Supplementary Material

"Knowledge Strength": maximising the reliability of evidence derived from environmental modelling in the face of uncertainty – the case of the salmon louse (*Lepeophtheirus salmonis*)

Supplementary Material A: Linking Science to Underpinning Policy Decisions with Scientific Evidence

Three case studies of policy environments behind salmon lice management covering Norway, Scotland and the Faroe Island are outlined below. Each nation has unique societal, environmental and economic drivers (Figure A.1), reflected in their policies and management actions, although societal commonalities between the three nations include a deep respect for the ocean and the environment. Clean, temperate oceanic waters in sheltered fjords, sounds and lochs provide ideal conditions for Atlantic salmon farming, which dominates the marine aquaculture industry for these three nations (Figure A.1).

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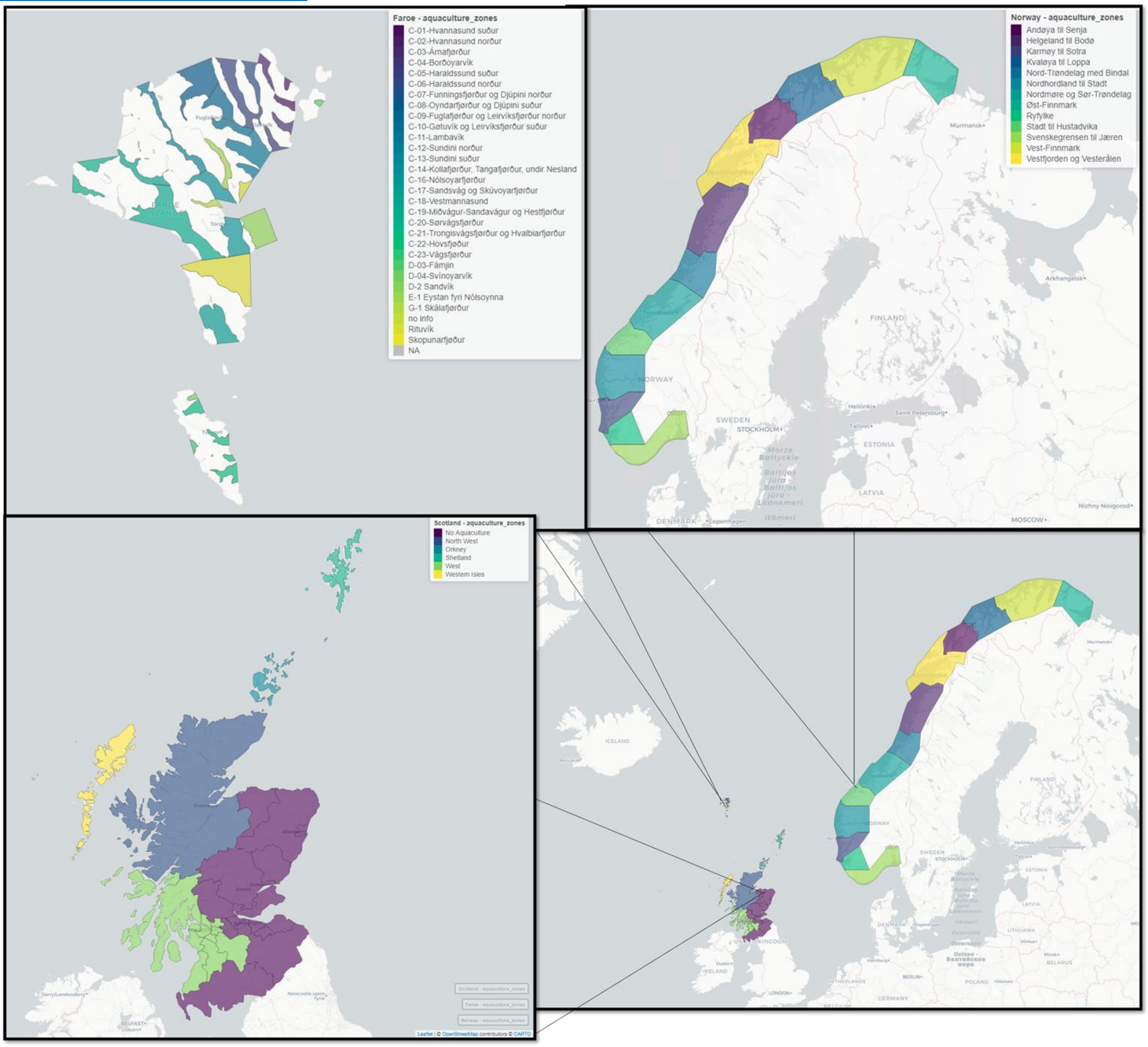

