will also underpin its regulation of the interactions between sea lice from farms and wild salmonids as it takes on this responsibility in due course[1].

The SPILLS project compared three models that had hitherto been developed by different organisations as tools to predict levels and distribution of sea lice in the environment as they spread from open-pen salmon aquaculture facilities. Such models have a role to play in understanding transmission of lice between fish farm sites and also to wild fish. This is the first attempt at a detailed configuration, calibration and validation exercise to compare the models. It has used best available information on actual lice levels in the environment and also set out to explore potential for collecting further such data as a source for fine-scale validation.

In addition to analysing model predictions from individual models, the project also applied an averaging "ensemble" approach as part of a research exercise to explore potential for combining model outputs. Use of an ensemble, together with geographic information tools, enabled an approach for visualising how coherence in model predictions varies throughout a sea loch i.e. where, locally, do the models tend to make similar or divergent predictions.

Key findings of interest to the development of sea lice models for regulation are:

[1] Salmon Interactions Working Group Report: Scottish Government Response - gov.scot (www.gov.scot)

1. Overall, the models worked reasonably well when evaluated against time-integrated (sentinel caged fish) data with a sufficiently strong signal (high signal-to-noise ratio). Therefore, targeted sampling for model validation should be focused on time periods when relatively high lice numbers are expected.
2. Planktonic sea lice data, collected using plankton trawls and pumps, did not produce useful data with which to evaluate model performance because lice distributions are so patchy in space and time.
3. There was variation in predicted local lice densities among the three models tested. Hence, for management applications, either model selection will be required, or a number of models can be averaged in an “ensemble”.
4. Calibration and testing of the individual model components is essential; in particular, thorough calibration and validation of the underlying hydrodynamic model is of importance because of the sensitivity of particle tracking results to hydrodynamic modelling outputs, and the relative difficulty in validating biological elements directly.
5. Model predictions are improved relative to simulations of passive particles when sea lice biology is represented; targeted laboratory experiments and further field studies to improve understanding of sea lice can be expected to help improve model parameterisation.
6. Model evaluation in the project was hampered by uncertainties in numbers of lice on farms and the deployment periods of sentinel cages. Had better data been available, it is likely that model fits would have been improved by reducing “noise”. A new programme of sentinel cage deployments to provide “clean” datasets would help with the wider validation of these models.
7. Overall, the project has made very substantial advances by bringing together three key modelling groups (research, government and industry) for a detailed exploration of their available models and clear signposting of next steps and cautions required for management applications.

Executive Summary

The Salmon Parasite Interactions in Linnhe, Lorn and Shuna (SPILLS) project was a 2-year, collaborative project (Annex 2) supported by Crown Estate Scotland and involving finfish farm operators (Mowi Scotland Ltd., Kames Fish Farming Ltd.), Argyll Fisheries Trust (AFT), Argyll District Salmon Fishery Board (ADSFB), Fisheries Management Scotland (FMS), the Scottish Association for Marine Science (SAMS), and Government researchers in Marine Scotland Science (MSS). Staff changes during the project led to participation from Scottish Sea Farms Ltd (SSF) in an advisory capacity.

The Project was designed to:

- Inform and refine the sea lice dispersal models which are used to estimate risks posed by sea lice to wild and farmed salmonids in Loch Linnhe, the Firth of Lorn and Shuna Sound region in West Scotland;
- Evaluate the performance of different sea lice dispersal models for application in managing interactions between sea lice and wild and farmed fish.

Sea lice dispersal modelling is a key component for making predictions of sea lice larvae dispersal in the environment (Figure 1). Sea lice dispersal models consist of hydrodynamic models coupled to particle tracking models. Hydrodynamic models simulate time-evolving physical characteristics of a sea area, including movement of water, water temperatures and salinities. Particle tracking models simulate the transport and dispersal of particles (representing sea lice in this case) from sources (existing farms and proposed farms) and the resulting sea lice concentrations in the modelled sea area. Particle tracking models can represent a range of sea lice behaviours, including: the rate of addition of sea lice larvae from farms; the maturation of the larvae from nauplii to the infective copepodid-stage; swimming behaviours; and mortality.

