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Published in:
Aquaculture

DOI:
10.1016/j.aquaculture.2023.740274

First published: 15/02/2024

Document Version
Publisher's PDF, also known as Version of record

Aquaculture 580 (2024) 740274

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Sea lice management measures for farmed Atlantic salmon (*Salmo salar*) in Scotland: Costs and effectiveness

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ARTICLE INFO

Keywords:
Aquaculture
Sea lice management measures
Salmonids
Costs

ABSTRACT

Cultured and wild Atlantic salmon around the world are affected by sea lice. Salmon culturing countries have policies in place to minimize sea lice abundance on cultured salmon in open net pens in the marine environment. To adhere to these policies, salmon producers deploy a range of management measures against sea lice throughout the production cycle. The cost effectiveness of these sea lice management measures is not well quantified. This study provides estimates for cost effectiveness in Scotland of (1) individual sea lice management measures and (2) integrated management strategies that span an entire production cycle. Estimates were based on the cost-effectiveness ratio, in which costs consist of those associated with equipment, implementation, environment and side effects (mortality). Effectiveness was based on interviews and expert opinions. For single measures, skirts and the use of in-feed medicines had the best cost-effectiveness. Cleaner fish, fresh or brackish water baths, the physical removal measures (thermolicer and hydrolicer) and medicinal baths were among the next most cost-effective measures, followed by hydrogen peroxide baths. Tarpaulins were more cost-effective than well boats due to lower costs under the assumption of equal effectiveness. Direct comparison of cost effectiveness among measures may not always be constructive as they are deployed at different times in the production cycle and their functionality is different. A holistic approach to sea lice management, a common practice in industry as shown by the integrated management strategies, may reduce risk of developing resistance. For the single measures, carbon costs were insignificant compared to other costs. If measures would have a lasting effect on production through to harvest, such as ongoing increased mortality as a result of a management measure, carbon costs may become significant. Better quantification of effectiveness is important because the scarcity of data led to uncertainty that had a large impact on cost-effectiveness estimates. Generally, this study demonstrated a lack of reliable publicly available data and lack of standardization of data, which constrains research. Highlighted gaps in knowledge can serve as a guide to improve further understanding.

1. Introduction

The sea louse *Lepeophtheirus salmonis* is a persistent key ectoparasite copepod of Atlantic salmon worldwide. The louse has received much focus from industry, academics, and the government over the last three decades leading to better understanding and management but has also been a source of negative perception of the salmon industry by the public (Bron and Bricknell, 2022). Sea louse have been estimated to cost

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https://doi.org/10.1016/j.aquaculture.2023.740274
Received 11 February 2023; Received in revised form 21 June 2023; Accepted 23 October 2023
Available online 30 October 2023
0044-8486/

around 9% of farm revenues, the most relevant costs being treatment costs, reduced fish growth, and reduced food conversion efficacy (Abolofia et al., 2017; Costello, 2009). Part of the life cycle of lice is free-living. They disperse as planktonic larvae on currents and have been estimated to travel in some cases over 80 km (Cantrell et al., 2021; Kragesteen et al., 2018). When attached, this parasite damages their hosts' skin, which can result in secondary infections, stress, and immune suppression. The severity of the effect of lice on salmon can range from superficial to mortality and depends e.g. on salmon size, smaller fish are more affected, and lice abundance (Ives et al., 2023; Taranger et al., 2015; Tully and Nolan, 2002). Lice abundance thresholds that are developed for lice management are T1 at 0.08 lice per gram, which estimates the lice level at which lice loads causes systemic sub-lethal effects on smolts likely to impact performance, and T2, 0.24 lice per gram, which identifies the lice load causing direct mortality Ives et al., 2023). In addition, higher densities of salmon in farms correlates to more sea lice (Jansen et al., 2012; Kristoffersen et al., 2018). Biological processes such as louse development time and louse survival depend on temperature and salinity (Cantrell et al., 2018).

All salmon producing countries have policies in place to ensure that *L. salmonis* abundances on salmonids in marine open net pens remain low, especially during the migration season of wild salmon. For example, in Scotland, government regulations include a mandatory weekly reporting of lice and require increased monitoring when average adult female lice count per fish reach 2 or above and have an intervention limit at 6 average adult female L. *salmonis* per fish, both during a weekly count. These are mandated to be reported by industry to the Fish Health Inspectorate according to the Aquaculture and Fisheries (Scotland) Act 2007 and the 2020 Order (Scottish Government, 2020, 2007). The Code of Good Practice management group developed a Code of Good Practice for Scottish Finfish Aquaculture (CoGP), which states that sea lice management measures should be guided by the build-up of preadults to prevent the development of gravid females (Salmon Scotland, 2022). The CoGP includes a suggested sea lice management measure criteria of 0.5 adult female *L. salmonis* per fish between 1st February to 30th June, and 1.0 adult female *L. salmonis* per fish during the rest of the year.

To adhere to sea lice management policy thresholds, most salmon producers need to treat their stock several times throughout a production cycle (Murray and Hall, 2014). The salmon sector spends a significant amount of money on sea lice control measures, costing around £700 million globally and £65 million in Scotland per year (SAIC, 2019). The type of management measures used to control sea lice has evolved much over the last two decades. In 2002, most lice management measures were medicinal. For example, in Scotland the approved sea lice management measures were the bath measures Cypermethrin (Exis), Azamethiphos (Salmosan) and Hydrogen peroxide (Salartect, Paramove), and in-feed management measures Emamectin benzoate (SLICE) and Teflubenzuron (Calicide) (Grant, 2002). Most of these medicinal delousing measures were still approved 15 years later, though Cypermethrin (Exis) and Salarect are no longer approved, but Deltamethrin (AMX) and Asperix have now been added. The approved in-feed measures are the same as they were 15 years ago (Kenyon and Davies, 2018), though Calicide has not been available since 2013 (personal communication).