Figure A.1: Map showing the Faroe Islands, Scotland and Norway's salmon aquaculture regions.

Wild Atlantic salmon is found throughout the North Atlantic region (Fig. A1), where its abundance has declined since the 1970's. The IUCN classification ranges from Near Threatened (globally) to Endangered (Great Britain) (Nunn et al., 2023). A number of factors are associated with this decline, such as increased natural mortality at sea, potentially associated with climate change (Thorstad et al., 2021). Globally, other threats include river pollution, overfishing and dams (Scottish Government, 2022). Commercial salmon farms also pose various ecological threats. These threats include eutrophication caused by concentrated waste products (Luthman et al., 2019), elevated levels of pathogens and introgression from escaped farm salmon (Taranger et al., 2015).

To minimise the risks of sea lice from salmon farms impacting wild salmon, Norway has implemented area-based sea lice regulations (Section A.1), and Scotland is moving in the same direction (Section A.2), seeking to adopt a spatially-based risk assessment framework. The Faroe Islands manage sea lice at farm level (Section A.3).

A.1 Norway: Managing Salmon Lice under the Production Zone Traffic Light System

In Norway, the government has enacted a framework where the coast is divided into 13 management areas/production zones (PZ) (Anon, 2017; Eliasen et al., 2021). The borders between the zones are defined to be where the hydrodynamic dispersion of salmon lice between the zones is minimal, related to coastline and the farm positions (Ådlandsvik, 2015).

A report to the Parliament (Stortingsmelding 16 2014-2015, Anon 2015) states that the conditions within each PZ shall be based on the mortality of wild salmonids (out-migrating post smolt of Atlantic salmon, first-time emigrating post smolt of sea trout and char, and on grazing sea trout and char, though so far the main emphasis has been on Atlantic salmon post smolt) as a consequence of infection from salmon lice. Thus, the carrying capacity of wild salmonid populations to salmon lice is the present sustainability indicator, and other sustainability indicators (e.g., eutrophication and welfare) may be given weight in the future.

To assess the carrying capacity of the wild fish, the Ministry of Trade, Industry and Fisheries (NFD) has appointed a steering group, which in turn has appointed an expert group consisting of 10 researchers, to annually perform comprehensive sustainability assessments from a set of evidence-based proxies (both observations and numerical model results) in each of the 13 zones. An overview of the datasets used for the assessment is shown in Figure A.2 (from Vollset et al., 2023).

The mandate of the expert group is: "Each year, the expert group will carry out a thorough scientific assessment of how wild salmonids are affected by salmon lice in each production area." This management system was evaluated by an international committee (Eliassen et al., 2021), who recommended to use an accepted best practice standard elicitation methods for the assessment (e.g. IPCC (https://www.ipcc.ch/documentation/procedures/), European Food Safety Authority (EFSA 2022)). The expert group therefore implemented the Sheffield Elicitation Framework (SHELF, https://shelf.sites.sheffield.ac.uk/) in 2022, and a probability distribution is presented, where one can read out which of the categories (low, medium, high salmon lice-induced wild fish mortality) are considered most likely. The likelihood scale follows IPCC, Table 1 in https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