There are multiple particle tracking models in use, including commercially available packages. The Project used three different particle tracking models to predict the lice exposure of fish in different locations in two study areas, the Shuna Sound area; and Loch Linnhe and the Firth of Lorn.

Modelling objectives vary but can be ascribed to three main categories:

i. "Screening" models(US EPA, 2022a), which represent risk as simply as possible. They are designed to triage clear high and low risks, and identify situations that require further assessment (Pendleton et al. 2015). Simple models can make robust, but generally conservative, predictions with limited data.
ii. "Refined" models (US EPA, 2022b) , used to aid decision making or assess regulatory compliance, including in refinement of screening model results where more detailed assessment is required. The models may include a more sophisticated representation of the system being modelled than screening models and require a greater degree of calibration and validation. The level of sophistication and validation for a refined model should be proportionate to the questions being addressed or the decisions the models are intended to support, but ultimately should demonstrate that the model is "fit for purpose" (FWR, 1993).
iii. "Research" models, intended to improve understanding of the system and of the models themselves, with the resulting knowledge being used to support and improve screening and refined models.

The focus of the Project was on the development and evaluation of sea lice dispersal research models used in Scotland and associated field observation methods. Key goals were to assess and improve the models' prediction capability in Scotland, and to establish their suitability for supporting sea lice management and regulation.

The models developed by the Project and the lessons learned can be used:

- To provide data against which to benchmark the performance of screening models.

- To determine the essential processes and model characteristics that need to be incorporated by sea lice dispersal models in Scotland.
- As practical reference material for those developing sea lice models for other areas.

The Project was designed around the conceptual framework shown in Figure 1. By considering modelling and observations together, better predictions of the "current environment" can be made than by using any one element in isolation (Figure 1). This can facilitate appropriate action to achieve a healthier environment. Societal and policy definitions of an acceptably "healthy" environment enable better allocation of resources for management goals. This is part of a wider conversation, not explored within the Project.