Awareness about increased resistance of lice against medicinal delousing measures (Jones et al., 2012; Lees et al., 2008a, 2008b) has led to the need to diversify, which led to an increase in the use of non-medicinal measures (Jensen et al., 2020; Salmon Interactions Working Group, 2020; Torrissen et al., 2013). Using Scotland as example, common sea lice management measures in use today include, in addition to the longer-established medicinal delousing measures, biological control by co-habituating salmon with the cleaner-fish species lumpsuckers (*Cyclophterus lumpus L.*) and wrasse (*Labridae*) which will eat lice off salmon, thermal and mechanical delousing methods which will respectively remove lice using warm water for a short duration, or use flushing, brushing or turbulence to remove lice (Noble et al., 2018), skirts which prevent lice from entering the salmon pens, and fresh or brackish water baths (SAIC, 2019).

Evaluating sea lice management is complex. Different pest management measures are deployed, of which each can vary their deployment protocol. They can be deployed alone or simultaneously to others, in different sequences. Synchronizing of management measures within regions is difficult to quantify (Arriagada et al., 2017), as is mixing of preventive and reactive measures (Kenyon and Davies, 2018; Marine Scotland, 2012). In addition, unpredictable time varying factors affect management decisions, such as availability of infrastructure and services to deploy specific management measures (Barrett et al., 2022), general fish appearance, and expected future problems (Westcott et al., 2004).

Costs and effectiveness are quantifiable characteristics of management measures that allow comparisons between measures when combined in a cost-effectiveness estimate. However, they are not always straightforward to quantify and combine in a single estimate. For instance, effectiveness can be affected by e.g. sea water temperature, salmon weight and welfare status prior to sea lice management measures (e.g. the thermolicer is recommended only for fish that weigh less than 4 kg (Gismervik et al., 2017 (in Norwegian) in Overton et al., 2019), sea lice numbers (Gautam et al., 2017a), most abundant sea lice stages prior to sea lice management measures (e.g. delousing using freshwater is less efficient at older louse stages, Wright et al., 2016), oxygen saturation and medicinal dispersion during sea lice management measures (Treasurer et al., 2000), and many more. Second, a methodology to evaluate management measures can be complicated. Lice counts, the method used to quantify management measure effects, are often not comparable between sea lice management measures which can lead to inaccurate estimations (Gautam et al., 2017b; Jimenez et al., 2013). Some sea lice management measures are preventive and thus need an estimate on how many lice there would have been in their absence, whereas others are reactive. The duration of effect varies; some management measures are deployed on-demand and affect fish for a short duration (e.g. bath-based medicinal delousing measures) whereas others are implemented over a longer period of time (e.g. cleaner fish). Some management measures are therefore often combined together (e.g. cleaner fish and medicinal delousing measures) making it difficult to quantify their individual effects. Third, frequent use of one type of sea lice management measure may selectively remove susceptibility from the population leading to resistance against the measure (Bui et al., 2019; Groner et al., 2019; Lees, 2009), implying that a mix of different management measures is preferrable. These, as well as practical constraints such as the unavailability of a management measure type when needed, complicate decision-making for the management of sea lice.

These complicating factors associated with costs and effectiveness, in combination with constantly evolving protocols, differences between salmon producing companies' internal policies on sea lice management measures and sensitivity towards sharing data (Brugere et al., 2017) have led to a lack of quantitative information on sea lice management measures in Scotland. Internationally published studies on economics and effectiveness of sea lice control measures are at a farm level, using a bioeconomic model to simulate the economy of the production (Abolofia et al., 2017; Bjørndal and Tusvik, 2019; Liu et al., 2011; Liu and Bjelland, 2014) or used real farm data on isolated sea lice management measures (Powell et al., 2018). Such methodology provides valuable insights but requires many resources. Therefore, such elaborative studies are ideally targeted, for example, towards a selection of management measures, or towards input that are expected to have a large impact on output.

A simplified overview of cost-effectiveness of a range of management measures, with a sensitivity analysis that shows which input affect the output most, can therefore provide a framework that can be used as a basis for understanding differences and to inform the direction of future research and development. The objective of this study was to provide quantitative estimates for cost effectiveness of sea lice management measures for farmed salmon in Scotland. This main objective was split into two sub-objectives: to rank cost-effectiveness of (1) individual sea lice management measures and (2) integrated management strategies that span an entire production cycle.

2. Material and methods

2.1. Cost effectiveness

Cost-effectiveness analysis (CEA) may be used to assess measures to prevent or mitigate the effects of a disease where the impacts of the measure cannot be measured routinely in monetary terms. This is a common method in the field of animal and human health economics that is often used to help determine the optimal resource allocation between interventions (Hall et al., 2014; Benedictus et al., 2009; Mangen, 2007; Valeeva et al., 2007). CEA uses the Cost-Effectiveness ratio (CE ratio), explained by Eq. (1), to determine the effectiveness of an intervention (Rushton et al., 2018).

$$CE\ ratio = \frac{\text{cost of the intervention}}{\text{effectiveness of the intervention}} \tag{1}$$

We used Cost-Effectiveness Analysis (CEA) to investigate cost-effectiveness of management measures as eleven single use management measures and three realistic examples of integrated management strategies, applied in sequence between stocking and harvesting of a cohort of salmon. Costs were divided into costs of equipment, costs of implementation, environmental costs and costs of side effects. The CE ratio specified for this study is shown in Eq. (2).

$$CE\ ratio_{T_n} = \frac{C_{eqp}T_n + C_{imp}T_n + C_{env}T_n + C_{se}T_n}{EFT_n} \tag{2}$$

Where T_n is the n^{th} sea lice management measure.