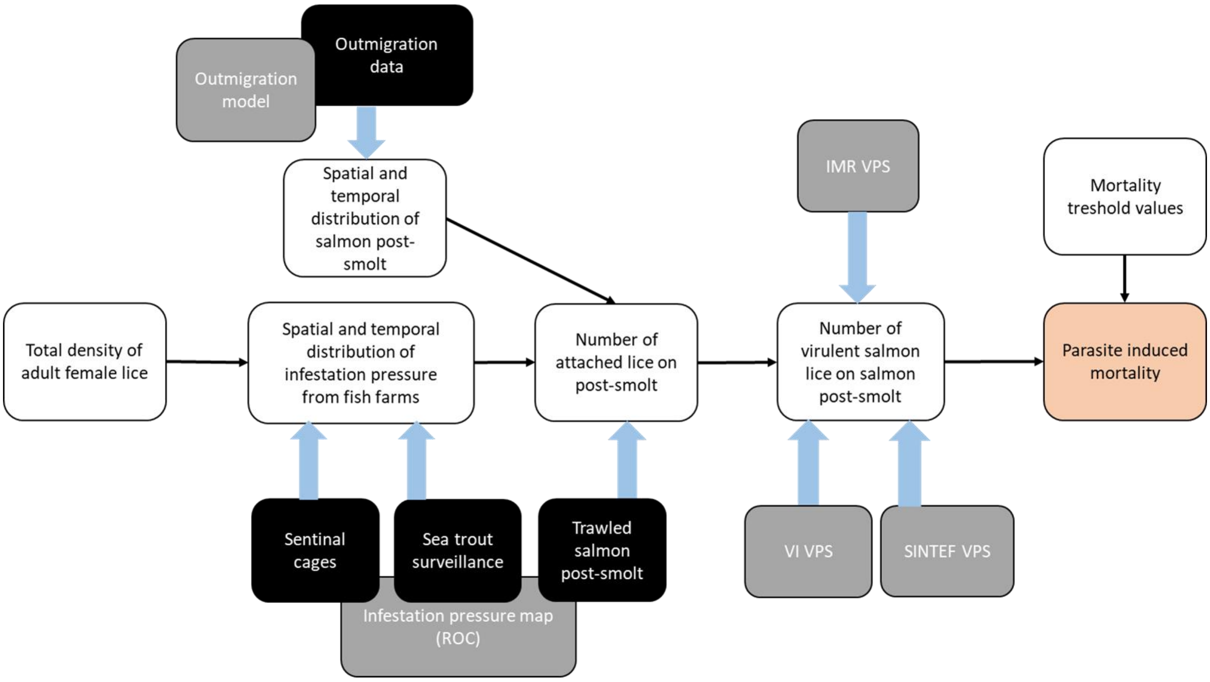

Figure A.2: Sequence of events for assessment of salmon lice-induced wild fish mortality (orange box), showing how the different methods (indices/models) provide information. White boxes and black arrows are the sequence of events from the release of lice and distribution of salmon smolt to salmon lice induced wild fish mortality, while the grey and black boxes are modelled and empirical data, respectively. The blue arrows indicate where in the sequence of events the method provides information. ROC = relative operating characteristic, VPS = virtual post-smolt model, IMR = Institute of Marine Research, VI = Norwegian Veterinary Institute, SINTEF = The Foundation for Industrial and Technical Research (Vollset et al., 2023)

A.2 Scotland: the Sea Lice Risk Assessment Framework

In Scotland, the Scottish Environmental Protection Agency (SEPA) is developing an area management approach for the management of salmon lice, following consultation with stakeholders (SEPA 2022, 2023). This is in partial support of a Wild Salmon Conservation Strategy (Scottish Government, 2022) and a Blue Economy Vision for Scotland (Marine Scotland, 2022a) following a Parliamentary Report into Salmon Farming in Scotland (RECC, 2018). The role of policy and stakeholders is to determine what an acceptable outcome is, while scientists assess how that outcome can be achieved. Multiple salmon lice dispersal models are being assessed to understand our ability to predict infection pressure as measured in the environment, and particularly on sentinel cage data (Pert et al., 2014), and to help to understand the variance in these models' predictive ability (Marine Directorate, 2023).

