Understanding the Relative Cost-Effectiveness of Sea Lice Management Measures for Farmed Salmon Production in Scotland

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by
SRUC Research

Dr Luiza Toma*, SRUC
Dr Shailesh Shrestha, SRUC
Dr Ilkka Leinonen, SRUC
Dr Annette Boerlage, SRUC
Dr Mona Dverdal Jansen, Norwegian Veterinary Institute, Oslo
Dr Crawford Revie, University of Strathclyde
Dr Aaron Reeves, SRUC

*Department of Rural Economy, Environment and Society, Central Faculty, SRUC Research, West Mains Road, Edinburgh, EH9 3JG, Telephone: 0131 535 4394, luiza.toma@sruc.ac.uk

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CE ratio (Cost-Effectiveness ratio)
CEA (Cost Effectiveness Analysis)
CLD (Causal Loop Diagram)
CO_{2e} (Carbon Dioxide Equivalent)
CoGP (Code of Good Practice for Scottish Finfish Aquaculture)
EF (efficacy score)
FCR (feed conversion ratio)
GHG emissions (greenhouse gas emissions)
GMB (Group Model Building)
H2O2 (Hydrogen Peroxide)
LCA (Life Cycle Analysis)
P&I (prevention and intervention)
RAS (recirculating aquaculture system)
SD (System Dynamics)
VMD (Veterinary Medicines Directorate)

Executive Summary

The sea louse *Lepeophtheirus salmonis* is a key parasite of cultured Atlantic salmon throughout most farmed salmon producing countries, including Scotland. The louse feeds on the salmon, and causes multi million pound commercial losses to the salmon aquaculture industry globally. Its life-cycle includes free-living life stages, and life stages attached to fish. The sea-louse life cycle is heavily affected by water temperatures, making the louse more abundant in summer and autumn months, and thus more sensitive to climate change, which may increase management challenges in the future. Sea lice infestation can lead to reduced salmon welfare and lower productivity at farm level through low feed efficiency or growth reduction. Furthermore, the value of salmon at harvest may be reduced, and environmental costs of salmon production may increase due to inefficient resource use, greenhouse gas emissions and nutrient pollution as a result of lower productivity. Sea lice control involves measurable economic and environmental costs as well as costs that are more difficult to monetise, such as costs related to fish welfare and public perceptions.

The sea lice control measures methods investigated in this project include: (i) incidental sea lice management measures such as in-feed medication (Slice®); bath sea lice management measures using licenced veterinary medicines (AlphaMax®, Salmosan Vet® and hydrogen peroxide); fresh water bath sea lice management measures; and physical removal (hydrolicer, thermolicer and optilicer); (ii) continuous sea lice management measures such as biological control using cleaner fish (wrasse and lump-sucker, which eat lice off fish); and use of physical barriers (skirts) to keep lice at early life stages out of the pen.

One of the most important characteristics of a sea lice management measure is its efficacy. Efficacy is highly variable, and can be affected by a number of environmental factors, for example, water temperature, salmon weight and welfare status prior to sea lice management measures, sea lice numbers and most abundant sea lice stages, and oxygen saturation and medicine dispersion during sea lice management measures. Variability in these factors makes it difficult to evaluate efficacy of sea lice management measures. In addition, lice counts, the method used to measure efficacy, are often not comparable between sea lice management measures which can lead to inaccurate estimations. Moreover, frequently used sea lice management measures may reduce in efficacy over time as susceptibility is selectively removed from the population. Overall, efficacy of sea lice management measures is a very complex variable that is difficult to quantify precisely.

A management strategy to keep sea lice at bay for a group of fish between stocking and harvesting usually includes several mitigation methods, combined to enhance efficacy of the individual methods and reduce the risk of resistance. In general, a sea lice management plan includes continuous sea lice management measures such as co-habitation of salmon and cleaner fish or sea lice management measures that are embedded in management, such as good husbandry and synchronised fallow period between sites in one area. When these are not sufficient in keeping lice numbers low, incidental sea lice management measures are used where deemed appropriate.

Choosing the next sea lice management measure in the sequence or combination of methods used on a farm does not only depend on the efficacy of sea lice management measures, but also on other factors, such as method’s feasibility to producer and site, previously used methods, cost, weather forecast and availability of the measure.

For modelling purposes i.e. to create a quantitatively driven ranking, the study examined individual methods, however there is typically no individual method that achieves the desired level (no/very low numbers) of sea lice across a production cycle. Hence farm managers can and do use the wide range of methods available to them, which may include those lower ranked overall, as necessary to build the optimal sea lice management strategy.

Information about current industry practices and sequences of sea lice management measures for Scottish salmon producers is often not publicly available, mostly due to the commercially sensitive nature of some data. Companies rely on in-house assessment of the relative cost-effectiveness of sea lice management measures relevant to them. Reporting and publishing of sea lice management measures in Scotland is currently available only for licenced veterinary medicines. Media reports provide some qualitative information, such as Scottish producers spending less on approved medicines and more on cleaner fish and physical removal technology. This may imply that sea lice management measures that are not based on licenced veterinary medicines are becoming more common, but such reports are not always reliable. There is variation in data availability and resolution, with differences ranging widely between salmon producing countries, and depending on the type of health management measures employed.

The aim of this research project was to gather socio-economic and environmental information on sea lice management measures employed on Scottish salmon farms, and understand the relative cost-effectiveness of sea lice management measures from both the economic and environmental dimensions of disease control in the salmon industry. Specific objectives include assessment of the relative effectiveness of sea lice management measures; assessment of the cost of deploying sea lice management measures and provision of common measures of economic efficiency across the sea lice management measures. The project used a combination of methodological approaches to achieve the specific objectives.

Socio-economic and environmental information was gathered on sea lice control measures employed in the salmon sector based on a review of secondary sources of information from Scotland as well as other countries. Where no Scottish data were available and data from other countries had to be used, these were inspected and selected using expert opinion (health practitioners in the Scottish salmon sector and members of the research group conducting the study) to ensure closest possible relevance to the Scottish salmon sector, and sensitivity analysis was performed to account for uncertainty in the data. Primary data collection using in-depth interviews and participatory workshop involved a small number of Scottish salmon producers (not representative by region and farm size) and processors. Primary data was combined with secondary data to avoid potential bias due to uncertainty and sample size.

Results from the participatory workshop with stakeholders representing different stages of the supply chain were used to inform the analysis of farm-level behaviour (uptake of management measures). The analysis employed a newly developed participatory process from the system dynamics literature called group model building where stakeholders rank control measures based on their efficacy (estimated and/or perceived), and then collectively identify incentives linked to different stages of the supply chain to reduce occurrence of sea lice in primary production. The involvement of stakeholders contributed to identifying network or spill-over effects, supply chain constraints and gaps in skills and training requirements.

Cost Effectiveness Analysis (CEA) and Life Cycle Analysis (LCA) were used to assess the relative cost-effectiveness of sea lice management measures and their impact on the economic performance (including carbon cost) of Scottish farmed salmon industry. CEA and LCA have not been used, to the best of our knowledge, in other studies focussed specifically on the control of sea lice in the salmon sector; however, they have been extensively used in studies analysing the economic and environmental impacts of control of animal disease.

Cost-effective analysis (CEA) is a technique used to prevent or mitigate a disease where the impact cannot be measured routinely in monetary terms, which we used in this context to evaluate different sea lice management measures. The Cost-Effectiveness ratio (CE ratio) is a commonly used indicator to determine the effectiveness of an intervention. Determining the cost of the intervention and effectiveness of the intervention are essential steps to determine applicable CE ratios. The cost of the intervention includes all costs of controlling or preventing a disease. The effectiveness of an intervention is used to compare how effective different prevention or mitigation measures are, and is generally represented by an efficacy score for each measure. The Life Cycle Assessment (LCA) method considers the environmental burdens and resource use in the production and exploitation of a commodity within defined boundaries. LCA is arguably the most holistic method available for environmental impact assessment.

The methodological framework used in this study combines LCA and CEA, with the former feeding into the latter. All sea lice management measures tested in the study were modelled as single use measures. In addition, we modelled three combinations of measures applied in sequence between stocking and harvesting that represent realistic scenarios assumed to bring down and maintain sea lice count within acceptable (regulation compliant) efficacy levels assumed not to impact fish health, welfare and productivity. Intervention cost of the sea lice management measures included cost of equipment, cost of implementation, environmental cost and cost of side effects. The accumulative cost was assessed against the reduction of sea lice on an adult salmon fish, which is considered as the efficacy score for this study (not experimentally assessed). The models were estimated using a combination of primary and secondary data, and simplified modelling assumptions were made to account for low availability of open source data on sea lice management. Detailed sensitivity analysis to substantiate the validity of results was required to account for simplified modelling assumptions, uncertainty due to limited data, absence of control farms to compare our results with, and subsequent use of expert opinion on efficacy of single use measures to obtain qualitative relative efficacy scores, and to design combination measures.

Results of the quantitative analysis indicate that sea lice management by in-feed and long term usage of skirts to prevent sea lice from entering the pens have the highest relative cost-effectiveness. Findings from the workshop analysis indicate that, according to stakeholders' perceptions, skirts' relatively lower impacts on environment and fish welfare are translated into positive impacts at the retail side of the supply chain and positive consumers' perceptions. The cleaner fish, fresh water, physical removal measures and the licensed veterinary medicines were among the second most cost-effective measures, and this is supported by their mixed and at times contradictory environmental, health and welfare impacts. The use of hydrogen peroxide (both well boat and tarpaulin) represented the least cost-effective measures among single use measures and, based on the opinions of stakeholders involved in the participatory workshop, these were also regarded as less positive methods by the public in view of their fish welfare and environmental aspects, and human health implications. As presented in the qualitative part of this study, i.e. findings from the participatory workshop, cost-effectiveness of prevention and mitigation of sea lice is not the only measure of importance as, for example, skirts were perceived to reduce oxygen flow and may have a detrimental effect on fish with compromised respiratory functions, and therefore their effectiveness concerning general fish health and welfare can be low.

To account for the wide range of expert opinion based efficacy rates for each sea lice management measure, we ran sensitivity analysis at the extreme values to identify any corresponding variation in the ranking and magnitude of measures' cost-effectiveness. No major changes in ranking occurred under the maximum efficacy values, with the exception of physical removal (thermolicer) measure, which became less cost-effective. Under assumed minimum efficacy level, the ranking changed considerably. Skirts and in-feed measures remained as the most cost-effective measures under assumed minimum values for efficacy scores, and hydrogen peroxide remained the least cost-effective among the single use measures. Physical removal measures and use of other licensed veterinary medicines became significantly more cost-effective, while fresh water measures became significantly less cost-effective. In addition to changes in ranking, cost-effectiveness exhibits the expected changes in magnitude under both the minimum and maximum efficacy assumptions. Sensitivity analysis results indicated the variability in cost-effectiveness related to changes in efficacy levels, namely that the higher the efficacy of a measure, the higher the cost-effectiveness.

To account for uncertainty owing to combined data sources, additional sensitivity analyses were carried out to assess the impacts of varying values for the costs of interventions on the model outcomes, such as feed conversion ratio. Changes in the costs of interventions to similar extent for all management measures did not change the overall cost-effectiveness rankings of the management measures although the absolute values of cost-effectiveness were changed. However, changing costs of single use measures showed some changes in cost effectiveness rankings. For example, a significant increase in the price of cleaner fish led to decreased cost-effectiveness of the measure per unit of effectiveness to the extent of cleaner fish becoming slightly less cost-effective than the hydrolicer measure.

Results indicate that sea lice management measures using tarpaulins were more cost-effective than measures using well boats under the whole range of efficacy values used in this study. This relates to the higher costs associated with operating well boats compared to tarpaulins. However, we assumed that efficacy was unaffected by the method of performing these bath measures, while in practice the level of control and monitoring provided when using a well boat may mean that such an approach will likely lead to improved outcomes.

Cost-effectiveness of combination measures are not comparable to that of single use measures as these combine different measures in different sequences, with many of them repeated and as such, aspects of cost additivity apply. When comparing the three combination measures, results indicate a small difference between the most cost-effective and least cost-effective combination ranging from £1.23 per fish per unit of effectiveness to £1.67 per fish per unit of effectiveness. Depending on farm circumstances, the difference may be even smaller, as well as the magnitude of total costs, for the cases where cost additivity can be adjusted to account for cost synergies across measures. Sensitivity analysis employed to test results for combination measures indicate high sensitivity to fish mortality.

Fish welfare was taken into account in both, the qualitative workshop analysis and the quantitative models, the latter through sea lice management measure related mortalities, which affect primarily the economic performance (including carbon cost) and is, arguably, a proxy welfare indicator. Results of the workshop showed that perceived importance of both salmon and cleaner fish welfare is high, equally for industry and consumers. Where cleaner fish are used as a sea lice control method, the welfare and health of both salmon and cleaner fish are affected by any other sea lice management measures applied. The differences between these fish species, not only in size but also many other biological parameters, imply that measures optimised for salmon may affect cleaner fish differently. Results of the workshop indicate that cleaner fish are perceived as cost-effective and their welfare is key to positive consumer perceptions.

Participatory analysis identified potential incentives for further improving control of sea lice on farm, many of these already taken into account in the Scottish salmon sector. These include: better balancing of science-based evidence and precautionary principle based policies (health, environment, welfare); public sector driven positive incentives such as subsidised access to technology; research on consumers' willingness to pay for sustainably farmed salmon; media campaigns and education to the public on implications of disease control in aquaculture; market based incentives (price differentiation through labelling re sustainable disease control); market based incentives (traceability); development of health monitoring/preventative technologies;

development of delousing technologies from product/flesh at packing; research on salmon welfare linked to sea lice control; research on cleaner fish welfare linked to sea lice control; media campaigns to maintain/improve industry image to the public; private driven stick type incentives such as higher environmental/welfare standards required under processor/retail contracts; research on efficacy of disease control; and improved collective action to sea lice control along the supply chain.

It should be noted that caution should be applied when comparing cost-effectiveness of single use measures based on the limitations previously mentioned regarding data availability and uncertainty as well as the consequent simplified modelling assumptions. Data sources are a combination of primary and secondary data, and expert opinion, moreover the geographical distribution of data sources from e.g. Norway and Canada were translated to the Scottish situation as closely as possible, but might not fully represent the Scottish salmon industry situation, more specifically as regards regional differentiation. With additional as well as more robust primary data, further ways to improve the analysis include the methodological integration of economic, biological and epidemiological modelling. The findings from the participatory workshop indicate the complexity of sea lice control not only on farm but beyond farmgate, as supply chain, regulatory and environmental effects, and the need to address it as a holistic challenge.

As demonstrated by the limited literature on the topic, which this study adds to, this type of research will always be constrained by access to data for reasons detailed in this report. Thus, while much information has been collected on the variables included in the analyses and the robustness of results tested using sensitivity analysis, there may be other factors for which neither data nor robust proxies could be identified under this study, and this should be taken into consideration when reviewing these findings as basis for future research.

1. Background and rationale

The sea louse *Lepeophtheirus salmonis* is a key parasite of cultured Atlantic salmon worldwide, and is widely distributed throughout most farmed salmon producing countries, including Scotland. The louse feeds on the salmon, and causes multi million pound commercial losses to the salmon aquaculture industry globally (Costello, 2009). Its life-cycle includes free-living life stages, and life stages attached to fish (Costello, 2006). The sea-louse life cycle is heavily affected by water temperatures, making the louse more abundant in summer and autumn months, and thus more sensitive to climate change, which may increase management challenges in the future. Mitigation throughout the farmed salmon production period in open-sea net pens is needed to keep lice numbers at bay.