EF in Eq. (2) stands for effectiveness. This was defined for the individual measures as the reduction of sea lice on an adult salmon, e.g. 0.5 would represent a 50% decrease in the number of sea lice as a result of the measure. For the integrated measures it was set at 1, under the assumption that the sequence of management measures was successful (100% effective) at keeping sea lice levels within regulatory thresholds for the full production cycle.

C_{eqp} in Eq. (2) stand for cost of equipment. This included the cost of licensed 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 included cost of H_2O_2 and cost of oxygenation.

C_{imp} in Eq. (2) stands for cost of implementation. This included the cost of the application of the sea lice management measures, such as the cost of boats, labour and other provisions that are required to implement the measures. For example, to implement H_2O_2, this cost included well boat and labour.

C_{env} in Eq. (2) stands for environmental cost. This included the carbon cost for applying each of the sea lice management measures. This was based on the estimated carbon emissions from all the activities associated to provide and implement each measure. The emissions were converted into carbon cost by using a standard carbon cost rate £12.8/tCO2eqv. See a description of the estimation of the emissions in Appendix 1.

C_{se} in Eq. (2) stands for cost of side effects. This cost included loss in revenue due to increased mortality of salmon under a sea lice management measure according to Eq. (3).

$$C_{se}T_n = mT_n{*}ps - fsT_n{*}pf \tag{3}$$

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

2.2. Sources of information for costs and effectiveness

Costs, socio-economic and environmental information on sea lice control measures employed in the salmon sector were gathered based on a review of secondary sources of information from Scotland. Where no Scottish data were available, data from other countries (such as Norway and Canada) often reported in literature reviews were used. These sources were inspected and selected using expert opinion (health practitioners in the Scottish salmon sector through telephone interviews and email communications, with members of the research group conducting the study) to ensure the closest possible relevance to the Scottish salmon sector. Additionally, a sensitivity analysis was performed (see end of section) to evaluate the influence for the values of these data on the modelled results. Secondary data collection was combined with primary data collection using a participatory workshop and in-depth interviews with Scottish salmon producers and processors.

For measures of effectiveness, no detailed quantitative evidence could be found. Therefore, the reduction in sea lice count was based on in-depth interviews with Scottish salmon producers and processors, expert opinion from aquaculture experts and health practitioners in the Scottish salmon sector, as well as literature reviews.

A participatory workshop with stakeholders representing different stages in the supply chain was used to obtain expert opinions. This workshop took place on the 20th of January 2020, at the SRUC campus in Inverness, Scotland. Ten workshop participants representing 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) were involved. The workshop organising team was comprised of social (economics) and non-social (aquaculture veterinary) science expertise. Not all salmon producing companies in Scotland were part of the workshop. Three out of ten attendees representing processing and retail, policy (disease modelling) and academia (salmon health) provided further information (email communication) and also agreed to provide responses to the interview questionnaire. The questionnaire included questions on uptake of sea lice control measures, efficacy of sea lice control measures, benefits of using the sea lice treatments, and barriers to uptake of sea lice control measures. The workshop and interviews were approved by the Institute's Social Science Ethics Committee, and informed consent was obtained from participants.

2.3. Sea lice management measures

We included a selection of common management measures in use in Scotland. These were analysed in two different ways. Firstly, we analysed the different management measures in isolation, which does not represent the field situation but provides insight on their individual efficacy. Secondly, we introduced three combinations of measures that represent realistic field scenarios. These have the disadvantage that they represent only a small proportion of possible combinations; in addition, the denominator estimates of effectiveness become redundant. However, outputs from these representative combination measures do provide insights that can be further explored.

The management measures explored in this study can be grouped into the categories of: in-feed, bath – medicines, bath – fresh or brackish water, mechanical, preventive, and biological. The in-feed measure we considered was Slice (Emamectin Benzoate) mixed into salmon feed and recommended to be fed for seven consecutive days (MERCK, 2012). Medicinal bath delousing measures included were Paramove (Hydrogen Peroxide), Alphmax and Salmosan. These delousing measures consist of medicines dissolved in water, they help detach lice from fish and are designed to then kill the lice. Baths can be implemented in two ways – using tarpaulins or using well boats (Whyte et al., 2016). Fresh or brackish water baths are similar to medicinal bath delousing measures, but instead of medicines being dissolved in sea water, fresh or brackish water is used (Andrews and Horsberg, 2020; Ljungfeldt et al., 2017). The mechanical management measures considered were the so-called 'hydrolicer' and 'thermolicer'. We included the preventive measure "skirts", which are tarpaulins without a bottom that provide a barrier between sea lice outside a pen and the salmon within, thus preventing the lice from reaching their host (Barrett et al., 2020). The biological management measure considered was cleaner fish, which may be permanently employed in salmon pens (Overton et al., 2020). The many variations in protocols and subcategories were ignored to reduce artifactual differences due to a lack of input data.

The three integrated management measures (Fig. 1) are based on realistic integrated strategies representing sequences of individual management measures applied between stocking and harvesting on a salmon farm used to comply with regulations and limit sea lice levels between stocking and harvesting. The mechanical removal measures (hydrolicer and thermolicer) are only deployed once salmon reach a weight of at least 1 kg, and therefore appear towards the second half of the combinations. In contrast, Slice, the in-feed medicine, is deployed when fish are smaller and require less food (Lees et al., 2008a, 2008b). The costs of equipment, implementation and side effects for a single measure were assumed to be additive under each combination of management measures. Possible variability over time in susceptibility of lice towards the various measures was ignored.

2.4. Study farm scenario

Management measures were compared based on a fictitious but realistic study salmon farm. The parameters used in this study farm were derived from literature and expert opinions to resemble characteristics common for a Scottish salmon production cycle (Table 1). Our study farm had 1.2 million fish with an average harvest weight of 5 kg. The average length of a production cycle on this farm was 20 months in the marine environment and each fish required 5.75 kg of feed per production cycle, which resulted from assuming an overall background mortality of 15%. Further details such as distance from freshwater source, number of cages and diameter of cages were not part of the

Table 1
Basic farm parameters used in the models.