The complex Blue Economy requires a balance of multiple interests of multiple stakeholders in a policy framework in Scotland (Marine Scotland, 2022). Wild salmon declines are occurring due to numerous pressures on salmon (Scottish Government, 2022). The salmon lice impact is one of these drivers, if a large one (Vollset et al., 2016). The Scottish Government supports other science and policy work streams to control other pressures, for example, introgression (Gilbey et al., 2021), modelling juvenile salmon to inform sport fishery policy supported by data from a National Electrofishing Programme for Scotland (Malcolm et al., 2021) and riparian tree planting to protect salmon breeding habitat against climate change (Jackson et al., 2021). Other Scottish Government policy drivers support sustainable aquaculture by, for example, identifying needs for science to improve fish health on farms (Marine Scotland Science, 2018). Therefore, the impact of salmon lice on wild salmonids is only a part of a wider policy and science environment of the Blue Economy and salmon lice modelling described here can be focused on the specific questions of interest to policy.

A simplified description of the framework (SEPA, 2022, 2023) is illustrated in Figure A.3. Under this, planned aquaculture developments will be assessed using a screening model that triages these into: (a) assessed .as not posing a salmon lice risk to wild salmonids; (b) clear salmon lice risk identified; and (c) an intermediate status. These intermediate status sites may then be reassessed using more detailed management modelling. These more detailed models could provide evidence that, where initial screening identifies a potential risk, this risk can be avoided. In practice, the process is more detailed (SEPA, 2023), with potential for secondary screening models. Hence, Fig A3 is not intended as a definitive description of a policy which continues to develop (SEPA 2022, 2023). Applicants are able to submit modified plans and more detailed modelling for sites that were rejected at initial screening. The detailed models must reach accepted standards for sea lice dispersal models (e.g. Murray et al., 2022; Marine Directorate, 2023).