In the absence of preventative sea lice management measures, sea lice infestation can lead to reduced salmon welfare and lower productivity at farm level through low feed efficiency or growth reduction. Furthermore, the value of salmon at harvest may be reduced, and environmental costs of salmon production may increase due to inefficient resource use, greenhouse gas emissions and nutrient pollution as a result of lower productivity, or potential spread of lice through interactions with wild fish. Altogether, sea lice infestation without mitigation may reduce the overall economic performance of farmed salmon production. Sea lice control involves measurable economic and environmental costs as well as costs that are more difficult to monetise, such as costs related to fish welfare and public perceptions.

As in other salmon producing countries, lice numbers per fish are regulated in Scotland. Scottish Government regulations include a mandatory reporting when average adult female lice counts per fish are 2 or above, and have an intervention limit at 6 average adult female sea lice per fish, both during a weekly count. These are to be reported by industry to the Fish Health Inspectorate (Aquaculture and Fisheries (Scotland) Act 2007; Aquaculture and Fisheries (Scotland) Act 2013, updated in 2019). There is also a Code of Good Practice for Scottish Finfish Aquaculture (CoGP) developed by industry, which states that sea lice management measures should be guided by the build-up of preadults to prevent the development of gravid females, and it includes a suggested sea lice management measure criteria of 0.5 adult female lice per fish between 1st February to 30th June inclusive, and 1.0 adult female lice per fish between 1st July to 31st January inclusive.

Sea lice control measures can be incidental, continuous, or embedded in management. The methods investigated in this project were selected based on a review of the literature (Murray, 2015; Overton *et al.* 2019) and expert opinion, which include those of the members of the project steering group. The selected methods include: (i) incidental sea lice management measures such as in-feed medication (Slice®); bath sea lice management measures using licenced veterinary medicines (AlphaMax®, Salmosan Vet® and hydrogen peroxide); fresh water bath sea lice management measures; and physical removal (hydrolicer, thermolicer and optilicer); (ii) continuous sea lice management measures such as biological control using cleaner fish (wrasse and lump-sucker, which eat lice off fish); and use of physical barriers (skirts) to keep lice at early life stages out of the pen.

One of the most important characteristics of a sea lice management measure is its efficacy. Examples of factors that affect the efficacy of sea lice management measures are water temperature, salmon weight and welfare status prior to sea lice management measures (for instance thermolicer is recommended for fish up to 4 kg (Gismervik *et al.*, 2017 in Norwegian, in Overton *et al.*, 2018), sea lice numbers (Gautam *et al.*, 2017b), most abundant sea lice stages prior to sea lice management measures (freshwater is less efficient at older louse stages (Wright, Oppedal and Dempster, 2016), and oxygen saturation and medicine dispersion during sea lice management measures (Treasurer, Grant and Davis, 2000), and many more. Variability in these factors makes it difficult to evaluate efficacy of sea lice management measures. In addition, lice counts, the method used to measure efficacy, are often not comparable between sea lice management measures which can lead to inaccurate estimations (Jimenez *et al*., 2013; Gautam *et al.*, 2017a). Moreover, frequently used sea lice management measures may reduce in efficacy over time as susceptibility is selectively removed from the population (Lees *et al*., 2008; Svåsand *et al*. 2016 in Norwegian, in (Bui *et al.*, 2019)). Overall, efficacy of sea lice management measures is a very complex variable that is difficult to quantify precisely.

A management strategy for a group of fish between stocking and harvesting usually includes several mitigation methods, combined to enhance efficacy of the individual methods and reduce the risk of resistance. In general, a sea lice management plan includes continuous sea lice management measures such as co-habitation of salmon and cleaner fish or sea lice management measures that are embedded in management, such as good husbandry and synchronised fallow period between sites in one area. When these are not sufficient in keeping lice numbers low, incidental sea lice management measures are used where deemed appropriate. Choosing the next sea lice management measure in the sequence or combination of methods used on a farm does not only depend on the efficacy of sea lice management measures, but also on other factors, such as method’s feasibility to producer and site, previously used methods and weather forecast.

Information about current industry practices and sequences of sea lice management measures for Scottish salmon producers is often not publicly available, mostly due to the commercially sensitive nature of some data. Companies rely on in-house assessment of the relative cost-effectiveness of sea lice management measures relevant to them. Reporting and publishing of sea lice management measures in Scotland is currently available only for licenced veterinary medicines (ScotGov, 2019). Media reports provide some qualitative information, such as Scottish producers spending less on approved medicines and more on cleaner fish and physical removal technology (SSPO, 2018). This may imply that sea lice management measures that are not based on licenced veterinary medicines are becoming more common, but such reports are not always reliable. There is variation in data availability and resolution, with differences ranging widely between salmon producing countries[1], and depending on the type of health management measures employed.

2. Objectives

The aim of this research project is to gather socio-economic and environmental information on sea lice management measures employed on Scottish salmon farms, and understand the relative cost-effectiveness of sea lice management measures from both the economic and environmental dimensions of disease control in the salmon industry.

Specific objectives:

- to determine the relative effectiveness of sea lice management measures;
- to determine the cost of deploying sea lice management measures;
- to combine these assessments to provide common measures of economic efficiency across the sea lice management measures.

3. Application of methodology and data description

The project used a combination of methodological approaches to achieve the specific objectives noted above.

Socio-economic and environmental information was gathered on sea lice control measures employed in the salmon sector based on a review of secondary sources of information from Scotland as well as other countries such as Norway and Canada. Where no Scottish data were available and data from other countries had to be used, these were inspected and selected using expert opinion (health practitioners in the Scottish salmon sector through telephone interviews and email communications, and members of the research group conducting the study) to ensure closest possible relevance to the Scottish salmon sector, and sensitivity analysis was performed. Secondary data collection was combined with primary data collection using a participatory workshop and in-depth interviews with Scottish salmon producers and processors. The questionnaires used for primary data collection are presented in the Appendix together with the description of the data collection, storage and use rules followed in the project (ethical aspects of data collection/storage/analysis/reporting). Quantitative and qualitative data collected through survey questionnaires was used to inform the modelling and reference is made to it as part of modelling assumptions and data description.

[1] Much of the information publicly available is from Norway, and that is the case because Norway is the only salmon producing country where all delousing events have to be reported to the Norwegian Food Authorities after which they are made publicly available; however these data present many uncertainties (Overton et al., 2018).

Results from the participatory workshop with stakeholders representing different stages of the supply chain was used to inform our analysis of farm-level behaviour (uptake of control measures). To run this workshop, we employed a newly developed participatory process from the system dynamics literature called group model building (GMB) (Rich *et al.* 2018) where stakeholders rank control measures based on their efficacy (estimated and/or perceived), and then collectively identify incentives linked to different stages of the supply chain to reduce occurrence of sea lice in primary production. The involvement of all stakeholders contributed to identifying network or spill-over effects, supply chain constraints and gaps in skills and training requirements. Methodology is described in the section presenting results of the workshop.

Cost Effectiveness Analysis (CEA) and Life Cycle Analysis (LCA) were used to assess the relative cost-effectiveness of sea lice management measures and their impact on the economic performance (including carbon cost) of the Scottish farmed salmon industry. CEA and LCA have not been used, to the best of our knowledge, in other studies focussed specifically on the control of sea lice in the salmon sector; however they have been extensively used in studies analysing the economic and environmental impacts of control of animal disease.

Cost-effectiveness analysis (CEA) is a technique used to assess measures to prevent or mitigate a disease where the impact cannot be measured routinely in monetary terms, which we used in this context to evaluate different sea lice management measures. Many researchers working on animal and human health economics have used this method to determine the optimal resource allocation between interventions at their disposal (Mangen *et al.*, 2007; Valeeva *et al.*, 2007; Benedictus *et al.*, 2009). The Cost-Effectiveness ratio (CE ratio) is a commonly used indicator to determine the effectiveness of an intervention (Rushton and Jones, 2018). This ratio is represented as:

$$CE\ ratio = \frac{\text{cost of the intervention}}{\text{effectiveness of the intervention}}$$

Determining the cost of the intervention and effectiveness of the intervention are essential steps to determine applicable CE ratios. The cost of the intervention includes all costs of controlling or preventing a disease. It may consist of the cost of licenced veterinary medicines, equipment, implementing procedure including means of application, labour costs, administrative costs etc. The effectiveness of an intervention is used to compare how effective different prevention or mitigation measures are, and is generally represented by an efficacy score for each measure. This score is determined based on the specific aim of a study. For instance, Bergevoet *et al.* (2009) used lowering prevalence of salmonella in dairy herds, and Valeeva *et al.* (2007) used improvement in food safety on dairy farms as efficacy scores to conduct their cost-effectiveness assessment studies. Our study measured the relative cost-effectiveness of sea lice management measures for farmed salmon production (methodology details are presented below).

The Life Cycle Assessment (LCA) method considers the environmental burdens and resource use in the production and exploitation of a commodity within defined boundaries. The commodity (or end product) considered in the analysis is called Functional Unit in the LCA terminology, and it must be clearly specified and consistently used (also in terms of quantity) throughout the assessment. The boundary can be from cradle to grave, which includes the production, retail, consumption, and disposal stages, but it is also common, for pragmatic purposes, to focus the analysis on the earlier stages, for example in agricultural production, this may include stages up to the farm gate. LCA can be considered to be the most holistic method available for environmental impact assessment, and therefore it is the methodology favoured by major organisations, such as the United Nations Environment Program (http://www.uneptie.org/scp/).

The methodological framework used in this study combines LCA and CEA, with the former feeding into the latter. We modelled sea lice management measures separately as single use measures. In addition, we modelled three combinations of measures that represent examples of the many realistic sequences of measures possible between stocking and harvesting on a salmon farm. They simulate a situation where producers monitor fluctuating sea lice levels and use management measures as effectively as possible with the aim of maintaining sea lice counts within acceptable (regulation compliant) levels. Results of the LCA and CEA models run for single use measures provide a comparison and ranking between single measures, while those run for combination measures provide examples of total environmental impacts and total costs.

Life Cycle Analysis: modelling environmental impacts (carbon costs)

The LCA model applied in this study covered the whole salmon production chain from raw materials to the farm gate (cradle to gate). The functional unit of the study was one marketable salmon weighting 5 kg at the farm gate. The main components of the modelled system are shown in Figure 1.

Different sea lice management measures have effects on different parts of the production chain. This is also demonstrated in Figure 1. As a result, one measure may have a direct effect on a single component of the chain, but then the changes in this component may cause changes in other parts of the chain. Therefore, each measure could have potential indirect effects on the whole chain, and this can also generate both direct and indirect environmental impacts. To understand all these interactions, a systems approach to LCA modelling is necessary. It should also be noted that if any measures affect the performance of the fish (e.g. growth rate, feed efficiency, mortality and output of marketable fish), this is further reflected in the resource efficiency of the production through indirect environmental impacts.

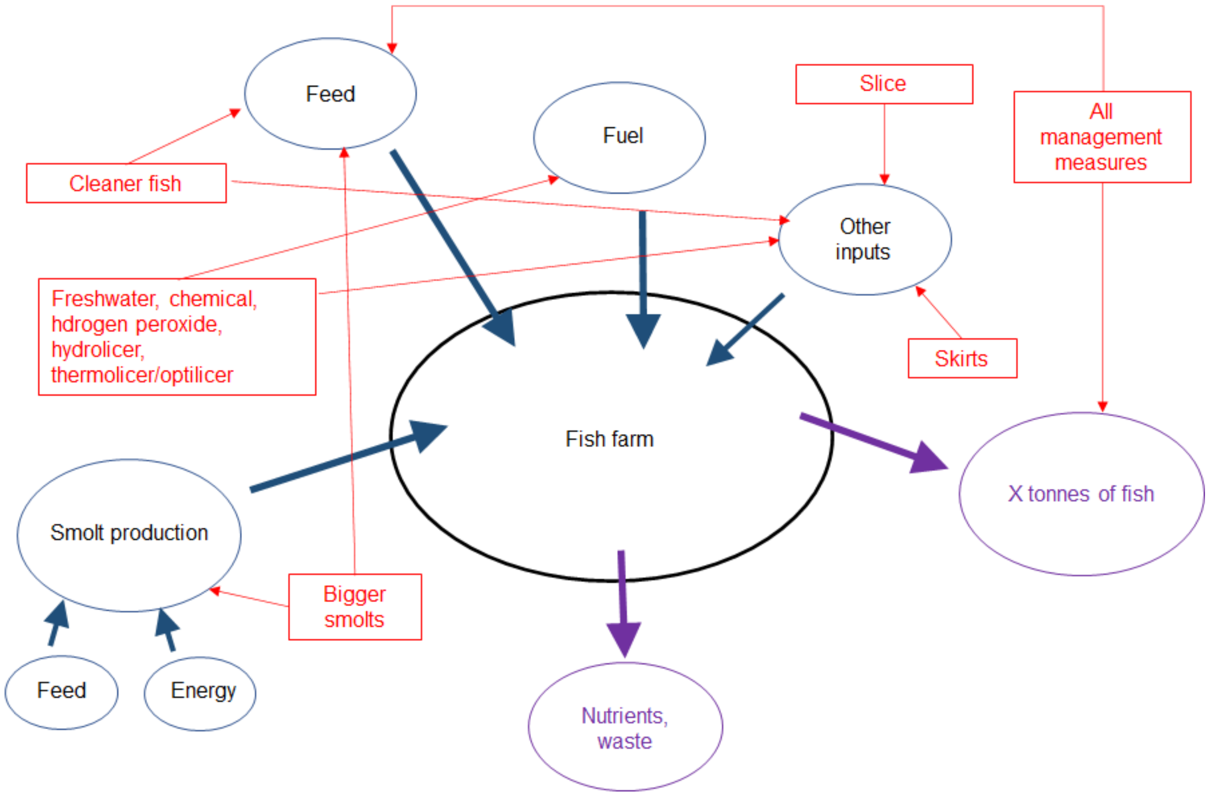

Figure 1. Main components of the salmon production system in the LCA model, and potential effects of some sea lice management measures on different parts of the production chain[2]

LCA: Data sources, assumptions and limitations

LCA is a data-intensive method, and the initial expectations were to base the model as much as possible on primary data collected through interviews with the Scottish salmon sector. Ultimately, the LCA model used a combination of primary and secondary data, and modelling assumptions:

1. Secondary data from literature and publicly available databases. Whenever possible, Scottish and UK data sources were used; non-UK data were selected to relate as closely as possible to the Scottish production and inputs e.g. comparable to other input data sourced from Scotland.
2. Modelling based on functional relationships
3. Expert opinion (health practitioners in the Scottish salmon sector and members of the research group conducting the study)

[2] Where: red bordered rectangles represent different types of management measures; blue bordered ovals represent inputs and their production processes; purple bordered ovals represent outputs; bold blue and purple arrows represent material and energy flows; red arrows represent relationships between the management measures and production inputs and outputs. These are elements of the LCA model and Figure 1 shows both flows and influences included in the model.

The limited amount of data on sea lice management measures in the Scottish salmon primary production that was available for this study made it necessary to simplify the modelling approach. This is presented in Figure 2. We assumed that the measures had no effect on the feed conversion ratio (FCR) per se, but the measure-related mortality increased the feed consumption per one marketable 5 kg fish to account for losses from feed consumed by fish not harvested. We assumed that the combination measures were effective in maintaining sea lice within acceptable levels between stocking and harvesting. This meant that, other than the measure-related mortalities, there were no effects of measures on the environmental costs related to production through changes in performance of the fish. We assumed no measure-related resistance as not within the scope of this study and adding a level of complexity not handled without experimental data.