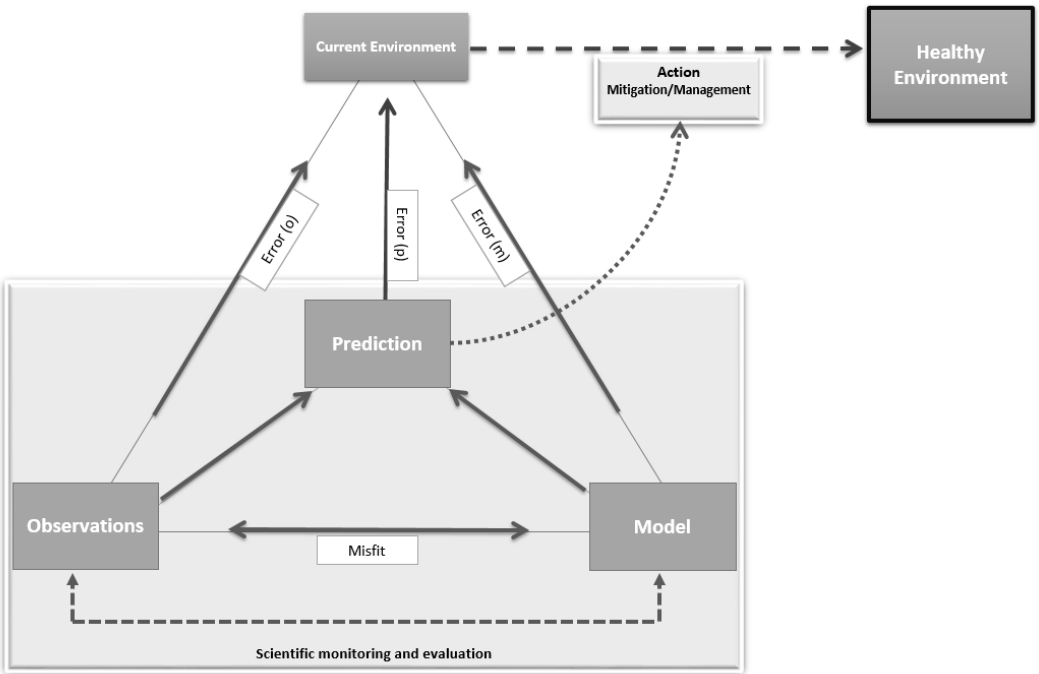

Figure 1: Conceptual framework of the interconnected nature of scientific monitoring and evaluation through modelling and observations, highlighting how it influences actions through management to reach a healthy environment (adapted after Lynch et al. 2009).

The Project provided the first ever systematic cross-comparison of different sea lice dispersal models produced by partners in different sectors (academic, Government, and industry), including validation against field data. The latter included collection and analysis of the following data sources and assessment of their potential for use to validate sea lice dispersal models:

- counts of lice infesting salmon held in moored sentinel cages, which are designed to measure infective pressure of lice on fish;
- lice captured in plankton tows, which are designed to measure sea lice in the water column;
- lice counts on wild-caught fish.

Model variability and uncertainty were investigated, recognising that understanding uncertainties and their contribution to the range and likelihoods of possible outcomes is critical to aid robust decision making (HM Treasury 2015).

The Project was carried out in connected work packages (Figure 2). An outline of the scope of each work package is provided in Annex 1 to this summary.

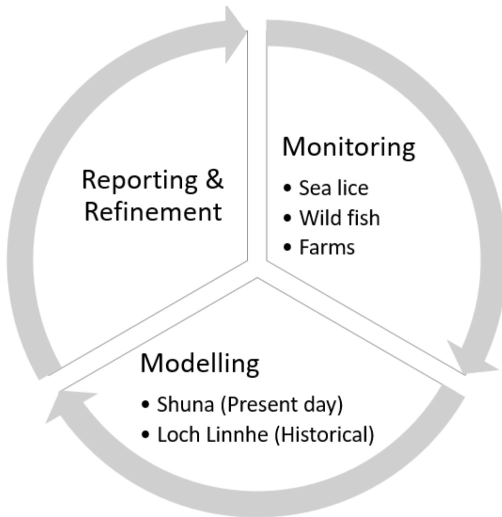

Figure 2: Summary of the iterative approach used during the SPILLS project.

This document summarises and synthesises the findings detailed in the reports from each of the Project's work packages. It also summarises use and dissemination of the information (Annex 3).

Synthesis of Key Findings and Recommendations

1. Overall, the sea lice dispersal models evaluated in the Project replicated the variability of observational data and produced a reasonable match to the most suitable infection pressure (sentinel cage) data.

All three sea lice dispersal models' predictions of sea lice infestation pressure were in broad agreement with sentinel caged fish sea lice count data in the Loch Linnhe study area, although there were inevitably some discrepancies. The best fit occurred when the signal-to-noise ratio was relatively high.

Model evaluation using pelagic larval sea lice counts in both study areas was not successful (see item 4 below).

2. Calibration, testing and sensitivity analysis of the individual components of sea lice dispersal models (both hydrodynamic and particle tracking models) is the best approach to ensuring robust model results.

Models and field data should be used together to strengthen monitoring and modelling methodologies and improve understanding of real-world sea lice larvae distributions.

Calibration and validation of hydrodynamic models is of particular importance because of the sensitivity of particle tracking results to hydrodynamic modelling outputs, and the relative difficulty in validating biological elements directly.

Standard tests are available that can be used for assessing the accuracy of particle tracking models in simulating advection and diffusion (e.g. Brickman et al., 2009).

Calibration and testing would benefit from the development of standard tests for the accuracy of particle tracking model simulations of lice behaviour (e.g. swimming behaviour), in addition to a standard protocol for sensitivity analysis

Testing showed that the use of passive, neutrally buoyant particles in particle tracking models does not represent sea lice larvae distributions well. Including sea lice larvae swimming behaviours improved model predictions.