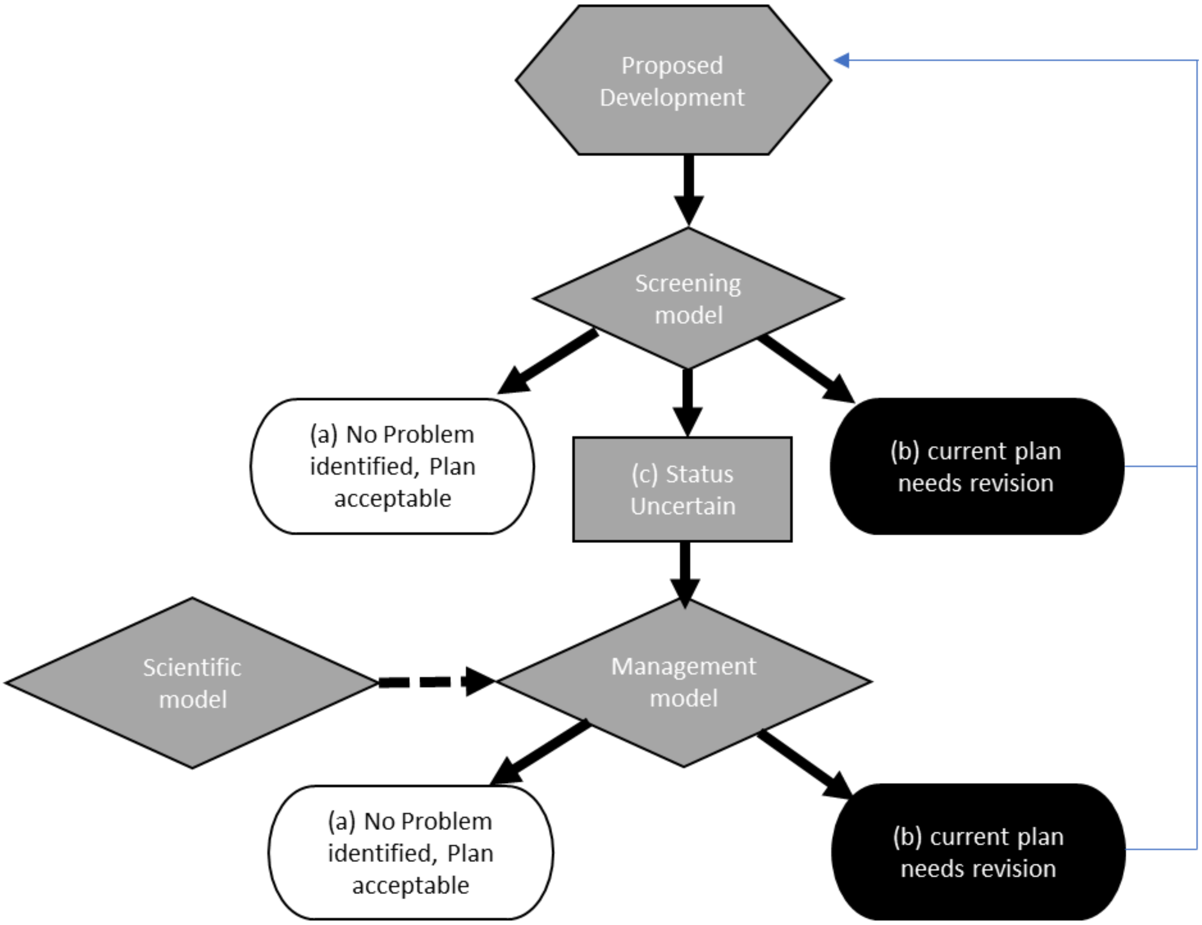

Figure A.3: A Screening Model system. Proposed developments are subjected to a simple robust screening model. Screening results can either be the plan is acceptable, unacceptable, or of uncertain status. If the status is uncertain more detailed management modelling can be applied to assess salmon lice impacts in more detail. More scientific modelling can be used to assess if the management model should be updated as knowledge advances. The screening process allows decisions to be made as to whether there is a need for more detailed modelling which requires detailed local data collection, taking more time and money.

Marine Directorate collected an extensive data set in Loch Linnhe (western Scotland), with focus on spring and autumn of 2011, 2012 and 2013 (Marine Scotland, 2022b). These (and other) data have been used for validating and improving models (Salama et al., 2013; Salama et al., 2018; Marine Directorate, 2023). These studies showed sentinel cage data was extremely useful in exploring the relationship between the number of lice on sentinel fish and the modelled infection pressure. The collected plankton trawl data exhibited far more short-term variability, making it more challenging to interpret the relationship between the plankton sample density and the model's prediction of plankton density.

A.3 Faroe Islands: Salmon Lice Management under the 2016 Executive Order

In the Faroe Islands persistent tidal currents around the islands (Erenbjerg et al. 2020) connect all salmon farms in a salmon lice infection network (Kragesteen et al., 2018). In addition, there can be considerable internal infection in individual fjords (á Norði et al., 2015; Patursson et al., 2017). Since all Faroese fish farms are more or less hydrodynamically connected, it is crucial for the entire salmon farming industry to collaborate in salmon lice management (Kragesteen et al., 2019). Salmon lice management is therefore at farm level with detailed description of monitoring, reporting and consequences in the Lice Executive Order (2016).

Regulation is based on salmon lice counts on fish by a third party, with thresholds on the average number of adult females per fish. Salmon lice are counted biweekly, and all stages are reported in a database held by the authorities. How salmon lice counts have to be performed and reported is described in detail in a guidance issued by the authorities (HFS, 2023). Twenty fish are counted in every net pen and salmon lice counts are mandatory during the entire production cycle, as the initial salmon lice count is mandated within 30 days after deployment of the first fish, while the last count is performed the fourth night the last fish is harvested.

For the individual fish farm, salmon lice management directly affects the allowed production. Penalty points are applied when salmon lice counts are above the threshold, as well as when chemicals are used for treatments. The total number of points is a key factor for determining the number of smolts the company is allowed to deploy in the following production cycle. A low number of points allows for an increase, provided that other issues are well managed, and the number of smolts must be reduced if the total penalty points exceed a threshold given in the Lice Executive Order (2016).

The salmon farming industry has improved its approach to salmon lice management by using the comprehensive data collected in the national database. These data serve as a foundational input for a salmon lice population dynamic model (Kragesteen et al., 2023) that forecasts on-farm salmon lice development throughout the entire production cycle. The model also provides projections on how the farm site lice population might respond to various control measures, including treatments and deployment of cleaner fish, depending on the effectiveness of these measures. This proactive and data-driven approach aims to maintain salmon lice levels below critical thresholds, thereby minimising the necessity for interventions and reducing the accrual of penalty points.

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