Variable	Average	Source
Fish	1.2 million per farm	Macaskill, 2014
Harvest weight	5 kg	Expert opinion
Length of production cycle	20 months	Expert opinion
Feed requirement	5.75 kg per fish per cycle	Expert opinion
Background mortality	15%	Expert opinion
Salmon farm gate price	£32.42 per fish	Expert opinion
Average price per kg of feed	£0.94	Expert opinion
Cleaner fish requirement	48,000 per farm	Macaskill (2014)

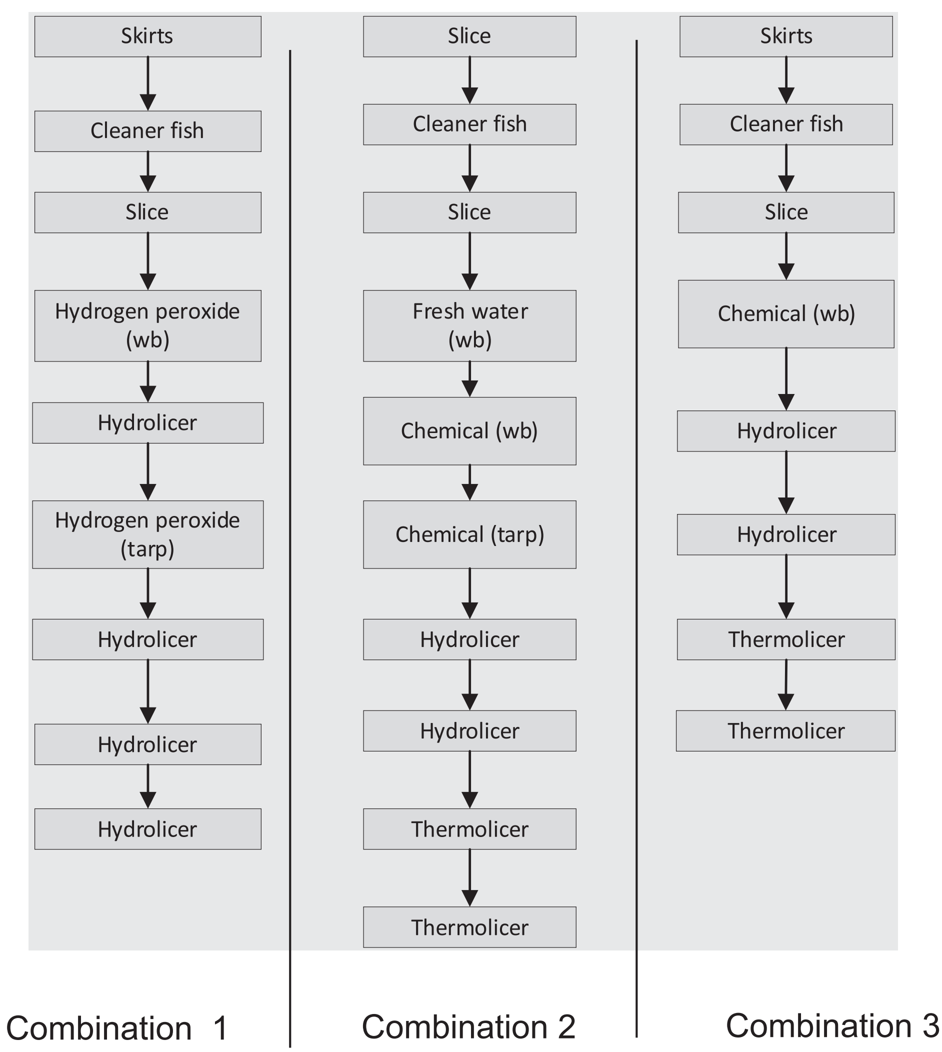

Fig. 1. Integrated management measure sequences in three combinations. Source: Combination 1: Patterson (2018), Combination 2: survey interviews, and Combination 3: designed by the research team. (wb = well boat).

analysis and thus not relevant, though they would be in a more complex model. An average farm gate price of live salmon (£32.42) and average price per kg of feed (£0.94), were used as input prices in the model. Price standardization was not considered and testing for the effect of nominal values of other variables was performed using a sensitivity analysis. The farm required 48,000 cleaner fish (1 cleaner fish per 25 salmon). Our study farm practiced synchronised fallowing, as is the standard practice on Scottish salmon farms, and hence this was not included as a sea lice management measure in this study.

2.5. Costs

An overview of the input cost for the different categories can be found in Table 2.

The costs for equipment (C_{eqp}) and implementation (C_{imp}) were merged as they were not always separatable based on their source. These costs are justified in Appendix 2. For the combination measures, costs were a sum of costs in Table 2 according to how often combinations occurred.

The costs for environment (C_{env}) for single measures have a high uncertainty because of the lack of primary data. They are based on CO_2 emissions from farm-to-farm gate, defined as a salmon weighting 5 kg at harvest. A standard carbon cost of £12.8 per tCO_{2e} was used to determine total carbon emissions (UK Government, 2019). Environmental costs are further explained and justified in Appendix 1.

The costs for side effects (C_{se}) due to mortality when using the hydrolicer or thermolicer have been derived from Norwegian estimates (Iversen et al., 2017), while for others, expert opinions were used.

2.6. Effectiveness

The effectiveness of single sea lice management measures represented relative efficacy and were 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). Effectiveness of the measures were made relative so they could be compared. This was done by computing what the costs would be for the same efficacy under each measure, e.g. the same reduction in number of sea lice per fish.