3. **Sentinel caged fish sea lice counts currently provide the best data for validation of sea lice dispersal model predictions.**

Sentinel caged fish sea lice counts provide a useful time-integrated signal of the infection risk to fish and an indirect inference on distributions of copepodid life stages, which are an output of sea lice dispersal models.

A good fit was found between sea lice dispersal model predictions and sentinel caged fish lice counts for two of the models when lice were relatively abundant (autumn 2011 in the Loch Linnhe study area), such that there was a high signal-to-noise (prediction error) ratio. The fit of the third model was not significant; therefore, this model requires further development. When the signal-to-noise ratios were lower, the model fits to data were less good, as the ability of models to detect signals in the higher relative noise is reduced (Silver, 2012).

Development of a more geographically comprehensive sentinel cage deployment programme may presently be the most appropriate way of providing wider validation of these and similar models, provided that good data are available on lice numbers in salmon farm cages.

4. **Observations of pelagic sea lice larvae concentrations obtained using the implemented monitoring techniques are not suitable for use in validating sea lice dispersal models.**

Sea lice were detected in 4.8 % out of a total of 372 collected zooplankton samples.

Modelling results predict that sea lice concentrations in the sea are patchy and transient.

The level of variability in observed sea lice larvae concentrations was comparable between model and observational data.

Current sea lice monitoring techniques sample small volumes of water over short time periods. The mismatch between the fine-scale resolution but limited coverage (in time and space) of monitoring and the much coarser resolution of predicted sea lice concentrations produced by sea lice dispersal models means that achieving good agreement between observed sea lice concentrations and model predictions is probably unrealistic.

Capturing planktonic sea lice larvae and identification by microscope is very resource intensive due to the small size of the larvae, and relative low average abundance within high density and diverse zooplankton communities.

The limitations and potential bias of all field data sources should be recognised and understood (Skogen et al. 2022). Failure to capture and definitively quantify sea lice larvae does not equate to an absence in the water column. As such, care must be taken to avoid concluding from a negative result that no larvae were present in the sampling area at the time of sampling.

5. **The Project was unable to draw conclusions about the potential for sea lice counts on wild-caught salmonids to help validate sea lice dispersal models.**

There were significant logistical difficulties in collecting sea lice counts from wild-caught salmonids due to scarcity of the fish and a lack of detailed knowledge of their movement within Shuna Sound. Consequently, the Project was unable to use the data collected to help in validating the models.

Further work is needed to assess whether it is practical to design and operate a suitable wild fish monitoring programme (as has been done in Norway) and utilise the data obtained to help validate sea lice dispersal models.

6. **An ensemble modelling approach can provide a means of improving understanding of areas of least, and greatest, uncertainty in model predictions. This can improve confidence in decision-making (Oidtman et al. 2021).**

An ensemble approach enables identification of geographic areas of agreement and disagreement between predictions given by different particle tracking models (or different plausible configurations of a single particle tracking model). The approach can help identify where model predictions are most and least coherent.

The use of an ensemble approach is more resource-intensive than using a single, well-calibrated and validated particle tracking model. More research development is required to assess the practicality of using an ensemble approach of multiple simulations for management decisions in Scotland.

7. **Targeted laboratory and field experimentation to assess sea lice behaviours, such as diurnal vertical migration, could help improve calibration and accuracy of particle tracking models.**

Vertical distributions of sea lice larvae are fundamental to dispersal patterns and must therefore be correctly reproduced by models. This could be assessed using laboratory experiments or field observations (e.g. Nelson et al. 2018).

Development of improved methods for capturing and identifying sea lice larvae from the plankton would facilitate field studies.

Novel methods showing early promise for improving identification of sea lice in samples include automated image analysis, fluorescence microscopy, and eDNA, ideally in conjunction with large-volume depth stratified sampling.