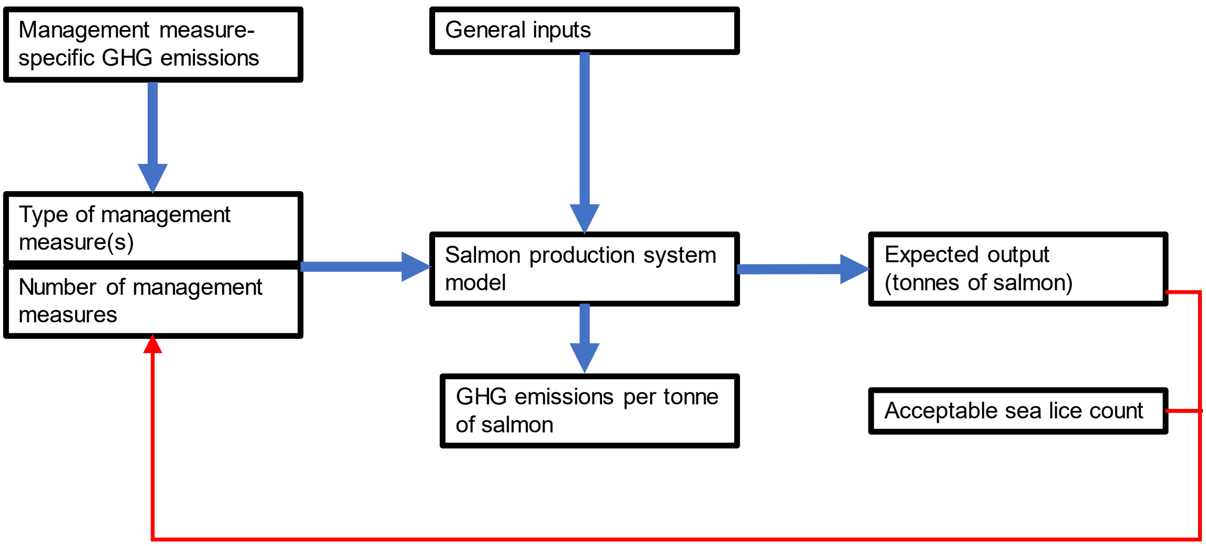

Figure 2. A simplified LCA system modelling approach

The data for modelling the general performance of the salmon production chain (excluding sea lice management measures) were obtained from a review of the literature (e.g. Newton and Little 2018, Philips *et al.* 2019, Boissy *et al.* 2011, Marine Scotland 2018, ecoinvent 2020). The data sources for each separate sea lice management measure are presented in Table 1.

Table 1. Sea lice management measure-specific inputs and their sources.

Sea lice management measure	Inputs	Sources
Incidental		
Bath		
Fresh water (well boat & tarpaulin)	• Amount of water per measure • Amount of fish treated per measure • Transport distance of fresh water • Transport emissions • Emissions from desalination (if applied) • Wellboat fuel consumption (if applied)	• Mowi 2016, 2018 • Watanabe 2016 • UK Government 2018 • Vince *et al.* 2008 • Modelling (functional relationships) • Expert opinion
Licenced veterinary medicines† (well boat & tarpaulin)	• Amount of water per measure • Amount of fish treated per measure • Salmosan Vet concentration • Salmosan Vet production emissions • Fuel consumption	• Mowi 2016, 2018 • Watanabe 2016 • UK Government 2018 • ecoinvent 2020 • Marine Institute 2007 • Modelling (functional relationships) • Expert opinion
Hydrogen peroxide (well boat & tarpaulin)[3]	• Amount of water per measure • Amount of fish treated per measure • H2O2 concentration • H2O2 production emissions • Fuel consumption	• Mowi 2016, 2018 • Watanabe 2016 • UK Government 2018 • ecoinvent 2020 • Marine Institute 2007 • Modelling (functional relationships) • Expert opinion

[3] This method is now only very infrequently employed on Scottish salmon farms, however we have included it in the analysis for comparison purposes.

Sea lice management measure (continued)	Inputs (continued)	Sources (continued)
In-feed Slice	• Amount of emamectin benzoate per kg feed • Daily feed consumption per fish • Duration of measure, days • Emamectin benzoate production emissions	• ecoinvent 2020 • The Fish Site 2004 • Marine Institute 2007 • Modelling (functional relationships) • Expert opinion
Physical removal Hydrolicer and Thermolicer and Optilicer	• Number of fish treated • Equipment construction emissions • Lifetime of the equipment • Fuel consumption	• Mowi 2016, 2018 • Watanabe 2016 • UK Government 2018 • Modelling (functional relationships) • Expert opinion
Continuous		
Skirts	• Construction emissions • Weight of a skirt • Lifetime of a skirt • Number of fish in pen	• Stien *et al.* 2012 • ecoinvent 2020 • Tarpaflex 2020 • Modelling (functional relationships) • Expert opinion
Cleaner fish (captured & farmed)	• Amount of cleaner fish used • Cleaner fish feed consumption • Number fish captured by a boat • Emissions associated with construction and using a boat • Cleaner fish hatchery emissions	• Boissy *et al.* 2011 • Macaskill 2014 • Watanabe 2016 • Powell *et al.* 2017 • ecoinvent 2020 • Modelling (functional relationships) • Expert opinion

†includes AlphaMax (deltamethrin), Salmosan Vet (azamethiphos).

***Combination sea lice management measures*.** We model three combination measures (Figures 3, 4, 5). The costs of equipment, implementation and side effects were assumed to be additive under each combination of measures (no resistance).

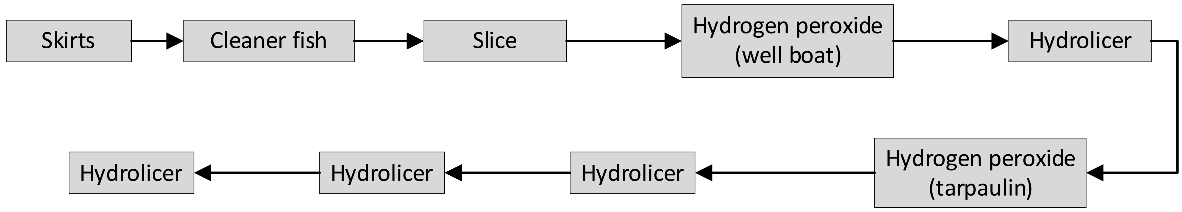

Figure 3. Combination measure 1
Source: Mowi, 2018

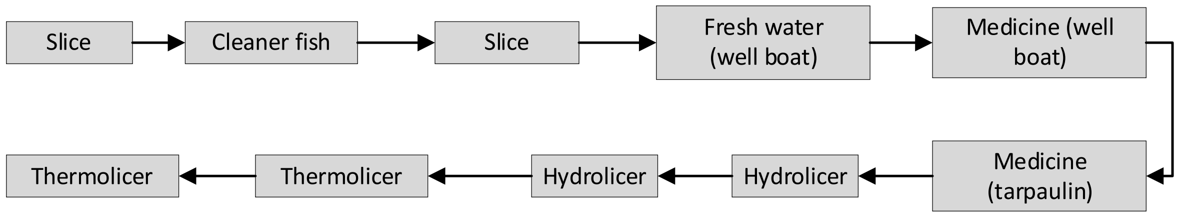

Figure 4. Combination measure 2
Source: based on survey data

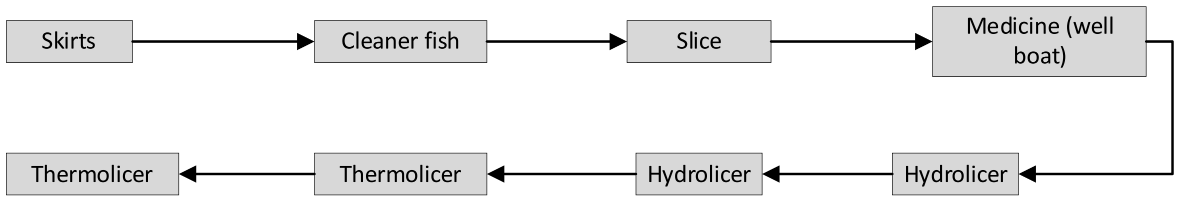

Figure 5. Combination measure 3
Source: own assumptions

Sensitivity analysis was performed to account for uncertainty of data inputs for the LCA model. In this analysis, a two-fold amount of all inputs (e.g. diesel, veterinary medicines, licenced veterinary medicines used in the bath measure, fresh water, construction costs of boats and other equipment, cleaner fish, cleaner fish feed) compared to the default values was used, and the resulting greenhouse gas (GHG) emissions for management measures, separate and in combination, were compared with the original results. Sensitivity analysis for combination measures was also run in a purely hypothetical scenario, 'Combination 4', with a limited number of sea lice management measures (1 x skirts, 1 x H2O2, 1 x hydrolicer), and a two-fold increase in background mortality/rejects, i.e. the standard background mortality (not including any additional mortality caused directly by the sea lice treatments) from 15% (assumed in this study) to 30%. This part of the sensitivity analysis was performed to demonstrate the impact of potential output losses on the carbon costs of the production chain.

Cost Effectiveness Analysis

We aimed to determine cost-effectiveness of different sea lice management measures on Scottish salmon farms. We considered the reduction in sea lice count as an indicator of effectiveness used for this study. This was not based on quantitative evidence but on a combination of expert opinion (aquaculture experts and health practitioners in the Scottish salmon sector), and literature review as the effectiveness measure.

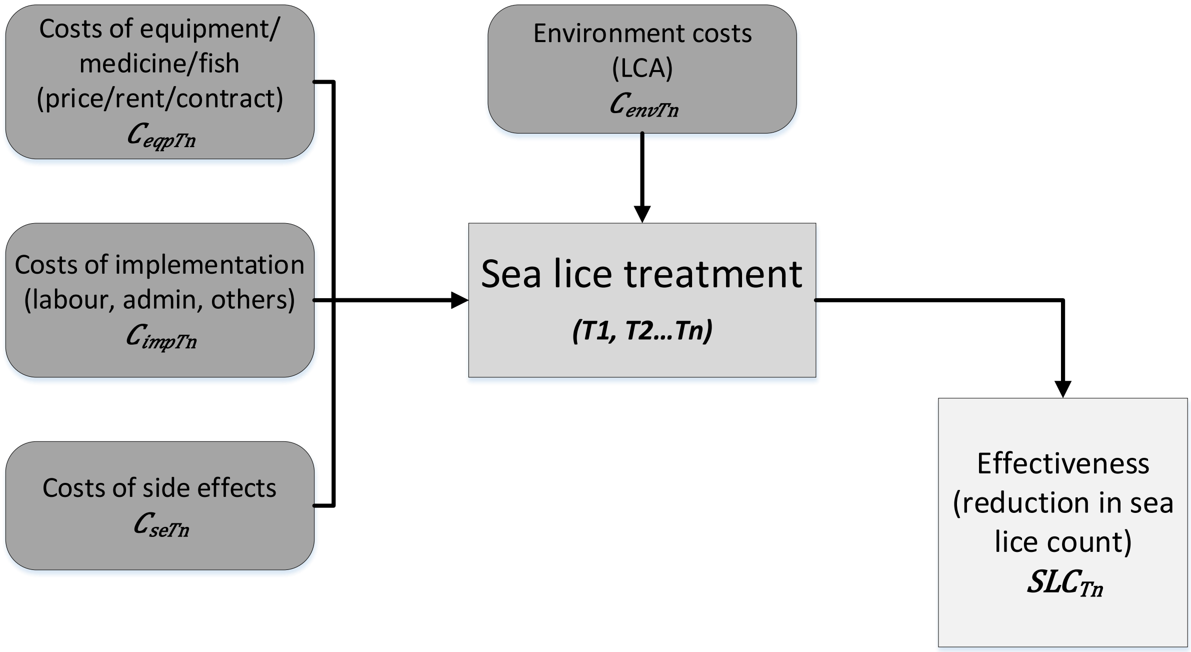

Figure 6. A schematic diagram of different parameters used in the analysis

We identified the cost of intervention under each of the sea lice management measures into 4 categories; cost of equipment, cost of implementation, environmental cost and cost of side effects (Figure 6). The accumulative cost was assessed against the reduction of sea lice on an adult salmon fish, which is considered as the efficacy score for this study (not experimentally assessed). The updated CE ratio used in this study is:

$$\text{CE ratio}_{Tn} = \frac{CeqpTn + CimpTn + CenvTn + CseTn}{EFTn}$$

Where, T_n is the n^{th} measure, C_{eqp} is the cost of equipment, C_{imp} is the cost of implementation, C_{env} is the environmental cost, C_{se} is the cost of side effects and ***EF*** is the efficacy score

i. Cost of equipment, $\boldsymbol{C_{eqp}}$:
   This cost includes the cost of licenced veterinary medicines (if any) used and other especial equipment required to use the sea lice management measures. For instance, for H_2O_2, this cost includes cost of H_2O_2 and cost of oxygenation.

ii. Cost of implementation, $\boldsymbol{C_{imp}}$:
   This covers the cost of the application of the sea lice management measures. It includes costs of boats, labour and other provisions that are required to implement the measures. For example, to implement H2O2, this cost will include well boat and labour.

iii. Environmental cost, $\boldsymbol{C_{env}}$:
   The carbon cost for applying each of the sea lice management measures is determined by using a Life Cycle Analysis (LCA) model developed for this study. The LCA uses carbon emissions from all the activities associated to providing and implementing each measure. The emissions are converted into carbon cost by using a standard carbon cost rate £12.8/tCO_{2eqv}.

iv. Cost of side effects, $\boldsymbol{C_{se}}$:
   This cost includes any loss in revenue due to increased mortality of salmon under a sea lice management measure.

$$\boldsymbol{CseTn = mTn * ps}$$

   Where, *m* is increased mortality under sea lice management measure *Tn*, *ps* is price of salmon, *fs* is feed saved due to starvation and *pf* is price of feed per kg

CEA: Limitations

The first limitation of this study was the limited availability of secondary data sources and limited primary data or access to it. As a result, the majority of the financial information related to different sea lice management measures applied on Scottish farms were taken only from one source (Macaskill, 2014). For information not available for Scottish farms, we used estimates based on similar information available from other salmon producing countries, such as Norway (Iversen *et al.*, 2017). As mentioned in relation to LCA limitations, we have selected data as closely as possible to the Scotland/UK salmon sector, and detailed sensitivity analysis was performed.

A second limitation was the absence of control farms to compare our results with. Most health economic studies rely on empirical data in a ‘with- and without- ‘format which provides a reliable source of generating the indicators. Sea lice infestation is a significant problem for Scottish salmon producers so a ‘without-sea lice management measure’ scenario is almost non-existing. For this reason, we have used expert opinion on efficacy of each of the single use measures to obtain qualitative relative efficacy scores. Because there was a wide variability in the expert opinion on the efficacy of sea lice management measures, we included a sensitivity analysis to explore how the minimum and maximum efficacy estimates affect model outcomes.

Another limitation of this study concerns the combinations of measures. Because there is no standard combination of sea lice management measures that farms use, we modelled single use measures separately, and three realistic combination measures based on expert opinion (survey data) and members of the research team (as it was beyond the scope of this study to include all possible combinations).

CEA: Assumptions

We used the following assumptions relating to a Scottish salmon farm and sea lice management measures (Table 2). We assumed that an average salmon farm has 1.2 million fish with an average harvest weight of 5 kg per fish. The average length of the production cycle is 20 months in the marine environment and each fish required 5.75 kg of feed per production cycle, when assuming a 15% "background" mortality. An average farm gate price of live salmon is set to £32.42 and average price per kg of feed is £0.94[4]. For the cleaner fish, it was assumed that 48,000 fish are required on an average salmon farm. We also assumed that synchronised fallowing is the standard practice on each Scottish salmon farm and hence, it was not included as a sea lice mitigation method in this study.