The efficacy of three combinations of management measures used was assumed to be 100% because the sequence of management measures evolved throughout the production cycle to successfully comply with regulations and keep sea lice levels adequately managed between stocking and harvesting.

Table 2
Input values of costs including equipment costs (C_{eqp}) + implementation costs (C_{imp}) in £ per measure, environmental costs (C_{env}) represented by carbon costs in £ per fish for the entire cycle, and side effect costs (C_{se}) represented by % of mortality as a result of a measure.

Type	Management measure	C_{eqp} + C_{imp} (£/measure)	C_{env} (£/fish)	C_{se} (% mort/ measure)
1. In feed	Slice	35,000	0.0001	0.10
2. Bath – medicinal	Medicinal, hydrogen peroxide (well boat)	69,809	0.0020	1.00
	Medicinal, hydrogen peroxide (tarpaulin)	67,521	0.0016	1.00
	Medicinal, other (well boat)	69,809	0.0010	0.50
	Medicinal, other (tarpaulin)	67,521	0.0008	0.50
3. Bath – fresh or brackish water	Fresh or brackish water (well boat)	33,620	0.0012	0.50
	Fresh or brackish water (tarpaulin)	12,281	0.0006	0.50
4. Mechanical	Hydrolicer	139,104	0.0007	0.25
	Thermolicer	181,440	0.0008	0.50
5. Preventive	Skirts	48,384	0.0000	0.00
6. Biological	Cleaner fish	115,515	0.0003	0.00
7. Combinations	Combination 1	892,645	0.0070	3.1
	Combination 2	816,113	0.0071	3.2
	Combination 3	909,796	0.0056	2.6

2.7. Sensitivity analysis

A sensitivity analysis was included to explore the influence of input variables on the modelling output. This helped in identifying the most influential input variable as the actual value of the most influential variables is more important to estimate correctly than variables that have only a small impact on the output. This is important for this study because limited availability of input data, absence of control farms to compare our results against, and the subsequent use of expert opinion on efficacy of single use measures to obtain qualitative relative effectiveness were all sources of uncertainty.

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. Second, we investigated the effect of costs by doubling the input costs. Third, to account for uncertainty owing to combined data sources, sensitivity analyses were carried out to assess the impacts of varying values for the costs of interventions on the model outcomes, such as the feed conversion ratio. Fourth, we explored the effect of varying mortality percentages. Appendix 1 includes a sensitivity analysis to account for uncertainty of data inputs for calculation of environmental costs.

3. Results

3.1. Cost effectiveness of single measures

The horizontal lines in Fig. 2 (Standard CEA) indicate the cost of the sea lice management measures for the same unit of effectiveness per fish, implying that the higher the line, the higher the cost to reach the same efficacy. Fig. 2 is ranked with the most cost-effective measures on the left, to the least cost-effective measures on the right.

In-feed and skirt measures cost under £0.10 per fish per unit of effectiveness. They were the most cost-effective measures. The cleaner fish, fresh or brackish 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 separately analysed licensed veterinary medicine 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.

Fig. 2 also visualizes results of the sensitivity analysis by the coloured bars, i.e., the CEA when efficacy was at minimum value, efficacy was at maximum value, or the input costs were twice as high. "Medicinal other" refers to medicinal bath treatment excluding hydrogen peroxide.

For a maximum efficacy level, there was no major change in ranking of the measures by cost-effectiveness compared to the results under the standard efficacy level assumption. There was a small change in the ranking, with only the thermolicer becoming slightly less cost-effective than the other medicinal 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.

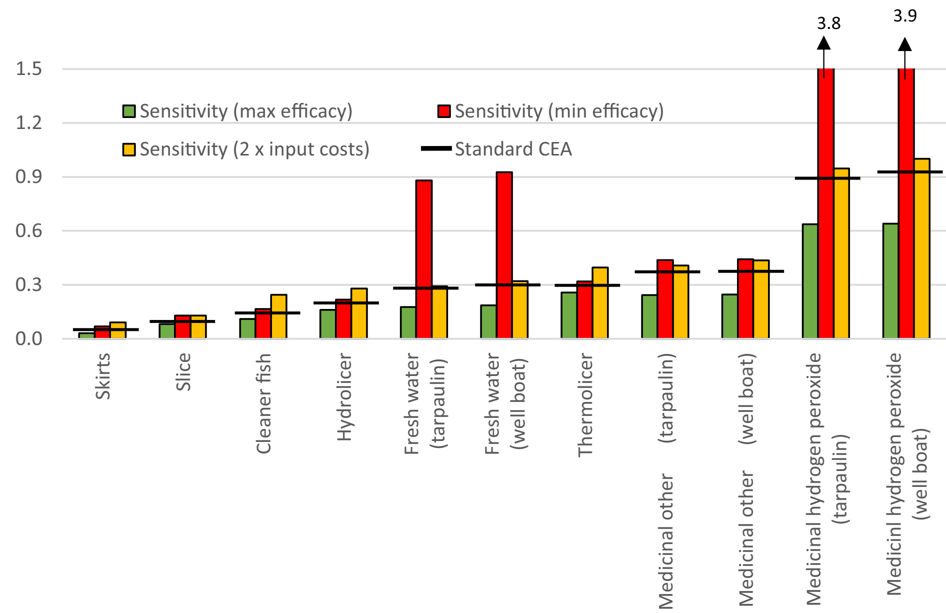

Fig. 2. Ranked cost-effectiveness of using different sea lice management measures on Scottish salmon farms for 1) the standard efficacy level (£/unit of effectiveness per fish; black horizontal line), 2) maximum efficacy level (green vertical bar), 3) minimum efficacy level (red vertical bar) and 4) double the input costs (yellow vertical bar). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For a minimum efficacy level, the ranking of the sea lice management measures changed substantially for fresh or brackish water. Both fresh or brackish water and hydrogen peroxide measures had the lowest minimum effectiveness estimate according to our panel (see Table 3), so at minimum efficacy they both changed substantially. 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 medicinal measures 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 three-fold for hydrogen peroxide measures and two-fold for fresh or brackish water measures.