8. **Models validated at one location may have to be used in locations for which observations are lacking. Where this is the case, model predictions should be treated with appropriate caution.**

Model predictions of sea lice concentrations should be validated using suitable field data wherever possible.

Good data for validation may not always be feasible to obtain. There are currently limits to the suitability of planktonic field data (e.g. due to patchiness) for use in validation, and the collection of extensive field data can be resource intensive.

Where validated models must be applied in another location without equivalent field validation, appropriate calibration and sensitivity analysis of the individual model components remains essential.

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US EPA (2022b) Air Quality Dispersion Modeling - Preferred and Recommended Models https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models

Annex 1 – Summary of the objectives of the work packages

Work package 1: The development of sea lice dispersal modelling for Shuna Sound

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The main objectives of this work package were to:

- simulate the sea lice infection risk to wild salmonids from salmon farms in the Shuna Sound area.
- assess the performance of the models against planktonic sea lice data collected by SAMS at sites in Shuna Sound in 2021 and sea lice count data from wild fish monitoring by AFT (WP 3) in the same year.

Four different hydrodynamic model configurations coupled with three lice dispersal models were used.

The comparison between models and field data aimed to test the performance of the various models and propose areas for improvement.

Preliminary modelling was carried out prior to the field season to develop a field sampling strategy for the monitoring strategy work package (WP 2).

The report for the work package describes in detail the modelling methodologies and results from this work.

Work package 2: Development of a monitoring strategy for infective sea lice stages.

The main objective of this work package was to develop a coherent field sampling strategy for the Shuna Sound area to generate field data for the validation of the models.

The outcomes of the work package are included in the work package 3 report.

Work package 3: Wild fish monitoring and planktonic lice sampling in the coastal water catchment.

The main objective of this work package was to collect field data to help validate and refine sea lice dispersal models developed for the Shuna Sound area.

It involved:

- sampling pelagic sea lice larval distributions in Shuna Sound .
- recording attached sea lice on wild-caught salmonids (primarily juvenile sea trout) in Shuna Sound .

The report on this work package describes in detail the monitoring methodologies and results.

Delivery of the work package developed the skills of Scottish based researchers in sea lice larvae sampling, identification, and enumeration.

Work package 4: Model inter-comparison and validation in the Loch Linnhe and Firth of Lorn study area.

The main objective of this work package was to assess the robustness of the three sea lice dispersal models.

The results of the lice dispersal models for the Loch Linnhe and Firth of Lorn study area were compared against field data collected between 2011 and 2013. The field data consisted of sentinel caged fish counts and planktonic sea lice larvae data.

The sea lice dispersal models were all coupled with the Wider Loch Linnhe System (WLLS) model[2]. configured to give the best fit to observations on temperature, salinity, water elevation and currents for the period concerned.

[2] https://marine.gov.scot/information/wider-loch-linnhe-system-model

Sensitivity analysis led to a better understanding of the degree of bio-physical complexity required in the particle tracking models to have confidence in the outputs.

This included developing an ensemble approach using the three particle tracking models. Ensemble approaches are widely used in other modelling fields such as weather forecasting and epidemiology (Probert et al. 2022), where multiple models are used to identify areas of low and high agreement and thus identify where forecasts are likely to be most reliable (high agreement). This is the first ensemble application in sea lice modelling and demonstrates potential for improving communication on model uncertainty and variability.

Project synthesis and reporting

Final detailed work package reports are available for WP 1 (Gillibrand et al., 2023), WP 2 and 3 (Reinardy et al., 2023), and WP 4 (Moriarty et al., 2023).