Table 2. Basic assumption used in the LCA and CEA models

Variable	Average	Source
Fish	1.2 million per farm	Macaskill (2014)
Harvest weight	5 kg	
Length of production cycle	20 months	
Feed requirement	5.75 kg per fish per cycle	
Salmon farm gate price	£32.42 per fish	
Cleaner fish requirement	48,000 per farm	Macaskill (2014)

Considering the large variation in efficacy of a sea lice management measure, we assumed the efficacy score of each measure was consistent and based on a general optimal outcome. We also assumed costings of each single use measure to be additive when used in combination and achieve the efficacy necessary in bringing down and maintaining sea lice count within acceptable (regulation compliant) levels i.e. with no impact on fish health, welfare and productivity, thereby ignoring resistance effects or variation in efficacy.

[4] The prices used in the analysis (mostly for years 2013/14 and 2017/18) were comparable. Price standardisation was not considered and testing for nominal values of other variables e.g. sourced for the LCA analysis feeding into CEA was performed using sensitivity analysis.

CEA: Costs of equipment, implementation and side effects

The sea lice management measures included in this study could be grouped based on characteristics. The costs of equipment, implementation and side effects associated with these groups of measurements are briefly described below.

i. Sea lice management by fresh water bath can be implemented in two ways – using tarpaulins or using well boats. The costs of fresh water batch treatment were provided for both implementation procedures as shown in Table 3 and Table 4.

   Fresh water using well boat: For this measure, the costs included were water costs, cost of a well boat and labour costs.

Table 3. Total cost of fresh water using a well boat for sea lice management

	Costs (£/per measure)	comment
Equipment		
Water	1008	Water charge £0.13/m^3*; well boat capacity 2500m^3**
Implementation		
Well boat	18,000	Macaskill, 2014
Labour	3,773	Macaskill, 2014
Total	33,620	

Source: * https://www.scottishwater.co.uk; ** https://www.fishfarmingexpert.com

   Fresh water using tarpaulin: the costs included water costs, tarpaulin and labour costs.

Table 4. Total cost of fresh water using a tarpaulin for sea lice management

	Costs (£ per measure)	comment
Equipment		
Water	1008	Water charge £0.13/m^3*
Implementation		
Tarpaulin	7,500	Macaskill, 2014
Labour	3,773	Macaskill, 2014
Total	12,281	

Source: *https://www.sepa.org.uk; **https://www.fishfarmingexpert.com

ii. Bath:
   The bath medicines included hydrogen peroxide, AlphaMax (deltamethrin), Salmosan Vet (azamethiphos). Baths can be implemented in two ways – using tarpaulins or using well boats. The costs for both implementation procedures were as shown in Table 5 and Table 6. Due to lack of information on individual prices as currently used in the Scottish salmon industry, cost of licenced veterinary medicines were taken from literature.

Table 5. Total cost of licenced veterinary medicines by bath using tarpaulin for sea lice management

	Costs (£ per measure)	comment
Equipment		
Licenced veterinary medicines	30,000	Macaskill, 2014
Implementation		
Application	25,536	Including tarpaulin
Boat	8,212	
Labour	3,773	
Total	67,521	

Table 6. Total cost of licenced veterinary medicines by bath using a well boat for sea lice management

	Costs (£ per measure)	comment
Equipment		
Licenced veterinary medicines	30,000	Macaskill, 2014
Implementation		
Application	18,036	
Well boat	18,000	
Labour	3,773	
Total	69,809	

iii. In-feed (Slice):

The cost of in-feed measures included licenced veterinary medicines, equipment and implementation costs. No separated costs were available and hence, total cost was determined to be £35,000 per measure based on Macaskill, 2014.

iv. Physical removal:

The physical removal measures currently relevant are hydrolicer, thermolicer and optilicer. Costs for these measures were not available for Scottish salmon farms and hence were based on information provided in a project report assessing the main production costs in Norwegian salmon farms (Table 7). It should be noted that the physical removal measures are only applied on farms to adult salmon fish (> 1 kg of weight). For smaller and younger fish, other sea lice management measures are used.

Table 7. Total cost of physical removal measures for sea lice management

	Total Costs per measure	comments
Hydrolicer	139,104	Includes machine depreciation, cost capital, service vessels, fuel and labour
Thermolicer/Optilicer	181,440	Includes machine depreciation, cost capital, service vessels, fuel and labour

Source: Iversen *et al.*, 2017 http://hdl.handle.net/11250/2481501

v. Skirts

The skirts are tarpaulins with an open bottom. They form physical barriers around salmon pens to minimise contact between sea lice drifting in from outside the pen, and fish. There are different kinds of materials (dense or semi permeable) used to make skirts. We assumed that skirts used in Scottish farms were dense skirts (e.g. tarpaulin) which generally could survive at least the whole salmon production cycle. We used total costing of applying skirts (£48,384 per cycle) which included cost of the material, application and maintenance of the skirts.

vi. Biological (Cleaner fish)

In Scotland, the common cleaner fish used are different species of wrasse and lumpfish. These are permanently employed in the salmon pens. The costings used in the model were for wrasse species as shown in Table 8.

Table 8. Total cost of cleaner fish for sea lice management

	Costs £ per measure	Comments
Equipment		
Fish (wrasse)	91,200	£1.9 per fish; 48000 fish
Implementation		
Hides	11,040	£230 each; 48 hides
Feeders	2,400	£50 each; 48 feeders
Feed	10,875	Expert opinion
Total	115,515	

Source: Macaskill (2014)

CEA: Environmental costs

The environment costs of each of the sea lice management measures are presented in Table 9. These are technical inputs used in the LCA model, and not comparable with each other as based on different functional units. CO_{2e} emissions generated by the LCA model are presented in Table 10. These costings were based on emissions from the whole production cycle when using one sea lice management measure. A standard carbon cost of £12.8 per tCO_{2e} was used to determine total carbon emissions per fish (BEIS, 2019).

Table 9. Direct carbon costs and mortalities associated with single use and combination measures for sea lice management. Results of the sensitivity analysis are shown in italic font

Sea lice management measures	Carbon costs (£ per fish)	Mortalities[♯] (% per measure)	*Carbon costs (£ per fish) in sensitivity analysis when assuming 2x input quantities*
Incidental			
Bath			
Fresh water (well boat)	0.0012	0.5	*0.0018*
Fresh water (tarpaulin)	0.0006	0.5	*0.0010*
Hydrogen peroxide (well boat)	0.0020	1.0	*0.0029*
Hydrogen peroxide (tarpaulin)	0.0016	1.0	*0.0020*
Other licenced veterinary medicines † (well boat)	0.0010	0.5	*0.0014*
Other licenced veterinary medicines † (tarpaulin)	0.0008	0.5	*0.0010*
In-feed			
Slice	0.0001	0.10	*0.0001*
Physical removal			
Hydrolicer	0.0007	0.25	*0.0012*
Thermolicer/Optilicer	0.0008	0.50	*0.0011*
Continuous			
Skirts	0.0000	0.00	*0.0001*
Cleaner fish (capture & farmed)	0.0003	0.00	*0.0006*
Entire production cycle			
Combination 1	0.0070	3.1	*0.0105*
Combination 2	0.0071	3.2	*0.0106*
Combination 3	0.0056	2.6	*0.0083*
Combination 4	0.0170	16.25	*0.0181*

†includes AlphaMax (deltamethrin), Salmosan Vet (Azamethiphos).
[♯]Source: for mortality of physical removal measures (Iversen *et al.*, 2017 http://hdl.handle.net/11250/2481501); for others (expert opinion)
Source: own calculation (LCA)

Table 10. GHG emissions associated with the combination measures, as estimated through LCA. Results of the sensitivity analysis are shown in italic font.

Sea lice management measures	Total lifecycle GHG, t CO2e per harvested 1 t liveweight at farm gate at the end of the cycle	Total lifecycle GHG, t CO2e per harvested 5 kg fish at farm gate at the end of the cycle	*Total lifecycle GHG, t CO2e per harvested 5 kg fish at farm gate at the end of the cycle in sensitivity analysis when assuming 2X input quantities*
Combination 1	2.220	0.01110	*0.01137*
Combination 2	2.221	0.01111	*0.01138*
Combination 3	2.198	0.01099	*0.01120*
Combination 4 (sensitivity analysis assuming 2X mortality)	*2.377*	*0.01189*	*0.01196*

The results with the default inputs and additional results from the sensitivity analysis show that the differences in the GHG emissions between the different measures are small, and due to the high uncertainty in the input values, any ranking or detailed comparison between the measures is not meaningful. Inclusion of the hypothetical ‘Combination 4’ scenario shows that a high increase in mortality/rejects could potentially result in a strong increase in the GHG emissions, and this increase could be much higher than the direct emissions related to any sea lice management measures. The main reason is that the increased mortality would reduce the number of harvested fish, while a large part of the resources (most notable feed) would be wasted, and therefore the resource use would be higher per harvested fish (e.g. higher FCR). In such a case, the sea lice measures should not be considered as a source of carbon costs, but instead as a method to achieve carbon saving as a result of more efficient production.

CEA: Efficacy scores

The efficacy scores of sea lice management measures represent the relative efficacy and are based on expert opinion. Experts were asked to base their perceived efficacy on the difference between pre- and post- sea lice counts around a measure through a questionnaire. Expert opinion considered in this study consisted of health practitioners and experts in the Scottish salmon sector who participated in the workshop (three out of ten attendees provided further responses) or responded to the in-depth interview, members of the research group conducting the study, and expert opinion recorded in the literature (SAIC, 2019). The physical removal measures were the highest-ranked measures achieving more than 80% of efficacy scores and hydrogen peroxide was the lowest-ranked measure with 43% efficacy score (Table 11). The sensitivity analysis included maximum and minimum levels of efficacy scores for each sea lice management measure.

Table 11. Average and min/max levels of efficacy scores for each of the sea lice management measures

Sea lice management measures	Efficacy scores	Efficacy range	
		Maximum	Minimum
Incidental			
Bath			
Fresh water (well boat & tarpaulin)	0.64	1.00	0.20
licenced veterinary medicines† (well boat & tarpaulin)	0.60	0.90	0.50
Hydrogen peroxide (well boat & tarpaulin)	0.43	0.60	0.10
In-feed			
Slice	0.73	0.80	0.50
physical removal			
Hydrolicer	0.80	0.95	0.70
Thermolicer/Optilicer	0.80	0.95	0.70
Continuous			
Skirts	0.58	0.90	0.40
Cleaner fish (capture & farmed)	0.72	0.90	0.60

†includes AlphaMax (Deltamethrin), Salmosan Vet (Azamethiphos).

4. LCA & CEA results

We integrated LCA and CEA, with the LCA results i.e. environmental impacts (GHG emissions) of the whole salmon production chain when applying different types of sea lice management measures (Table 10), feeding as input variables into the CEA. In this section we present the results of the combined LCA & CEA analysis.

Relative cost-effectiveness for theoretical single use sea lice management measures and combination measures for a full production cycle are presented separately in Figure 7 and 9, because they are not comparable.

Caution should be applied when comparing cost-effectiveness of single use measures based on the limitations previously mentioned regarding data available for this study as well as the consequent simplified modelling assumptions.

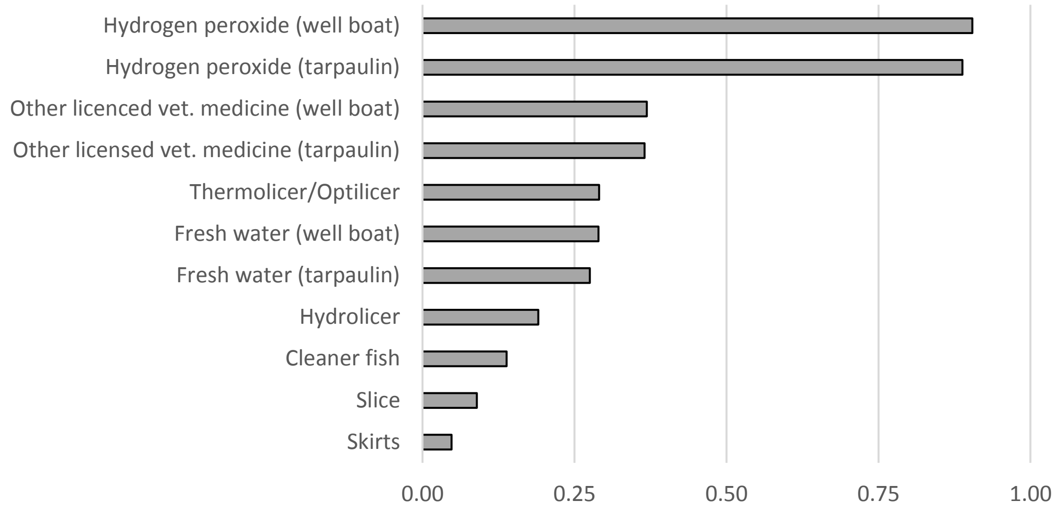

Figure 7. Cost-effectiveness of different sea lice management measures applied on Scottish salmon farms under standard efficacy level (£/unit of effectiveness per fish)

The horizontal bars indicate the cost of the sea lice management measures for the same unit of effectiveness per fish, implying that the longer the bar, the higher the cost to reach the same efficacy. In-feed and skirts measures all cost under £0.10 per fish per unit of effectiveness, and were the group of most cost-effective measures. The cleaner fish, fresh water, physical removal measures and the licensed veterinary medicines were among the second most cost-effective measures, with a cost ranging between £0.14 to £0.37 per fish per unit of effectiveness. The use of hydrogen peroxide (both well boat and tarpaulin) represented the least cost-effective measures among single use measures, with a cost of around £0.90 per fish per unit of effectiveness.

Sensitivity analysis

Sensitivity analysis was conducted using maximum and minimum levels of efficacy scores, Cost-effectiveness for these maximum and minimum levels of efficacy are presented in Figure 8.

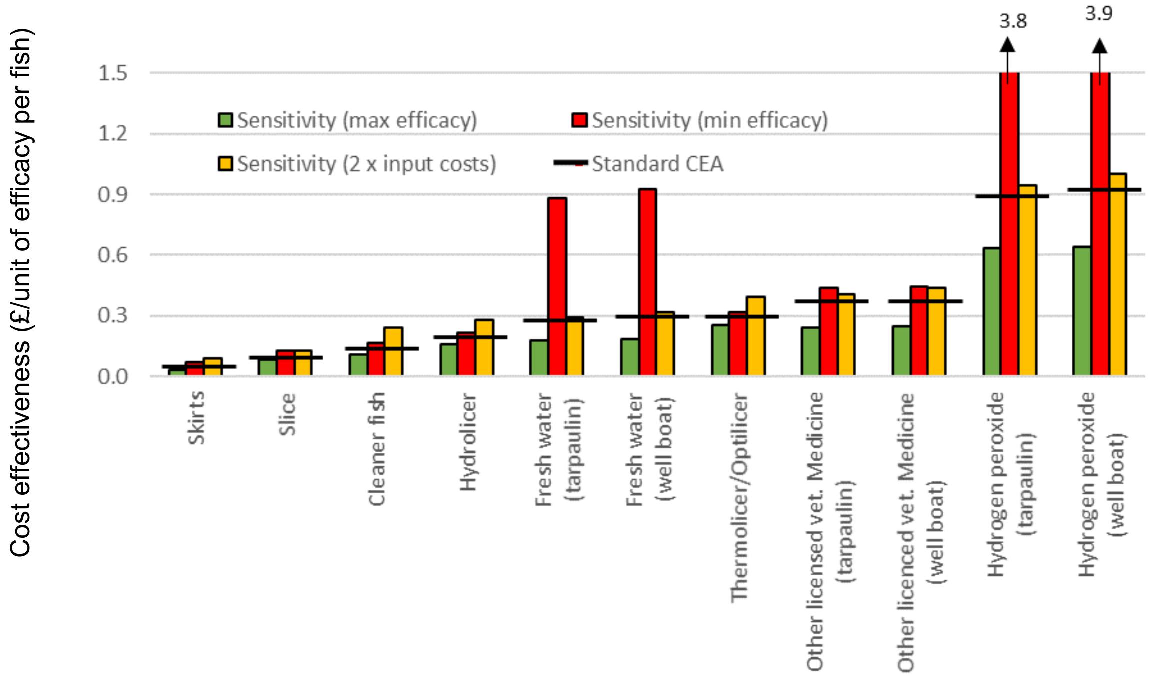

Figure 8. Cost-effectiveness of different sea lice management measures applied on Scottish salmon farms under sensitivity analysis compared to the standard CEA

There was no major change in ranking of the measures by cost-effectiveness under a maximum level of efficacy (green columns in Figure 8) compared to the results under the default efficacy level assumption (represented by black horizontal lines in Figure 8). There was a small change in the ranking, with only the thermolicer measure becoming slightly less cost-effective than the other veterinary medicine measures. In terms of a change in magnitude, the cost for each of the single use measures became more cost effective by up to 36% per unit of effectiveness.