Table 3
Average and min/max levels of efficacy scores (rates) for each of the sea lice management measures.

Type	Management measure	Standard efficacy	Minimum efficacy	Maximum efficacy
1. In feed	Slice	0.73	0.50	0.80
	Medicinal, hydrogen peroxide (well boat)	0.43	0.10	0.60
	Medicinal, hydrogen peroxide (tarpaulin)	0.43	0.10	0.60
	Medicinal, other (well boat)	0.60	0.50	0.90
2. Bath – medicinal	Medicinal, other (tarpaulin)	0.60	0.50	0.90
	Fresh or brackish water (well boat)	0.64	0.20	1.00
3. Bath – fresh or brackish water	Fresh or brackish water (tarpaulin)	0.64	0.20	1.00
	Hydrolicer	0.80	0.70	0.95
4. Mechanical	Thermolicer	0.80	0.70	0.95
5. Preventive	Skirts	0.58	0.40	0.90
6. Biological	Cleaner fish	0.72	0.60	0.90
	Combination 1	1.00	1.00	1.00
	Combination 2	1.00	1.00	1.00
7. Combinations*	Combination 3	1.00	1.00	1.00

* : efficacy set at 1 because it is assumed the combinations were successful to comply with regulations and keep sea lice levels at bay between stocking and harvesting.

Doubling all the input costs did not change the overall cost-effectiveness rankings of the management measures although the absolute values of cost-effectiveness did change. Changing costs of single use measures did lead to changes in the ranking of cost effectiveness. For example, increasing only the price of cleaner fish by 50% and 100% led to a worse cost-effectiveness of the measure by £0.04 and £0.10 respectively per unit of effectiveness. This led to the cleaner fish measure becoming slightly less cost-effective than the hydrolicer measure.

Doubling mortality for all measures reduced the cost effectiveness of all measures significantly. It cost up to £5.6 per fish per unit of effectiveness, the most expensive being the hydrogen peroxide measure. Thus, the analysis is highly sensitive to fish mortality, which is because the loss of fish due to mortality is fully accounted for as loss of revenue (included as costs of side effects) in the CEA model.

3.2. Combination measures

Comparison of integrated management measures expressed by three combinations are visualized separately in Fig. 3 because they are not comparable to the single measures shown in Fig. 2. Results on the CEA of the three sea lice combination management measures 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 Fig. 3).

Fig. 3 also shows that by doubling the input costs, 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). The change in ranking was due to the nature of the inputs used in each combination.

4. Discussion

Sea lice management using skirts or an in-feed medicine (Slice) had the best cost effectiveness of the measures analysed. Cleaner fish, fresh or brackish water bath, the physical removal measures (thermolicer and hydrolicer), as well as medicinal baths were among the second most

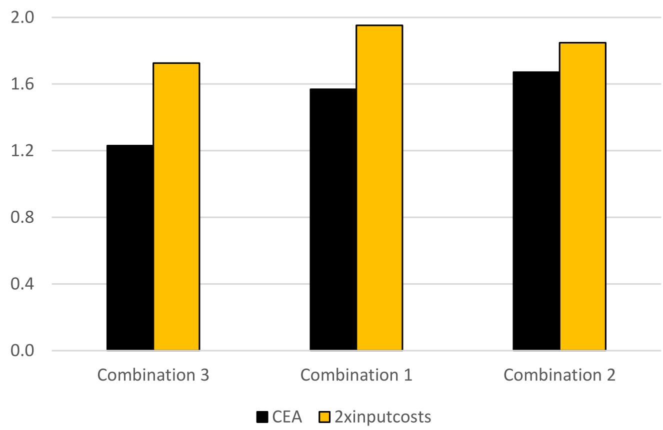

Fig. 3. Ranked cost-effectiveness of using different combinations of sea lice management measures on Scottish salmon farms for 1) the standard efficacy level (£/unit of effectiveness per fish; black vertical bar), and 2) double the input costs (yellow vertical bar). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cost-effective measures, followed by hydrogen peroxide bath. Efficacy was estimated by experts who exhibited the highest level of contradictory option for the cases of hydrogen peroxide and for fresh or brackish water baths. Ranking the management measures provides insights that can help understand differences between methods, unravel complexity, and focus research efforts. In reality, decision-making on management strategy envelops much more than cost-effectiveness, such as availability of resources, responses to pressure from e.g. other fish health stressors, environmental concerns, impact of the measure on farmed salmon, and potential impact on stocks of wild salmon (Jackson et al., 2018).

The moderate effectiveness of skirts that was indicated by experts in our study was similar to estimates of effectiveness reported by Barrett et al. (2020). Skirts reduce encounter rates between parasite and host using barrier technology, but they are not effective after lice invade the pen and become attached to their host (Barrett et al., 2020). Skirts can therefore be deployed early in a production cycle, complementary to and ahead of the other measures analysed in this study, as can be seen in our integrated management example combinations 1 and 3. They can delay attachment of lice and might therefore buy time until lice become attached, which may result in a reduction in the number of delousing measures needed during a production cycle. Skirts were the only preventive barrier measure included in the study; we can therefore not comment on ranking different preventive measures. However, in general, effective implementation of preventative measures may reduce the need for reactive measures (Barrett et al., 2020). This corresponds with our results of ranking our three combination measures, where we showed that the string with the fewest measures had the best cost effectiveness. Deploying fewer measures may lead to fewer costs and a better overall cost-effectiveness in terms of an integrated management strategy over a production cycle between stocking and harvest. Thus, effectiveness of skirts as a single measure may be perceived as moderate, but it could lead to larger cost savings when considering over an entire production cycle. Next to lice infections, there is a wider picture of fish health and welfare to consider. Because skirts can reduce oxygen flow into a fish pen (Stien et al., 2012) they can have a negative effect on fish, especially when fish already have other stressors such as compromised respiratory functions.