Annex 2 - List of participants and roles

Project Leads: Alejandro Gallego, Sandy Murray (Marine Scotland Science - MSS)

Project Coordinator: Meadhbh Moriarty (MSS)

Work Package Leads:

- WP 1: Philip Gillibrand (MOWI)
- WP 2: Helena Reinardy (SAMS)
- WP 3: Helena Reinardy (SAMS), Philip Gillibrand (MOWI)
- WP 4: Meadhbh Moriarty (MSS)
- WP 5: Alejandro Gallego, Sandy Murray (MSS)

Steering Group: Alan Wells (FMS), Peter Pollard (SEPA), Alex Adrian (CES), John Armstrong (MSS)

Project Team:

Alan Kettle-White (AFT), Alejandro Gallego (MSS), Chris Allen (SAMS), Helena Reinardy (SAMS), Kim Last (SAMS), Lars Brunner (SAMS), Eilidh McLeod (SAMS), Gail Twigg (SAMS), Lianne Harrison (MSS), Louise Campbell (MSS), Berit Rabe (MSS), Lynne Coley (KAMES), Meadhbh Moriarty (MSS), Philip Gillibrand (MOWI), Rory O'Hara Murray (MSS), Sandy Murray (MSS), Sarah Reed (SAMS), Soizic Garnier (MSS), Stephen Macintyre (MOWI), Stevie Brain (SAMS), Tom Adams (SSF)

Annex 3 - Research use and dissemination

Potential impact and main dissemination activities / exploitation of results

The Crown Estate Scotland has an Action (2020-23 Corporate Plan) to “Help create and deliver overarching vision for Scotland’s blue economy, in line with Scottish Ministers’ purpose”. One of the Scottish Government’s Blue Economy Vision outcomes states that “Scotland’s marine ecosystems are healthy and functioning, with nature protected and activities managed using an ecosystem-based approach to ensure negative impacts on marine ecosystems are minimised and, where possible, reversed”. The work carried out in the SPILLS project contributes to the new aquaculture management framework to minimise any negative impact of sea lice from fish farms adversely impacting wild salmonid populations. In such a framework, numerical modelling will play an important role – initially within the pre-screening process and subsequently for detailed impact modelling where required. Through these different stages, the suitability of the modelling tools will be scrutinised by stakeholders, industry and regulators. This project has provided the most detailed test of modelling tools in Scotland (in their individual components) against the best available observational datasets, and has been accompanied by substantial developments of model components and how modelling results are analysed and displayed. In addition to the project results, we have identified a number of sensitivities, knowledge gaps and future research and development opportunities. These will be pursued through future work and the complementary “Model tools for a spatial management framework for sustainable aquaculture development” CES-MS Priority Project (C45500), which has contributed significantly to elements of the sensitivity analyses in SPILLS and is investigating other aspects of model sensitivity.

Scientific and technical results

Project Website > Salmon Parasite Interactions in Linnhe, Lorn, and Shuna (SPILLS) | Marine Scotland Information

Presentations >

- MASTS Webinar Series 2020 > Evaluation of multiple coupled biological physical models in Loch Linnhe. 29th April 2020
- MASTS 2021 > Sea lice dispersal modelling and population assessment workshop: Where are the gaps in the current research and monitoring?: Presentations from all WP leads on all aspects of SPILLS. 7th October 2021
- Sea lice 2022 > "Towards ensemble models for predicting sea lice distributions", 10th May 2022, Faroe Islands
- MASTS 2022 > "Salmon Parasite Interactions in Linnhe, Lorn, and Shuna: Sea lice dispersal model evaluation using an ensemble approach" Moriarty et al. 8th November 2022, Glasgow, Scotland

Reports >

- Argyll Fisheries Trust, 2021. Sea lice burdens of sea trout at Sound of Shuna, Argyll, 2021.
- Gillibrand, PA. Moriarty M., Brain S. (2023) Final Report: Sea Lice Dispersal Modelling in Shuna Sound
- Moriarty M., O'Hara Murray R. Rabe B., Brain S. Gillibrand PA., Gallego A. (2023) Final Report: Model inter-comparison and validation in Inner and Outer Loch Linnhe.
- Reinardy, H. Last, K., Brunner L., Twigg, G., McLeod, E., Ofori, A., Stollberg, I., Reed S., Gillibrand PA (2023) Final report on sampling and analyses of sea lice larvae in Shuna Sound (I), and sampling of sea lice on wild fish in Shuna Sound (II)

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