The ranking of the sea lice management measures (red columns in Figure 8) changed substantially for fresh water measures when minimum efficacy scores were used. These became less cost-effective compared to all other measures except for hydrogen peroxide measures which remained the least cost effective (Figure 9). The fresh water measure had the lowest possible efficacy as shown in Table 11, which lowered its cost effectiveness significantly. Skirts and in-feed measures remained the most cost-effective measures under assumed minimum values for efficacy scores, and hydrogen peroxide remained the least cost-effective among the single use measures. Physical removal measures and use of other licensed veterinary medicines became significantly more cost-effective. In terms of a change in magnitude, the cost per unit of effectiveness for all single use measures increased by threefold for hydrogen peroxide measures and twofold for fresh water measures.

Changes in the costs of interventions to similar extent for all management measures (for instance, doubling the costs) did not change the overall cost-effectiveness rankings of the management measures although the absolute values of cost-effectiveness were changed (orange column in Figure 8). Changing costs of single use measures however, showed some changes in cost effectiveness rankings. For example, increasing the price of cleaner fish by 50% and 100% led to a decrease in the cost-effectiveness of the measure by £0.04 and respectively, £0.10 per unit of effectiveness. This led to the cleaner fish measure becoming slightly less cost-effective than the hydrolicer measure.

When comparing the three sea lice combination management measures, results indicate Combination 3 as the most cost-effective, with £ 1.23 per fish per unit of effectiveness, and Combination 2 as the least cost-effective with £1.67 per fish per unit of effectiveness (black columns in Figure 9).

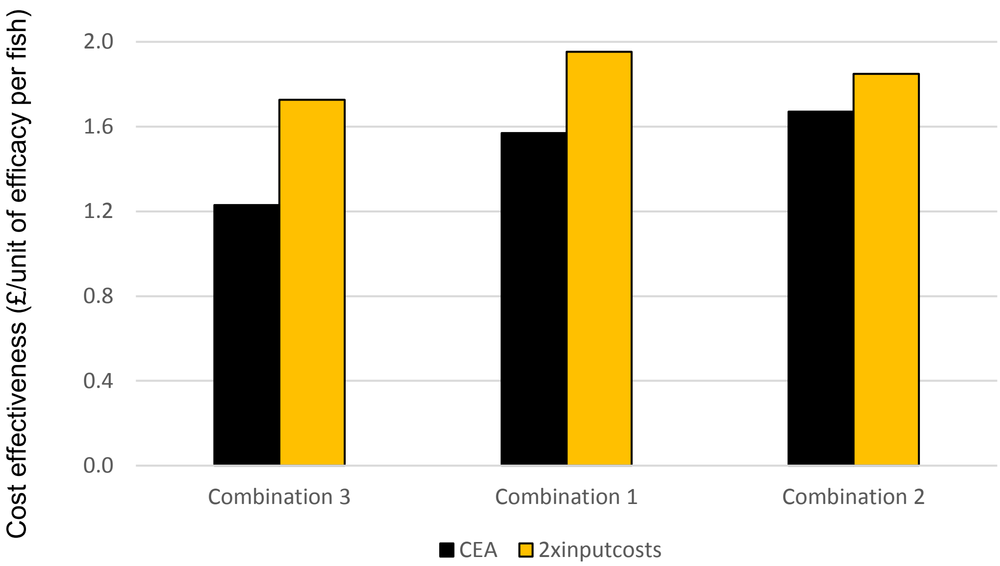

Figure 9. Cost-effectiveness of different combinations of sea lice management measures applied on Scottish salmon farms under a standard and 2xinput costs scenarios.

We tested results of the analysis of combination measures using sensitivity analysis for 2 x input costs (Combinations 1-3) and 2 x fish mortality (hypothetical scenario Combination 4). Combination measure 1 became the least cost-effective measure, with an increase in cost to £1.9 per fish per unit of effectiveness (orange columns in Figure 9). The change in ranking is due to the nature of the inputs used in each combination. Under Combination 4, the cost effectiveness of the measures was significantly reduced, and it costed up to £5.6 per fish per unit of effectiveness. This suggests that the analysis is highly sensitive to fish mortality. This is because the loss of fish due to mortality is fully accounted for as loss of revenues (included as costs of side effects) in the CEA model.

5. **Results of participatory workshop: wider implications of sea lice control**

The participatory workshop on sea lice control in salmon primary production took place on the 20th of January 2020, 11 am – 4 pm at SRUC, Inverness Campus.

Workshop participants (ten) included representatives of the different parts of the Scottish salmon supply chain (salmon producer association, salmon processing and retail, input related – cleaner fish, health practitioner), academia (salmon health and environmental aspects) and policy (disease modelling). Workshop organising team (four) comprised of social (economics) and non-social (aquaculture veterinary) science expertise.

The aim of this participatory workshop was to explore how factors leading to sea lice infestation and choice of sea lice control options can be mitigated and, respectively, influenced through incentives to producers and collaboration with others along the salmon supply chain.

The foundation of the participatory approach to follow at the workshop was system dynamics (SD). SD models map the flows, processes, decision rules and relationships between actors that operate within a complex system. Group model building (GMB) is used to develop SD models jointly through participation and direct collaboration between the actors involved in the system to identify leverage points and interventions (and potential delivering mechanisms) which may lead to more effective sea lice control in the system (salmon supply chain). GMB is ideally suited to SD language and concepts and particularly relevant when the system involves diverse types of actors, when many different control options exist, and when it is difficult for actors to understand individually the possible consequences of a collective decision made within a complex system.

Based on findings from previous studies we developed a process flow diagram that represents the flow of salmon through the supply chain from producer to consumer. It described a primary flow representing healthy salmon reaching the market, but also secondary flows to account for sea lice infested salmon and potential impact pre- and post- farmgate. The first step of the workshop was to validate the diagram with workshop participants. Subsequent sessions discussed the causes and consequences of salmon being infested with sea lice, ranked alternative control options and their effects on supply chain (primary production, transport, processing, retail, consumption), welfare and the environment. Incentives for multicriteria effective measures of sea lice control were identified and linked to causes of and control measures within causal loops. Causal loops help us to identify the options for intervention and their potential consequences in the system. The workshop followed the structured presented in the schedule (Appendix).

The scope was confined to the primary salmon flow from farm to processing, with main focus on the causes/destinations/consequences of sea lice control measures on the salmon supply chain, environment and fish welfare where any externalities are due to causes originating in primary production and sea lice management measures identified include those currently used in the Scottish salmon industry.

The participants identified the following potential factors influencing the choice of sea lice preventative/control measures:

- Farm health management: (previously tested) efficacy of preventative/control measure; (previously tested) cost-effectiveness of preventative/control measure; sea lice numbers and dynamics linked to different sequences of (combined) control measures; salmon overall health status; suitability of sea lice control measures within farm holistic health management/disease mitigation plan; sea lice preventative/control measures used on (neighbouring) farms; site/location suitability (location related sea lice prevalence).

- Farm economic factors: business scale/biomass level/production stage/fish size/harvest plan; compatibility to farm environment; farm type/practice - organic/standard/best practice; access to technology/medicines/equipment such as boats; skilled staff availability/time/knowledge, experience, understanding; access to information and training; access to financial resources; resource prioritisation.

- Environmental, salmon welfare, and health concerns: producers' perceptions re impacts of preventative/control measures on salmon welfare; producers' perceptions re impacts of preventative/control measures on cleaner fish welfare; environmental impacts of control measures such as residues affecting wild salmonid populations; potential of control measures such as medicines to induce resistance.

- Markets & consumers perceptions: impact of control measure on product quality (stress leading to lower quality flesh)/price/sales; consumers perceptions re welfare/environmental impacts of ('sea lice as a problem') control in salmon industry; consumers perceptions re human health impacts of sea lice control in salmon industry.

- Regulatory framework: compliance with environmental standards/regulations; compliance with food safety regulations; compliance with welfare regulations/welfare act/accreditation schemes/VMD standards.

- Other: weather/seasons.

The discussion focused on a set of sea lice control measures that included the following:

1. in-feed medicines
2. bath medicines
3. using cleaner fish during the seawater cycle
4. using skirts during (part of the) seawater cycle
5. area management / inter-producer collaboration
6. larger smolts at sea stocking

7 physical removal: hydrolicer
8 lowering biomass (farm/area)
9 physical removal: thermolicer
10 freshwater bath
11 breeding & genetics/ using lice-resistant salmon strains
12 functional feeds
13 healthy fish
14 reduced cycle length/ early harvest
15 adjusting stocking time
16 site location control
17 adjusting fallowing periods
18 stocking at favourable year classes

The stakeholders' perceived effects of the use of different sea lice control measures on the supply chain and externalities i.e. environment and welfare, are presented in Table 12.

Table 12. Economic, environmental and welfare effects of sea lice control measures (anonymised individual responses are presented in Table 13 Appendix)

Sea lice preventative/control measures	Prevention P & Intervention I	Farm economic impacts	Environmental impacts	Impacts on salmon welfare	Impacts on salmon health (sea lice)	Impacts on salmon health (other e.g. immunity)	Impacts on cleaner fish welfare	Impacts on cleaner fish health	Impacts on supply chain - transport	Impacts on supply chain - processing	Impacts on supply chain - retail	Impacts on consumers/ society perceptions
In feed medicines	P&I		-	+	+					-	-	-
Bath medicines	I	-	-	-	+		-		-	-	-	-
Cleaner fish	P&I	+	-	+	+		-		-	+	+	+
Skirts	P		+	+		-					+	
Area management	P&I		+	+	+						+	
Larger smolts quality	P	-	+	+	+				-		+	+
Hydrolicer	I	-	+	-	+	-	-			-	-	-
Biomass (farm/area)	P&I		+	+	+				+	+	+	
Thermolicer	I	-	+	-	+	-	-				-	-
Freshwater	I	-	+	+	+	+				+	+	+
Genetics	P	+	+	+	+	+						
Functional feeds	P&I	+	-	+	+	+				+	+	
Healthy fish	P	+	+	+						+	+	+
Reduced cycle length	P&I	+	+	+	+	+					+	+
Stocking time	P											
Site location control	P	-	+	+	+	+					+	+

strong negative effects	moderate negative effects	light negative effects	light positive effects	moderate positive effects	strong positive effects

The workshop participants have identified a number of potential effects of each of the sea lice preventative/control measures, at times contradictory and thus not always straightforward to summarise. Table 11 information is complemented by Table 12 (Appendix). The following points are based entirely on the opinions of stakeholders.

1 In-feed medicines may have negative impact on the environment in the short term, however positive long term due to disease eradication and lower/no need for in-feed medicines. Most likely low to no impact as in-feed medicines are targeted at smaller fish and thus will not be used for larger fish which are nearing harvest so that they interfere with neither harvest plans when residues have to be cleared from fish nor the subsequent processing and retail.

2 Bath medicines may have negative impact on farm as the measure is time consuming and requires increased staff & equipment resources. Negative impact on the environment through e.g. effect on marine invertebrates and on salmon welfare due to stress from handling & exacerbation of underlying health conditions. Both welfare and environmental impacts are overall negative in the short term, however there will be a positive impact in the long term depending on the efficacy of bath medicines to control sea lice. Welfare of cleaner fish may be negatively affected. The impact on overall health will be either positive or negative depending on underlying conditions, such as water temperature and fish health. Sea lice management measures may reduce the tolerance to transport and potentially increase mortality during transport. Sea lice management measures may impact processing and subsequently retail stages through reduced flesh quality, potential medicine residues in flesh and lower supply due to medicine withdrawal period. Retail and consumption stages may be affected due to perceptions linked to use of medicines and implicitly may affect the image of the salmon industry.

3 Using cleaner fish as sea lice management measure may impact on the farm economic situation with regard to increased requirement for staff and equipment. However that may be compensated by reduced need for other measures, overall it is very cost-effective if the seasonal aspects of cleaner fish are well managed as part of the overall fish health management. It may affect the environment negatively through impact on the wild populations/knock on effect on other species. However, the reduced need for sea lice management measures and efficacy of sea lice control may lead to positive impacts on the marine environment in the long term. Using cleaner fish has moderate to strong positive impacts on salmon health and welfare relative to salmon with baseline lice counts, however the opposite effects with regards to the welfare of cleaner fish themselves. The presence of cleaner fish may cause minor disruptions to transport, however subsequent impacts on processing and retail, consumption are overall positive due to no need for medicinal or other sea lice management measures that may affect salmon welfare. Negative effects at the demand side of the supply chain may occur based on consumers’ perceptions as regards the welfare of cleaner fish.

4 The use of skirts to control sea lice has light environmental and welfare effects, with positive impacts at the retail side of the supply chain. Negative impacts on salmon welfare and overall health may occur due to stress through reduced oxygen flow in the pens. No specific positive or negative effects were identified at any other stages of the supply chain.

5 The use of area management to control sea lice has moderate to strong environmental and welfare effects, with positive impacts also at the retail side of the supply chain. No specific positive or negative effects were identified at any other stages of the supply chain. It is very effective as a sea lice control measure and thus has strong positive impacts on salmon health.

6 While strong in terms of sea lice control and related impact on salmon health, using larger smolts quality as a sea lice control measure has a high cost to the farm. Smolts often come from freshwater recirculating aquaculture system (RAS), which is a very controlled environment, therefore costly to run. Salmon's shorter presence in the marine environment may lead to lower levels of waste and thus an overall positive impact on the marine environment. Also, a reduced duration of exposure of salmon to the environment including to sea lice reduces exposure to factors that impede health and welfare of the salmon. Overall, the effects at the demand side of the supply chain are positive, not affecting industry image due to no specific negative perceptions of the consumers related to the different aspects of this sea lice control measure.

7 Use of hydrolicer as a sea lice control measure involves high equipment costs to the business. It has overall a strong positive impact on the marine environment through reduced need for licenced veterinary medicines, however the equipment involved has a high carbon footprint. The short term impact on salmon welfare from using hydrolicers is strongly negative as this is a stressful method involving significant risks, however as any other measure of control, when effective in controlling sea lice, it may have a positive long term impact on salmon welfare. While effective in controlling for sea lice, the method has a negative damaging impact on the overall health of salmon (exacerbating underlying conditions through increased stress and high mortality) and the health and welfare of cleaner fish, if used on farm. The negative health and welfare effects may transfer to the processing stage and the method has overall negative effects at the retail/consumption end of the supply chain through mostly public perceptions. Depending on the information available to the public, perceptions may focus on reduced use of medicines with its subsequent environmental effects, however they are mostly negative due to direct impact on salmon health and welfare.