There are differences between the reactive measures in the way they target lice stages. In-feed medicine, medicinal baths and fresh or brackish water baths can reduce the attachment success and/or early post-settlement survival of copepodids, while mechanical measures and cleaner fish are effective at sessile and/or mobile stages alone (Bron and Bricknell, 2022). Among the in-feed medicine, medicinal baths and fresh or brackish water baths, the in-feed medicine (Slice) was the most cost-effective measure. Our perceived efficacy scores for Slice were lower than the 68–100% reported by Gustafson et al. (2006), which could perhaps be due to a difference in pre- and post-count timing (Gautam et al., 2017b), or to the build-up of resistance in lice populations (Lees et al., 2008a; Jensen et al., 2020). Slice is more cost-effective in smaller fish and thus is often used early in a production cycle, as shown in all our examples of integrated management combination measures.

Medicinal measures and fresh or brackish water measures ranked similar in cost-effectiveness, although there was more variation in ranking of fresh or brackish water due to more variation in perceived minimum and maximum efficacy provided by expert opinion. Hydrogen peroxide ranked less well due to its low perceived average effectiveness but ranked similar to the minimum perceived efficacy value for fresh or brackish water baths. The variation in cost-effectiveness between using minimum or maximum efficacy for fresh and brackish water measure and hydrogen peroxide was much larger than for the other measures, indicating that there was most contradiction and uncertainty expressed among experts for these measures. Better quantification of effectiveness of these measures would therefore be a valuable step to obtain a more accurate overall picture.

The bath measures were analysed with well boats or with tarpaulins. Consistently, tarpaulins were more cost-effective than well boats. This related to the higher costs associated with operating well boats compared to tarpaulins, in combination with the assumption that efficacy was unaffected by the method. A study exploring differences in the efficacy of using tarpaulins or well boats for applying licensed veterinary medicines found that efficacy in the case of tarpaulins was 2.2 times higher than when using a well boat (Whyte et al., 2016). The scarcity of evidence available on the matter supports the need for investigating differences in efficacy between these sea lice management delivery options in Scotland.

Generally, efficacy is a difficult metric to estimate and has historically been defined by comparing pre- and post- sea lice counts. But there is a much longer-term longevity concern related to resistance. Most measures lead to selective pressures on surviving lice, leading to resistance. There is increased understanding of the processes behind development of resistance in medicinal measures (Jensen et al., 2020; Jones et al., 2013). Further concerns have been discussed on the potential of development of resistance of lice to fresh or brackish water management measures, which might reduce the ability of wild fish to self-treat by swimming to freshwater rivers (Groner et al., 2019), and skirts could select for deeper swimming lice (Barrett et al., 2020). Deployment of multiple alternating methods into a balanced, holistic approach is recommended (Jackson et al., 2018; Jensen et al., 2020), and this is currently industry practice (see, for example, our integrated management Combination 1 and 2). An additional benefit of a holistic approach is cost synergies across measures when resources can be shared, thereby reducing cost and improving cost-effectiveness. Furthermore, environmental effectiveness needs to be taken into account. For example, if a strict delousing regulation, such as that currently in place in Norway, is motivated by protecting wild salmon, should efficacy not be measured as some effect of a measure deployed in aquaculture on the infestation pressure of sea lice to migrating wild salmon? The break-even point of implementing lice treatment solely based on economic effectiveness for Norwegian salmon farmers is estimated around 7–10 lice per fish which is well over the government regulation (Abolofia et al., 2017). However, quantifying such an association with environment effectiveness is complex, and in Norway there is no evidence that such strict L. *salmonis* regulations (a threshold of 0.2 lice per fish during the out-migration period) reduces infestation pressures on wild fish (Larsen and Vormedal, 2021). For Scotland, such analysis has to our knowledge not been attempted. Lastly, very little information is published on efficacy of sea lice measures, and this is a clear gap in knowledge. This might reflect ever evolving protocols of measures for which older estimates would no longer relevant, or perhaps a hesitancy of industry to share information.

Relying on expert opinions is a weakness of this study, but one that is often adopted in the absence of published information.

Understanding the effect of sea lice management on total environmental cost and greenhouse gas emissions is beyond the main scope of this study. However, estimates of limited environmental costs has been included because environmental sustainability is an important component of how costs are perceived in today's world. Very little work has been done on life cycle assessments in salmon aquaculture in Scotland and practically no primary data were available for this analysis. Therefore, the analysis includes both much uncertainty and no benchmarking opportunities. In Norway, pioneering work has been carried out on life cycle assessment of three alternative productions of cleaner fish (Philis et al., 2021), demonstrating how challenging it is to derive one value per management measure, as has been utilised in the current study. Estimated differences in the greenhouse gas emissions between the different measures in our study were large, any ranking or detailed comparison among the measures is of strictly limited value because the measures do not provide the same functions. We used estimates of the perceived monetary value of CO_2 emissions published by UK Government in 2018 (UK Government, 2019). These estimates fluctuate in time, based on many factors, such as political stability and targets described in the roadmap to net zero in 2030 developed by the UK government. However, even a large change in this estimate would be unlikely to affect conclusions regarding the individual measures because their magnitude was small in comparison to other values. However, long-term effects of lice management, which are not well described in literature and hence not considered, might have a larger impact. For example, when a measure results in reduced growth (Moltumyr et al., 2022), this could potentially result in an increase in greenhouse gas emissions. This indirect increase can be much higher than the direct emissions related to any sea lice management measure. The main reason is, in our example, that a part of the resources (most notable feed) would be higher per useable harvested fish. 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. 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 because of lower productivity, or potential spread of lice through interactions with wild fish. A better understanding of the environmental costs of management measures is a gap in knowledge that is important and further research would benefit decision making towards net-zero emission policies.