8 Reducing biomass (farm/area) as a measure of sea lice control has overall positive impacts at supply chain level, on the environment and salmon welfare and health.

9 Use of thermolicer as a sea lice control measure involves high equipment costs to the farm. It has overall a strong positive impact on the marine environment through reduced need for licenced veterinary medicines, however the equipment

involved has a high carbon footprint. The short term impact on salmon welfare from using hydrolicers is strongly negative as this is a stressful method involving significant risks, however as any other measure of control, as effective in controlling sea lice, it may have a positive long term impact on salmon welfare. While effective in controlling for sea lice, the method has a negative damaging impact on the overall health of salmon (exacerbating underlying conditions through increased stress and high mortality) and the health and welfare of cleaner fish, if used on farm. The negative health and welfare effects may transfer to the processing stage and the method has overall negative effects at the retail/consumption end of the supply chain through mostly public perceptions. Depending on the information available to the public, perceptions may focus on reduced use of medicines with its subsequent environmental effects, however they are mostly negative due to direct impact on salmon health and welfare.

10 The use of freshwater as a sea lice management measure involves a high cost to the farm and has mixed environmental and welfare impacts depending on management of the method e.g. it can be challenging to maintain water quality for the whole duration of the measure, and this may represent a moderate risk to salmon welfare. It is overall effective in controlling sea lice, particularly for free living or recently attached lice, however management of control i.e. duration has a direct influence on efficacy and subsequently overall salmon health. The impact on overall health will be either positive or negative depending on underlying conditions. The method has positive effects on processing and retail stages with strong positive impact on consumers perceptions.

11 Use of breeding and genetics to improve salmon resistance to sea lice has strong positive effects on salmon health and welfare, the environment and supply chain from production to processing. Selecting for a specific trait i.e. resistance to sea lice may compromise others. Due to the general lack of public knowledge and confusion generated on genetically modified organisms, production of sea lice resistant salmon may meet with negative perceptions of consumers and thus marketing/retail may be negatively affected by use of this control method.

12 Use of functional feeds to control for sea lice has positive impacts on salmon health and welfare, it is cost-effective and these effects are transferred throughout the supply chain. There may be negative impacts on the marine environment, e.g. through waste.

13 Use of healthy fish as a sea lice control measure has strong positive impacts on supply chain from production to retail, salmon health and welfare and the environment.

14 While there may be a financial and potentially environmental cost to producing smolts either in freshwater or closed systems, this method is overall cost efficient through reduced duration of the saltwater cycle by producing larger smolts and overall higher productivity. It has a positive effect on the environment and salmon health and welfare due to reduced need for intervention measures

(licenced veterinary medicines or physical removal measures) and if timing of cycle is managed to reduce wild-farm interactions. The positive impacts are transferred to the demand end of the supply chain. There is an overlap between this and 'larger smolts' control measure however we have not blended them into one as there are other ways to reduce cycle length e.g. at the end of the saltwater cycle through earlier harvest.

15 The use of a more favourable stocking time as a sea lice control measure has positive effects on the environment and salmon welfare. No specific effects were mentioned at production stage, however it has positive effects on processing and further on retail and consumers.

16 Use of site location as a sea lice control measure has positive effects on the supply chain, the overall salmon health and welfare, and the environment, resonates well with consumers perceptions and thus positively affects retail. However it may involve high equipment and production costs in offshore or high velocity sites.

The linkages between the causes and effects of current sea lice control measures and identified incentives for improved control are presented in the causal loop diagram (CLD[5]) (Figure 10).

Participatory analysis identified potential incentives for further improving control of sea lice on farm, many of these are already taken into account in the Scottish salmon sector. These include:
- better balancing of science-based evidence and precautionary principle based policies (health, environment, welfare)
- public sector driven positive incentives such as subsidised access to technology
- research on consumers' willingness to pay for sustainably farmed salmon
- media campaigns and education to the public on implications of disease control in aquaculture

[5] CLDs are a combination of different feedback loops that exist within a system. Feedback loops can be either reinforcing or balancing. Combinations of these loops state the specific behaviour of a system over time (K. Rich 2018. Causal loop diagrams for systems thinking. Training notes).
Notations in the CLD:
R - a reinforcing loop reinforces behaviour in a system, either leading to a virtuous or vicious cycle.
B - balancing loops which, by contrast, counteract and resist change. In a balancing loop, the system converges on a target.
CLD was created using Stella Architect software by ISEE Systems, 2016
± signs on arrows: links move in the same direction (denoted by +); links move in opposite directions (denoted by -)
Most variables also have an indirect influence on many other variables as shown by sequences of effects (arrows)

- market based incentives (price differentiation through labelling re sustainable disease control)
- market based incentives (traceability)
- development of health monitoring/preventative technologies
- development of delicing technologies from product/flesh at packing
- research on salmon welfare linked to sea lice control
- research on cleaner fish welfare linked to sea lice control
- media campaigns to maintain/improve industry image to the public
- private driven stick type incentives such as higher environmental/welfare standards required under processor/retail contracts
- research on efficacy of disease control
- improved collective action to sea lice control along supply chain

The causal relationships between causes and effects of sea lice control, effects of sea lice control and incentives for improved control, incentives for control and effects of improved control can be followed in the CLD diagram (Figure 10). An example of a causal loop is presented in Figure 11 Balancing loop.

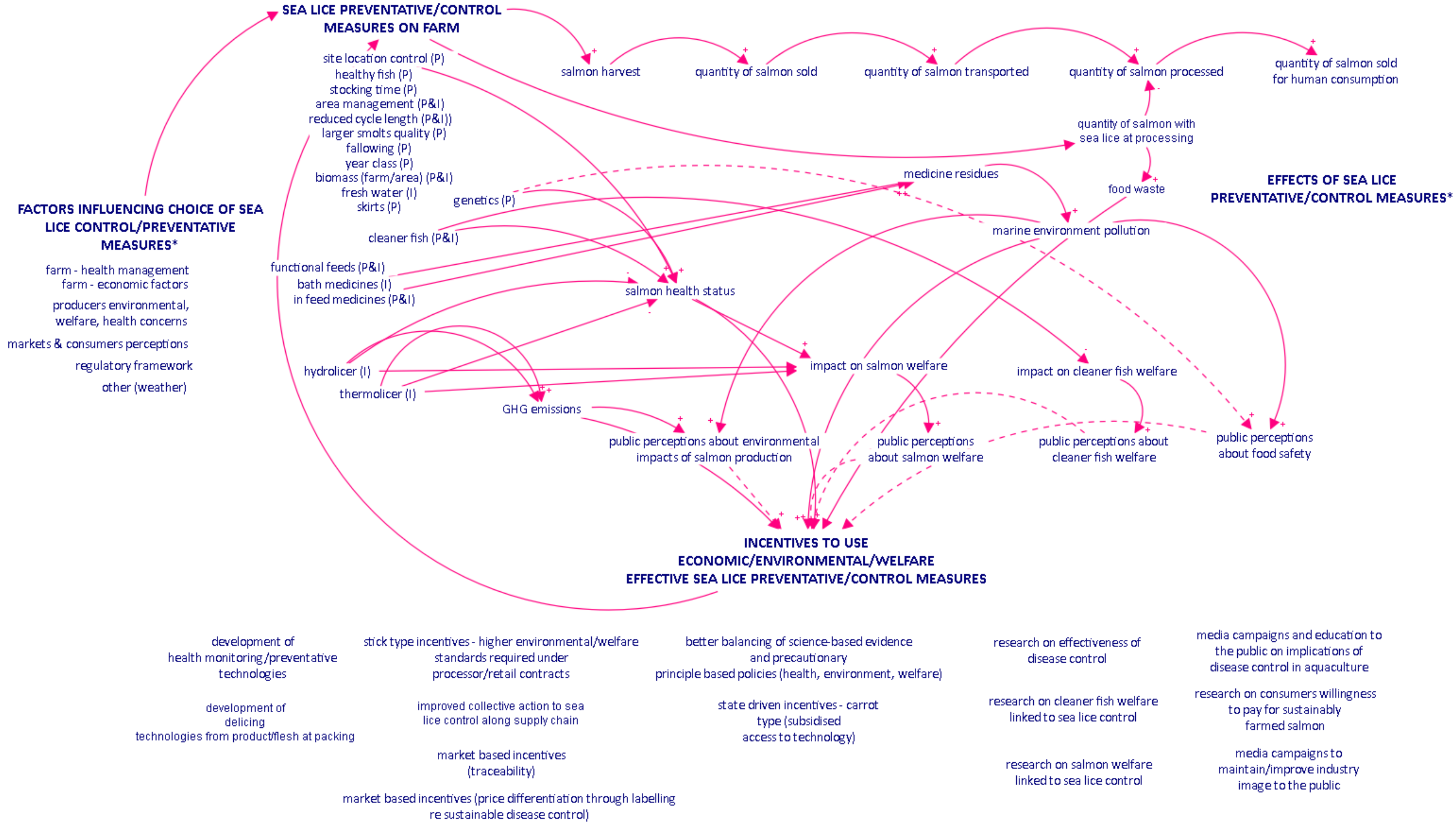

Figure 10. Causal loop diagram of cause-effect-incentives relationships linked to sea lice control on salmon farms

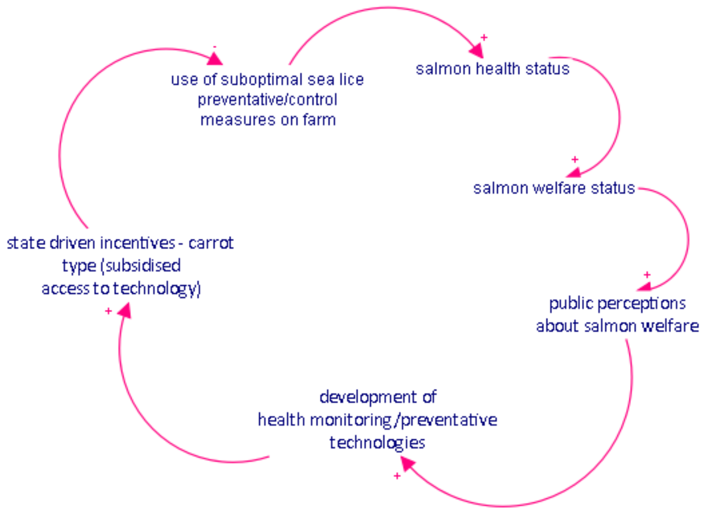

Figure 11. Balancing loop

The example depicts the effect of developing health monitoring technologies combined with subsidised access to the technology on sea lice control on farm and subsequently on salmon health and welfare, and public perceptions. The loop is balancing with the system converging on a target i.e. improved salmon health and welfare through reduced use of suboptimal measures of sea lice control.

Unlike this, the use of incentives such as development of delicing technologies at later stages e.g. packing/processing as opposed to sea lice control at source may create a reinforcing loop (and potentially leading to a vicious cycle) as it creates the possibility of reducing sea lice count and maintaining quantity and quality required by processors by means other than improved sea lice control at source.

The effects on health and welfare are mixed. The decision to delay a sea lice management measure when close to harvest will be a mix of the observed effect of the lice load on the animals at that time (i.e. salmon can take a minimal lice load without affecting appetite or behaviour etc.) and the potential for having additional stress and mortalities as a result of any sea lice management measures. The business decisions follow an even more complex set of factors e.g. when adding the commercial recognition that the fish, when close to harvest, are at maximum size and maximum cost to the business.

6. Discussion

This section discusses results of the quantitative cost-effectiveness and life cycle analyses in the context of qualitative findings from the participatory workshop on the wider impacts of sea lice control.

Results of the quantitative analysis indicate that sea lice management by in-feed and long term usage of skirts to prevent sea lice from entering the pens have the highest relative cost-effectiveness. Findings from the workshop analysis indicate that, according to stakeholders' perceptions, skirts' relatively lower impacts on environment and fish welfare are translated into positive impacts at the retail side of the supply chain and positive consumers' perceptions. The cleaner fish, fresh water, physical removal measures and the licensed veterinary medicines were among the second most cost-effective measures, and this is supported by their mixed and at times contradictory environmental, health and welfare impacts. The use of hydrogen peroxide (both well boat and tarpaulin) represented the least cost-effective measures among single use measures and, based on the opinions of stakeholders involved in the participatory workshop, these were also regarded as less positive methods by the public in view of their fish welfare and environmental aspects, and human health implications. The results confirm the behaviour of Scottish producers who have significantly reduced the use of this measure and currently employ it very infrequently.

Results indicate the ranking of single use sea lice management measures based on their relative cost-effectiveness show that for a measure to have the same efficacy effect (e.g. the same reduction in number of sea lice per fish), its costs may be higher than the costs of other measures. More specifically, when comparing incidental measures by the cost incurred to achieving the same level of efficacy, the use of hydrogen peroxide (well boat and tarpaulin) costs more than all other measures, while use of other licensed veterinary medicines, physical removal and fresh water measures cost less than these but more than the in-feed measure, which is the most cost-effective incidental measure. Among continuous measures, skirts were found to be the most cost-effective and ranked better than cleaner fish whose purchasing and maintenance costs were higher. As presented in the qualitative part of this study, i.e. findings from the participatory workshop, cost-effectiveness of prevention and mitigation of sea lice is not the only measure of importance as, for example, skirts are perceived to reduce oxygen flow and may have a detrimental effect on fish with compromised respiratory functions, and therefore their effectiveness concerning general fish health and welfare can be low.

To account for the wide range of expert opinion based efficacy rates for each sea lice management measure, we run sensitivity analysis at the extreme values to identify any corresponding variation in the ranking and magnitude of measures' cost-effectiveness. No major changes in ranking occurred under the maximum efficacy values, with the exception of physical removal (thermolicer) measure, which became less cost-effective. Under assumed minimum efficacy level, the ranking changed considerably. Skirts and in-feed measures remained as the most cost-effective measures under assumed minimum values for efficacy scores, and hydrogen peroxide remained the least cost-effective among the single use measures. Physical removal measures and use of other licensed veterinary medicines became significantly more cost-effective, while fresh water measures became significantly less cost-effective. In addition to changes in ranking, cost-effectiveness exhibits the expected changes in magnitude under both the minimum and maximum efficacy assumptions. Sensitivity analysis results indicated the variability in cost-effectiveness related to changes in efficacy levels, namely that the higher the efficacy of a measure, the higher the cost-effectiveness.

To account for uncertainty owing to combined data sources, additional sensitivity analyses were carried out to assess the impacts of varying values for the costs of interventions on the model outcomes, such as feed conversion ratio. Changes in the costs of interventions to similar extent for all management measures did not change the overall cost-effectiveness rankings of the management measures although the absolute values of cost-effectiveness were changed. However, changing costs of single use measures showed some changes in cost effectiveness rankings. For example, a significant increase in the price of cleaner fish led to decreased cost-effectiveness of the measure per unit of effectiveness to the extent of cleaner fish becoming slightly less cost-effective than the hydrolicer measure.

Results indicate that sea lice management measures using tarpaulins were more cost-effective than measures using well boats under the whole range of efficacy values used in this study. This relates to the higher costs associated with operating well boats compared to tarpaulins. We assumed that efficacy was unaffected by the method of performing the bath measures. A study exploring differences in efficacy tarpaulins and well boats for applying licenced veterinary medicines found that efficacy by tarpaulins were 2.2 times higher than efficacy by well boat, with results constrained by limitations such as sample size and bias from abundances and sea lice stages before applying a sea lice management measure (Whyte *et al.*, 2016). The scarcity of evidence available on the matter supports the need for investigating differences in efficacy between sea lice management measures in Scotland.

In addition to ranking single use measures based on their cost-effectiveness, we investigated a series of combination measures. These are based on realistic sequences of measures implemented throughout the production cycle to achieve acceptable efficacy by the end of the production cycle i.e. combination measures are chosen to bring down and maintain sea lice count within acceptable (regulation compliant) levels where they do not impact fish health, welfare and productivity. Cost-effectiveness of combination measures are not comparable to that of single measures as these combine different measures in different sequences, with many of them repeated and as such, aspects of cost additivity apply. When comparing the three combination measures, results indicate a small difference between the most cost-effective and least cost-effective combination ranging from £1.23 per fish per unit of effectiveness to £1.67 per fish per unit of effectiveness. Depending on farm circumstances, the difference may be even smaller, as well as the magnitude of total costs, for the cases where cost additivity can be adjusted to account for cost synergies across measures. Sensitivity analysis employed to test results for combination measures indicate high sensitivity to fish mortality.

For modelling purposes i.e. to create a quantitatively driven ranking, the study examined individual methods, however there is typically no individual method that achieves the desired level (no/very low numbers) of sea lice across a production cycle. Hence farm managers can and do use the wide range of methods available to them, which may include those lower ranked overall, as necessary to build the optimal sea lice management strategy.

Fish welfare was taken into account in both, the qualitative workshop analysis and the quantitative models, the latter through sea lice management measure related mortalities, which is, arguably, a proxy welfare indicator. Results of the workshop showed that perceived importance of both salmon and cleaner fish welfare is high, equally for industry and consumers. Where cleaner fish are used as a sea lice control method, the welfare and health of both salmon and cleaner fish are affected by any other sea lice management measures applied. The differences between these fish species, not only in size but also many other biological parameters, imply that measures optimised for salmon may affect cleaner fish differently. Results of the workshop indicate that cleaner fish are perceived as cost-effective and their welfare is key to positive consumer perceptions.

Participatory analysis identified potential incentives for further improving control of sea lice on farm, many of these already taken into account in the Scottish salmon sector. These include: better balancing of science-based evidence and precautionary principle based policies (health, environment, welfare); public sector driven positive incentives such as subsidised access to technology; research on consumers' willingness to pay for sustainably farmed salmon; media campaigns and education to the public on implications of disease control in aquaculture; market based incentives (price differentiation through labelling re sustainable disease control); market based incentives (traceability); development of health monitoring/preventative technologies; development of delicing technologies from product/flesh at packing; research on salmon welfare linked to sea lice control; research on cleaner fish welfare linked to sea lice control; media campaigns to maintain/improve industry image to the public; private driven stick type incentives such as higher environmental/welfare standards required under processor/retail contracts; research on efficacy of disease control; and improved collective action to sea lice control along the supply chain.

It should be noted that caution should be taken when comparing cost-effectiveness of single use measures based on the limitations previously mentioned regarding data available for this study, data uncertainty linked to combined sources, as well as the consequent simplified modelling assumptions. Data sources are a combination of primary and secondary data, and expert opinion, moreover the geographical distribution of data sources from e.g. Norway and Canada were translated to the Scottish situation as closely as possible, but might not fully represent the Scottish salmon industry situation, more specifically as regards regional differentiation. With additional as well as more robust primary data, further ways to improve the analysis include the methodological integration of economic, biological and epidemiological modelling. The findings from the participatory workshop indicate the complexity of sea lice control not only on farm but beyond farmgate, as supply chain, regulatory and environmental effects, and the need to address it as a holistic challenge.

Despite data limitations, ours is an analysis that adds useful insights to the current literature and creates a basis for further research. As demonstrated by the limited literature on the topic, this type of research will always be constrained by access to data for reasons detailed in this report. Thus, while much information has been collected on the variables included in the analyses and the robustness of results tested using sensitivity analysis, there may be other factors for which neither data nor robust proxies could be identified under this study, and this should be taken into consideration when reviewing these findings as a basis for future research.

7. References

Adams, T. P., Proud, R. and Black, K. D. (2015) Connected networks of sea lice populations: Dynamics and implications for control. Aquaculture Environment Interactions, 6(3), pp. 273–284. doi: 10.3354/aei00133.

Benedictus, A., Hogeveen, H., and Berends, B. R. (2009). The price of the precautionary principle: cost-effectiveness of BSE intervention strategies in the Netherlands. Prev. Vet. Med. 89: 212-222.

Bergevoet, R. H., van Schaik, G., Veling, J., Backus G. B. and Franken, P. (2009). Economic and epidemiological evaluation of Salmonella control in Dutch dairy herds. Prev. Vet. Med. 89: 1-7.

BEIS, 2019. Valuation of energy use and greenhouse gas. https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

Boissy J, Aubin J, Drissi A, van der Werf HMG , Bell GJ , Kaushik SJ. 2011. Environmental impacts of plant-based salmonid diets at feed and farm scales. Aquaculture 321: 61–70

Bui, S., Oppedal, F., Sievers, M., Dempster, T., (2019) 'Behaviour in the toolbox to outsmart parasites and improve fish welfare in aquaculture', pp. 168–186. doi: 10.1111/raq.12232.

Costello, M. J. (2006) 'Ecology of sea lice parasitic on farmed and wild fish', Trends in Parasitology, 22(10), pp. 475–483. doi: 10.1016/j.pt.2006.08.006.

Costello, M. J. (2009) 'The global economic cost of sea lice to the salmonid farming industry', Journal of Fish Diseases, 32(1), pp. 115–118. doi: 10.1111/j.1365-2761.2008.01011.x.

ecoinvent 2020. https://www.ecoinvent.org/

Gautam, R., Vanderstichel, R., Boerlage, A.S., Revie, C.W., Hammell, K.L (2017a) 'Effect of timing of count events on estimates of sea lice abundance and interpretation of effectiveness following bath treatments', Journal of Fish Diseases, 40(3), pp. 367–375. doi: 10.1111/jfd.12519.

Gautam, R., Vanderstichel, R., Boerlage, A.S., Revie, C.W., Hammell, K.L (2017b) 'Evaluating bath treatment effectiveness in the control of sea lice burdens on Atlantic salmon in New Brunswick, Canada', Journal of Fish Diseases, 40(7), pp. 895–905. doi: 10.1111/jfd.12569.

Iversen, A., Hermansen, Ø., Nystøyl, R. & Hess, E.J. (2017) Kostnadsutvikling i lakseoppdrett. Nofima rapport 24/2017. ISBN: 978-82-8296-522-4 (In Norwegian only) http://hdl.handle.net/11250/2481501

Jimenez, D. F., Revie, C. W., Hardy, S. P., Jansen, P. A., & Gettinby, G. (2013). Multivariate evaluation of the effectiveness of treatment efficacy of cypermethrin against sea lice (*Lepeophtheirus salmonis*) in Atlantic salmon (*Salmo salar*). BMC Vet. Res. 9(1), 1.

Lees, F., Baillie, M., Gettinby, G., & Revie, C. W. (2008). Factors associated with changing efficacy of emamectin benzoate against infestations of *Lepeophtheirus salmonis* on Scottish salmon farms. Journal of Fish Diseases, 31(12), 947–951. https://doi.org/10.1111/j.1365-2761.2008.00969.x.

Lees, F., Baillie, M., Gettinby, G., Revie, C. (2009). Strategic Sea Lice Control. Implementation and Impact within Scottish Tripartite Working Group Area Management Agreements. Final Report. University of Strathclyde.46 pp.

Macaskill, J. (2014) An investigation into the costs of different methods to control sea lice infestations in the Scottish Salmon (Salmo Salar) Farming Industry. MSc thesis, University of Glasgow.

Mangen, M.J.J., de Wit, G. A. and Havelaar, A. H. (2007). Economic analysis of Campylobacter control in the Dutch broiler meat chain. Agribusiness, 23: 173-192

Marine Institute 2007. Veterinary treatments and other substances used in finfish aquaculture in Ireland. http://www.wfdireland.ie/docs/19_DangerousSubstances/Veterinary%20treatments%20and%20other%20substances%20used%20in%20finfish%20aquaculture%20in%20Ireland%20Final.pdf

Marine Scotland 2018. Scottish Fish Farm Production Survey 2016

Mowi 2016. https://mowiscotland.co.uk/2016/04/11/new-wellboat-for-marine-harvest-is-a-first-for-scotland/

Mowi 2018. https://www.sepa.org.uk/media/404305/1002327_annex_1.pdf

Murray, A. G. (2015). Increased frequency and changed methods in the treatment of sea lice (*Lepeophtheirus salmonis*) in Scottish salmon farms 2005-2011. Pest Management Science. doi: 10.1002/ps.3996.

Newton RW and Little DC. 2018. Mapping the impacts of farmed Scottish salmon from a life cycle perspective. Int J Life Cycle Assess 23:1018–1029.

Overton, K., Dempster, T., Oppedal, F., Kristiansen, T.S., Gismervik, K., Stien, L.H., (2018) Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review. Reviews in Aquaculture, pp. 1–20. doi: 10.1111/raq.12299.

Philis G, Ziegler F, Gansel LC, Jansen MD, Gracey EO and Stene A. 2019. Comparing Life Cycle Assessment (LCA) of Salmonid Aquaculture Production Systems: Status and Perspectives. Sustainability 11, 2517; doi:10.3390/su11092517

Powell A, Treasurer JW, Pooley CL, Keay AJ, Lloyd R, Imsland and de Leaniz CG. 2017. Use of lumpfish for sea-lice control in salmon farming: challenges and opportunities. Reviews in Aquaculture xx: xx-xx. doi: 10.1111/raq.12194

Rich K.M., Rich, M., Dizyee, K. 2018. Participatory systems approaches for urban and peri-urban agriculture planning: The role of system dynamics and spatial group model building, Agricultural Systems 160, 110-123

SAIC 2019. Non-medicinal management of fish parasites. Scottish Aquaculture Innovation Centre workshop, Inverness February 2019

ScotGov (2019) http://aquaculture.scotland.gov.uk/. Last accessed 2020/03/05

SSPO (2018) https://www.fishfarmingexpert.com/article/scottish-2018-sea-lice-average-is-lowest-for-six-years/. Last accessed 2020/03/05.

Stien LH, Nilsson J, Hevrøy EM, Oppedal F, Kristiansen TS, Lien AM , Folkedal O. 2012. Skirt around a salmon sea cage to reduce infestation of salmon lice resulted in low oxygen levels. Aquacultural Engineering 51: 21– 25

Tarpaflex 2020. https://www.tarpaflex.co.uk/acatalog/Tarpaflex-Tarpaulins---Size-Guide.html

The Fish Site 2004. https://thefishsite.com/articles/slice-for-the-control-of-sealice

Treasurer, J. W., Grant, A. and Davis, P. J. (2000) Physical constraints of bath treatments of Atlantic salmon (Salmo salar) with a sea lice burden (Copepoda: Caligidae). Contributions to Zoology, 69(1–2), pp. 129–136.

UK Government 2018. GHG Conversion Factors for Company Reporting 2018. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2018

Valeeva, N. I., Huirne, R. B. M., Meuwissen, M. P. M. and Oude Lansing A. G. J. M. (2007). Modelling farm-level strategies for improving food safety in the dairy chain. Agri. Syst. 94: 528-540.

Vince F, Aoustin E, Bréant P and Marechal F. 2008. LCA tool for the environmental evaluation of potable water production. Desalination 220: 37–56.

Watanabe K and Tahara K. 2016. Life Cycle Inventory Analysis for a Small-Scale Trawl Fishery in Sendai Bay, Japan. Sustainability 8, 399; doi:10.3390/su8040399.

Whyte, S. K., Jimenez, D., Revie, C. W., & Hammell, K. L. (2016). Multivariate evaluation of the effectiveness of delousing treatment efficacy of azamethiphos (Salmosan®) against the salmon louse (*Lepeophtheirus salmonis*) in Atlantic salmon (*Salmo salar*) using wellboat, skirt and tarpaulin treatment modalities. Aquaculture, *450*, 301–307. doi: 10.1016/j.aquaculture.2015.08.009.

Wright, D. W., Oppedal, F. and Dempster, T. (2016) Early-stage sea lice recruits on Atlantic salmon are freshwater sensitive. Journal of fish diseases, 39(10), pp. 1179–1186. doi: 10.1111/jfd.12452.

8. **Appendix**

Ethical aspects of data collection/storage/analysis/reporting

In terms of the general ethical principles which will directly underpin the research being proposed, the research is GDPR compliant and followed the ISO 9001:2015 quality management system for auditing experimental and analytical practices, laboratory books and standard operating procedures (SOPs) as part of SAC's (and sub-contractors) research management system.

For primary data collection (i.e. interviews), a Participant Information Sheet was provided to participants that included: (a) enough information, in lay language, for the participant to understand what the project is about and what is required of them so that they can give informed consent; (b) details of who they can contact for more information and who is the organisation overseeing the research; and (c) assurances that their data will be held securely and treated correctly.

In the analysis of interviews data, we have ensured that all identifiable information was removed, and that interviewees were assigned a category rather than an individual or institutional label.

Where privacy could not be preserved within the research group, i.e. the participatory workshop, the individual opinions and responses of participants were treated in confidence.

Input and output data management comply with the General Data Protection Regulation (GDPR). Standard operating procedures for handling, archiving and backing up data were followed. The team have adhered to relevant Standard Operating Procedures (SOPs) regarding: Data generation and secure data storage to ensure data quality and security; Data confidentiality and sharing; and Publication of data and associated Intellectual Property assignations.

This research was conducted to avoid or minimise social harm to groups and individuals. Research was designed responsibly with the appropriate methodologies. We ensured that research participation was voluntary on the basis of informed consent. We also ensured that the views of all relevant stakeholders were taken into account.

We will ensure that research results presented in the final report, especially the executive summary and discussion of results, are accessible to the relevant stakeholders.

The project activities have been congruent with SRUC's sustainability/corporate social responsibility (CSR) objectives and will contribute to the Scottish Government Sustainability targets.

Survey of Scottish salmon producers on sea lice treatments for farmed salmon production
Questionnaire to farm health manager

Scotland's Rural College (SRUC) is conducting research supported by Scottish Government funding to understand the relative cost-effectiveness of sea lice treatments for farmed salmon production. The purpose of this survey is to help inform the Scottish Government how best it can target and improve investment in research and development of the available and emerging treatment options.

Participation in the survey is voluntary and the face-to-face interview should take about 30' to complete. We emphasise that only SRUC team has access to your data and this is not shared with the funder (Scottish Government) or anyone else. We confirm that all information given will be totally anonymous in any subsequent reports or publications, that you and your business will never be individually identifiable, and that the data will be stored and handled in accordance to the General Data Protection Regulation 2016/679, which also means that individual data will be deleted as soon as the analysis is completed. You are free to opt out at any time and are not obliged to answer any question you do not want to.