Mortality estimates also had a large impact on cost-effectiveness outcomes. Sensitivity analysis to evaluate results for combination measures indicated a high sensitivity to fish mortality. Our mortality estimates for mechanical measures and medicinal measures were similar, whereas Walde et al. (2021) estimate mechanical measures to have a 5–6 times higher mortality rate. That study also indicated that mortality related to sea lice management measures varied over years and was sensitive to the number of days post-deployment included in the estimation. It is therefore difficult to compare our exact estimates with those of Walde et al. (2021), and this illustrates that standardization of a protocol to estimate post-delousing mortality effects would help studies such as ours to directly compare estimates from different sources. Post-delousing mortality has, to our knowledge, not been estimated for a range of management measures in Scotland.

We used the CEA technique to determine the impacts of potential sea lice management approaches available on the Scottish salmon farms. This technique has been used commonly to examine cost effectiveness of various interventions in various fields such as in human medicine (Murray et al., 2000), water pollution (Lescot et al., 2013), and cattle disease (Valeeva et al., 2007; Benedictus et al., 2009). There are only a handful of studies in the past using the CEA or similar techniques to examine alternative disease management in aquaculture (Moran and Fofana, 2007; Liu and Bjelland, 2014). Hall et al. (2014) used the technique to identify optimal management policies to control bacterial kidney disease in salmon farming in the UK. The main limitation of this study was data, specifically availability of economic data, data uncertainty, and consequently simplified modelling assumptions. Our data sources are a combination of primary and secondary data, together with limited expert opinion. Data are constants which we modelled deterministically, whereas in reality they would vary in time and stochasticity would create variation in outcomes, which we explored by including a sensitivity analysis. Most of the Scottish financial information were obtained from one unpublished source (Macaskill, 2014). Geographically more distant data sources were mainly from Norway and Canada. These were translated to the Scottish situation as closely as possible but might not represent the Scottish salmon industry situation fully, considering the differentiation in costs that exists among salmon farming countries (Iversen et al., 2020). Workshop participants were also not fully representative of the entire Scottish industry. 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. Specific examples of how the model can be improved include diversifying loss parameters beyond mortality, such as including loss from reduced growth due to poor feeding (Asche and Guttormsen, 2001; Abolofia et al., 2017; Walde et al., 2022), and other price effects due to loss (Quezada and Dresdner, 2017). However, such methodologies are only appropriate if the inputs are of sufficient quality. Obtaining better quality data for studies such as these is challenging, because information on treatments is commercially sensitive, and treatment protocols are company specific and frequently adapted. Economic studies on sea lice in aquaculture with more complex and inclusive methodologies are sparse for that reason. If data regarding treatments, efficacies, costs and effects on production could be gathered more regularly in a standardized way, it would become possible to estimate sea lice cost-effectiveness better and under different circumstances, which may help improve sea lice management. Initial steps have been taken within the Scottish context to at least improve the level of reporting, with weekly farm-based reporting of sea lice numbers being required since 2021, where previously only monthly mean values were reported. However, only adult female sea lice abundances are reported which limits any validation of the entire population and can become particularly problematic when the stage being reported on is also the one against which regulatory thresholds are based (Jeong et al., 2023).

A second limitation was the absence of control farms to compare our results against. Most health economic studies rely on empirical data in a 'with- and without' format which provides a reliable source of generating indicators. Sea lice infestation is a significant problem for Scottish salmon producers so a 'without sea lice management measures' scenario is almost non-existent. We have accounted for this by using perceived efficacy estimates from experts for each of the single use measures and combined this with sensitivity analyses to take the wide variability in expert opinion into account.

Sea lice management is complex. This study is the first attempt to rank sea lice management measures in Scotland based on cost effectiveness. Extrapolations should be taken with caution because the study is based on many simplifying assumptions due to data limitations and a lack of standardization. Because of these limitations, the analysis was kept simple to avoid over interpretation of the outcomes. The methodology used in this study can be improved if more data is available, e.g., through running pilot projects on experimental farms to gather data on management options and their impact on sea lice control in real time. Despite these limitations, this study provides a much-needed framework for discussion, an understanding of the gaps in knowledge, and a guide for developing further research.

Funding

This work was supported by the Scottish Government through the Marine Scotland Directorate (project CR/2018/31) and the Rural and

Environment Science and Analytical Services Division (projects SRUC-B4-4, SRUC-B3-1 and EPIC 4). Luiza Toma and Shailesh Shrestha also acknowledge support from BBSRC grant BB/T004436/1.

CRediT authorship contribution statement

Annette S. Boerlage: Conceptualization, Investigation, Writing – original draft. **Shailesh Shrestha:** Conceptualization, Investigation, Formal analysis, Validation, Writing – original draft. **Ilkka Leinonen:** Conceptualization, Investigation, Formal analysis, Validation, Writing – review & editing. **Mona Dverdal Jansen:** Investigation, Writing – review & editing. **Crawford W. Revie:** Investigation, Writing – review & editing. **Aaron Reeves:** Investigation, Writing – review & editing. **Luiza Toma:** Funding acquisition, Project administration, Supervision, Conceptualization, Investigation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank the participants to the workshop and interviews. We are grateful for the comments and suggestions received from Peter Greene and Sandy Murray from the Marine Scotland Directorate of the Scottish Government. We thank Sam Houston and Robin Shields from The Scottish Aquaculture Innovation Centre for advice in the earlier stages of this research. The authors would like to thank the anonymous referees whose valuable comments have helped improve this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2023.740274.

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