Please confirm your consent to continue the interview yes no

Please state your name and position in the company	

A. Uptake of sea lice control measures

Which of the following (combinations of) sea lice control measures do you apply in your business?	No	I apply but plan to stop	Don't apply but intend to start	In process	Yes (fish < 1 kg)	Yes (fish >= 1 kg)
1x average freshwater treatment	❑	❑	❑	❑	❑	❑
1x average H2O2 treatment	❑	❑	❑	❑	❑	❑
1x average Alphamax treatment	❑	❑	❑	❑	❑	❑
1x average Salmosan treatment	❑	❑	❑	❑	❑	❑
1x period of slice treatment	❑	❑	❑	❑	❑	❑
1x hydrolicer	❑	❑	❑	❑	❑	❑
1x thermolicer	❑	❑	❑	❑	❑	❑
1x optilicer	❑	❑	❑	❑	❑	❑
Synchronising treatments with all sites in area	❑	❑	❑	❑	❑	❑
Synchronised fallowing with all sites in area	❑	❑	❑	❑	❑	❑
1x full cycle with cleaner fish (your normal use)	❑	❑	❑	❑	❑	❑

1x cycle with low stocking densities (<20 kg/m3)	❑	❑	❑	❑	❑	❑
1x cycle using smolts of 250 g	❑	❑	❑	❑	❑	❑
1x cycle with normal use of skirts	❑	❑	❑	❑	❑	❑
Combo1 (specify which)	❑	❑	❑	❑	❑	❑
Combo2 (specify which)	❑	❑	❑	❑	❑	❑
Combo3 (specify which)	❑	❑	❑	❑	❑	❑
Combo4 (specify which)	❑	❑	❑	❑	❑	❑

B. Efficacy of sea lice control measures (for fish < 1 kg)

On a scale from 1 to 10 where 1 is least effective and 10 is most effective, how effective you think the following sea lice control measures are **for fish < 1 kg**:	Least effective 1	2	3	4	5	6	7	8	9	Most effective 10
1x average freshwater treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x average H2O2 treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x average Alphamax treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x average Salmosan treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x period of slice treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x hydrolicer	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x thermolicer	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x optilicer	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Synchronising treatments with all sites in area	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Synchronised fallowing with all sites in area	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x full cycle with cleaner fish (your normal use)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x cycle with low stocking densities (<20 kg/m3)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x cycle using smolts of 250 g	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x cycle with to you normal use of skirts	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Combo1 (specify which)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Combo2 (specify which)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Combo3 (specify which)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Combo4 (specify which)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑

C. Efficacy of sea lice control measures (for fish >= 1 kg)

On a scale from 1 to 10 where 1 is least effective and 10 is most effective, how effective you think the following sea lice control measures are **for fish >= 1 kg**:	Least effective 1	2	3	4	5	6	7	8	9	Most effective 10
1x average freshwater treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x average H2O2 treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x average Alphamax treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x average Salmosan treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x period of slice treatment	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x hydrolicer	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x thermolicer	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x optilicer	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Synchronising treatments with all sites in area	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Synchronised fallowing with all sites in area	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x full cycle with cleaner fish (your normal use)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x cycle with low stocking densities (<20 kg/m3)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x cycle using smolts of 250 g	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
1x cycle with to you normal use of skirts	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Combo1 (specify which)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Combo2 (specify which)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Combo3 (specify which)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑
Combo4 (specify which)	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑

D. Benefits of using the sea lice treatments for ONE TYPICAL treatment														
When using any of the treatments (listed in columns), can you make an estimate of the treatment specific benefits for ONE TYPICAL treatment of sea lice	Measurement unit	1x average freshwater	1x average H2O2 treatment	1xAlphamax treatment	1x Salmosan treatment	1period of slice treatment	1x hydrolicer	1x thermolicer	1x optilicer	Cleaner fish	Combo1 (specify which)	Combo2 (specify which)	Combo3 (specify which)	Combo4 (specify which)
	Treatment efficacy (sea lice)													
	For fish < 1 kg													
What is the expected average post treatment average number of adult female/fish if pre treatment numbers were **low (0.3 adult female/fish)**														
What is the expected average post treatment average number of adult female/fish if pre treatment numbers were **medium (2.5 adult female/fish)**														
What is the expected average post treatment average number of adult female/fish if pre treatment numbers were **high (10 adult female/fish)**														
	For fish >= 1 kg													
What is the expected average post treatment reduction in average sea lice count (average number of adult female/fishlice) if treating atpre treatment numbers were a **low burden (0.3 adult female/fish)**														

What is the expected average post treatment average number of adult female/fish if pre treatment numbers were **medium** What is the expected average post treatment reduction in average sea lice count (number of lice) if treating at a **medium burden (2.5 adult female/fish)**														
What is the expected average post treatment average number of adult female/fish if pre treatment numbers were **high** What is the expected average post treatment reduction in average sea lice count (number of lice) if treating at a **high burden (15 adult female/fish)**														
	Other benefits of treatment													
Reduction in time-at-sea (# weeks)	#													
Also reduces AGD (y/n)	£													
Also reduces need for treatments of diseases other than AGD (y/n)	£													
Good for public image (y/n)	£													

E. Barriers to uptake of sea lice control measures

	Strongly Disagree	Disagree	Unsure	Agree	Strongly Agree	N.A.
Access to wellboats hinder the uptake of alternative sea lice control measures on your business	❑	❑	❑	❑	❑	❑
There is insufficient or unclear information or advice available to help with use of cleaner fish as sea lice treatment	❑	❑	❑	❑	❑	❑
There is little institutional and regulatory support for sea lice control	❑	❑	❑	❑	❑	❑
Using cleaner fish to control sea lice is not compatible with the specificities of my business	❑	❑	❑	❑	❑	❑
Using mechanical treatments to control sea lice is not compatible with the specificities of my business	❑	❑	❑	❑	❑	❑
Using mechanical treatments to control sea lice is expensive	❑	❑	❑	❑	❑	❑
Using cleaner fish to control sea lice is time consuming	❑	❑	❑	❑	❑	❑
I have no sufficient access to wellboats to be fully in control of sea lice	❑	❑	❑	❑	❑	❑
I have no sufficient access to chemical treatments (in-feed and/or bath) to be fully in control of sea lice	❑	❑	❑	❑	❑	❑
I have no sufficient farm labour to be fully in control of sea lice	❑	❑	❑	❑	❑	❑

Other (specify)	❑	❑	❑	❑	❑	❑
Other (specify)	❑	❑	❑	❑	❑	❑

Is there anything else you would like to add?

Thank you very much for your help with this research!

Survey of Scottish salmon producers on sea lice treatments for farmed salmon production
Questionnaire to farm site manager (or health manager if farm site manager unable to answer)

Scotland's Rural College (SRUC) is conducting research supported by Scottish Government funding to understand the relative cost-effectiveness of sea lice treatments for farmed salmon production. The purpose of this survey is to help inform the Scottish Government how best it can target and improve investment in research and development of the available and emerging treatment options.

Participation in the survey is voluntary and the face-to-face interview should take about 30' to complete. We emphasise that only SRUC team has access to your data and this is not shared with the funder (Scottish Government) or anyone else. We confirm that all information given will be totally anonymous in any subsequent reports or publications, that you and your business will never be individually identifiable, and that the data will be stored and handled in accordance to the General Data Protection Regulation 2016/679, which also means that individual data will be deleted as soon as the analysis is completed. You are free to opt out at any time and are not obliged to answer any question you do not want to.

Please confirm your consent to continue the interview yes no

Please state your name and position in the company	

F. Treatment questions. Please provide answers based on THE LAST CYCLE (to specify month/year of stocking).		
General		
What was the total biomass harvested (including discards)?	tonnes liveweight per cycle or year (specify):	
What was the total biomass treated for sea lice?	number or % of biomass per cycle or year (specify):	
What was the average weight of the fish harvested?	kg liveweight:	
What was the total amount of feed used for salmon and cleaner fish?	tonnes per cycle or year (specify):	
What was the total amount of fuel consumed?	tonnes per cycle or year (specify):	
What is the lifespan of the boats/wellboats used?		
Have you used freshwater treatments for lice (bath)	yes, number of treatments:	no
How many boats/wellboats did you use and for how long? Or tarps?	total number of days (including boat travelling to/from sites):	
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	
Hydrogen peroxide treatment for lice (bath)	yes, number of treatments:	no
How many wellboats did you use and for how long? Or tarps?	total number of days (including boat travelling to/from sites):	

What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	
Alphamax treatments for lice (bath)	yes, number of treatments:	no
How many boats/wellboats did you use and for how long? Or tarps?	total number of days (including boat travelling to/from sites):	
What was the average duration of an Alphamax treatment?	days:	
What would be an average amount of Alphamax?	kg per fish:	
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	
Salmosan treatment for lice (bath)	yes, number of treatments:	no
How many boats/wellboats did you use and for how long? Or tarps?	total number of days (including boat travelling to/from sites):	
What was the average duration of a Salmosan treatment?	days:	
What would be an average amount of Salmosan?	kg per fish:	
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	
Slice treatment (in-feed)	yes, number of treatments:	no
What was the average duration of a slice treatment?	days:	
What would be an average amount of slice fed?	kg per fish:	
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	
Hydrolicer/Thermolicer/Optilicer	yes, number of treatments (which):	no
How many boats/wellboats did you use and for how long?	total number of days (including boat travelling to/from sites):	
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	
Synchronised fallowing	yes:	no
How many weeks earlier than usual did you harvest?		
Was there a loss in product price due to synchronised fallowing?	%	
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	
Synchronised treating	yes, which treatments:	no
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	

Skirts	yes, number of pens:	no
How many weeks did you use the skirts for?		
How long did it take to install, maintain and take off the skirts?	number of man hours:	
Duration of use of boats to install, maintain and take off the skirts	total number of days (including boat travelling to/from sites):	
What is the lifespan of the skirts?		
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	
Cleaner fish	yes, number of pens:	no
How long did you use cleaner fish for?	number of weeks on average per pen:	
What was the total density of cleaner fish stocked?	% of biomass (or kg/m3):	
How long does it take to care for cleaner fish (bring in, maintain, remove)?	number of hours/day:	
What was the amount of additional feed you used for cleaner fish?	tonnes:	
What was the treatment specific mortality of cleaner fish (during/after treatment)	number or % of biomass:	
What was the treatment-specific mortality of salmon (during/after treatment)	number or % of biomass:	

Was the sequence of treatments used during the last cycle repeated from the previous two (three) cycles or different? Please indicate the 'typical' sequence of treatments you use and point out main departures from it. Is there anything else you would like to add?

Thank you very much for your help with this research!

Table 13. Unabridged list of impacts of sea lice control measures (based on anonymised individual responses from workshop participants)

	sea lice preventative/ control measures	prevention P & intervention I	farm economic impacts	environmental impacts	impacts on salmon welfare	impacts on salmon health (sea lice)	impacts on salmon health (other e.g. immunity)	impacts on cleaner fish welfare	impacts on cleaner fish health	impacts on supply chain - transport	impacts on supply chain - processing	impacts on supply chain - retail	impacts on consumers /society perceptions
1	in-feed medicines	P&I		-	+	+					-		-
1	in-feed medicines	P&I		-	+						-		-
1	in-feed medicines	P&I		-								-	
1	in-feed medicines	P&I		-								-	
1	in-feed medicines	P&I		-	+						-	-	-
1	in-feed medicines	P&I		-	+								-
1	in-feed medicines	P&I		-	+								
2	bath medicines	I		-	+								
2	bath medicines	I			-								
2	bath medicines	I		-	+								
2	bath medicines	I		-	-							-	
2	bath medicines	I	-	-	-	+						-	-
2	bath medicines	I	-	-	+								

2	bath medicines	I		-	-						-		-
2	bath medicines	I		+	+						-		-
2	bath medicines	I		-	-								
2	bath medicines	I	-	-	-					-	-	-	-
2	bath medicines	I	+										
2	bath medicines	I		-	+	+		-			-		-
3	cleaner fish	P&I		-	+			-	-	-			
3	cleaner fish	P&I		-	+							+	
3	cleaner fish	P&I		+	+			-			+		
3	cleaner fish	P&I	-	-	+					-			-
3	cleaner fish	P&I								-		-	-
3	cleaner fish	P&I	-	+	+			-				+	+
3	cleaner fish	P&I	+	-									
3	cleaner fish	P&I	+	-	+	+		-				+	
3	cleaner fish	P&I	-										
4	skirts	P		+	+							+	
4	skirts	P			+								
4	skirts	P			-								
5	area management	P&I		+	+								
5	area management	P&I		+	+							+	
5	area management	P&I		+	+	+							
5	area management	P&I		+	+								
6	larger smolts quality	P		+	+								
6	larger smolts quality	P		+	+							+	

6	larger smolts quality	P		+	+								
6	larger smolts quality	P	-	+	+								
6	larger smolts quality	P		+	+	+							+
6	larger smolts quality	P		+	+					-		+	
7	hydrolicer	I			-							-	
7	hydrolicer	I	-	+	-								
7	hydrolicer	I		+	+						-	-	
7	hydrolicer	I		-	-	+	-	-					
7	hydrolicer	I		+	-	+	-	-					-
7	hydrolicer	I											+
7	hydrolicer	I	-	+	-								
8	biomass (farm/area)	P&I		+	+							+	
8	biomass (farm/area)	P&I		-	+					-			
8	biomass (farm/area)	P&I		+						+	+	+	
8	biomass (farm/area)	P&I		+	+	+							
9	thermolicer	I		-	-							-	
9	thermolicer	I		-	-							-	
9	thermolicer	I			-								
9	thermolicer	I	-	+	-								
9	thermolicer	I		+	-	+	-	-					-
9	thermolicer	I	-	+	-								+
9	thermolicer	I	-	-	-	+	-						

10	freshwater	I		+	+								
10	freshwater	I		-	-							+	
10	freshwater	I		-	+						+	+	+
10	freshwater	I	-	+	-								
10	freshwater	I		+	+	+	+						+
10	freshwater	I	-	+	-	+							
11	genetics	P										-	
11	genetics	P		+	+							-	
11	genetics	P	+	+	+							-	-
11	genetics	P		+	+		-						
11	genetics	P			+	+	+						+
11	genetics	P	+	+	+						+		-
12	functional feeds	P&I		-	+							+	
12	functional feeds	P&I	+		+	+	+				+		
12	functional feeds	P&I									-		
13	healthy fish	P	+	+	+								
13	healthy fish	P		+	+							+	
13	healthy fish	P									+		+
13	healthy fish	P	+	+	+								
14	reduced cycle length	P&I			+								-
14	reduced cycle length	P&I		+	-							+	
14	reduced cycle length	P&I		+	+								
14	reduced cycle length	P&I	+	+									

14	reduced cycle length	P&I		+	+	+	+						+
14	reduced cycle length	P&I	+	+									
14	reduced cycle length	P&I	-	-									
15	stocking time	P		+	+								
15	stocking time	P									+		+
16	site location control	P		+	+							+	
16	site location control	P		+	+	+	+						+
16	site location control	P	-	+	+								
17	fallowing	P											
18	year class	P		+	+						+		+

strong negative effects
moderate negative effects
light negative effects
light positive effects
moderate positive effects
strong positive effects

Schedule of the participatory workshop on sea lice control in salmon primary production

Time	Topic
11:00 – 11:15	Welcome refreshments & introduction of participants
11:15 – 11:30	Aims & expectations
11:30 – 11:45	Salmon supply chain process flow validation
11:45 – 12:15	Session 1 Dynamic modelling: causes & implications (25mins + 5 mins break)
12:15 – 12:45	Session 2 Dynamic modelling: causes & implications (30mins)
12:45 – 13:30	Lunch
13:30 – 14:00	Session 3 Dynamic modelling: connecting causes (25mins + 5 mins break)
14:00 – 14:30	Session 4 Dynamic modelling: interventions & effects (25 mins + 5 mins break)
14:30 – 15:00	Discussion of cost-effectiveness modelling assumptions & data
15:00	Workshop close, refreshments

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Any enquiries regarding this publication should be sent to us at

The Scottish Government
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