Vol. 16: 27–42, 2024
https://doi.org/10.3354/aei00471

AQUACULTURE ENVIRONMENT INTERACTIONS
Aquacult Environ Interact

Published January 18

A gap analysis on modelling of sea lice infection pressure from salmonid farms. II. Identifying and ranking knowledge gaps: output of an international workshop

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ABSTRACT: Sea lice are a major health hazard for farmed Atlantic salmon in Europe, and their impact is felt globally. Given the breadth of ongoing research in sea lice dispersal and population modelling, and focus on research-led adaptive management, we brought experts together to discuss research knowledge gaps. Gaps for salmon lice infection pressure from fish farms were identified and scored by experts in sea lice–aquaculture–environment interactions, at an international workshop in 2021. The contributors included experts based in Scotland, Norway, Ireland, Iceland, Canada, the Faroe Islands, England and Australia, employed by governments, industry, universities and non-government organisations. The workshop focused on knowledge gaps underpinning 5 key stages in salmon lice infection pressure from fish farms: larval production; larval transport and survival; exposure and infestation of new hosts; development and survival of the attached stages; and impact on host populations. A total of 47 research gaps were identified; 5 broad themes emerged with 13 priority research gaps highlighted as important across multiple sectors. The highest-ranking gap called for higher quality and frequency of on-farm lice count data, along with better sharing of information across sectors. We highlight the need for synergistic international collaboration to maximise transferable knowledge. Round table discussions through collaborative workshops provide an important forum for experts to discuss and agree research priorities.

KEY WORDS: Salmon louse · Sea trout · Wild salmon · Stakeholder engagement · Opinion

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Publisher: Inter-Research · www.int-res.com

1. INTRODUCTION

According to the World Bank "the 'blue economy' concept seeks to promote economic growth, social inclusion, and the preservation or improvement of livelihoods while at the same time ensuring environmental sustainability of the oceans and coastal areas." And 'regardless of the size of operations, sustainable aquaculture, by definition, must be economically viable and environmentally sound.' (World Bank and United Nations Department of Economic and Social Affairs 2017, p. vi and p. 16). In many North Atlantic countries, such as Scotland, Norway, Ireland, the Faroe islands and Canada, blue foods farming resources are heavily dominated by Atlantic salmon aquaculture, which, as part of the blue economy vision, should be moderating or minimising impact on the wider environment (Lee et al. 2020, Hughes 2021, Scottish Government 2022a).

Sustainable aquaculture can form a key component of a thriving blue economy where economic growth, social inclusion and the preservation or improvement of livelihoods are coupled with ensuring the environmental sustainability of the oceans and coastal areas (Scottish Government 2022a). One barrier to sustainable aquaculture is the effect of sea lice (Wiese et al. 2023). Sea lice are naturally occurring ecto-parasites in the marine environment, and commonly recorded on wild salmonids. However, the numbers of sea lice are greatly inflated by presence of salmon aquaculture (Dempster et al. 2021). Sea lice are documented as having a major impact on salmon aquaculture sustainability (Krkošek et al. 2007, Costello 2009, Taranger et al. 2015, Forseth et al. 2017, Myksvoll et al. 2020, Johnsen et al. 2021, Bøhn et al. 2022). Production losses and additional costs associated with sea lice management and mortality are estimated to be an average of 9% of farm revenues (Abolofia et al. 2017).

The interaction between farmed Atlantic salmon and wild salmonids has been an area of much study, in part due to the ability of sea lice to disperse on currents over large distances and the increased numbers in the environment with increased hosts on farms (summarised in Moriarty et al. 2024, this volume). Wild Atlantic salmon are subject to a wide range of pressures in the marine environment (Utne et al. 2021, 2022, Dadswell et al. 2022), and populations have declined substantially in recent decades across much of their natural range (Dadswell et al. 2022). Attention has focused on assessment and management of pressures, including sea lice, to bolster wild stocks in many salmon-producing countries (Scottish Government 2022b). As part of this assessment, sea lice dispersal models have been developed to better understand abundance and distribution of the larval stages, and improve management in Norway, Scotland, Canada, Ireland and the Faroe Islands (Amundrud & Murray 2009, Johnsen et al. 2016, Cantrell et al. 2018, Kragesteen et al. 2018). Modelling lice distributions in the sea requires detailed hydrodynamic models with relevant regional meteorological, highly resolved tidal, temperature, salinity and fresh water inflow forcing data. Research exists on the processes required for modelling of sea lice transmission (e.g. Myksvoll et al. 2018), including simulating important aspects such as sea lice larval behaviour (e.g. McEwan et al. 2015, Johnsen et al. 2016). This behaviour can be coupled with wave–wind–tide interactions in 3D flow fields (e.g. Lewis et al. 2019). However, many parameter values remain uncertain (Moriarty et al. 2023a). A review of published international research into the key stages of sea lice infection processes to support modelling is presented by Moriarty et al. (2024), while monitoring that may help address key gaps is discussed by Pert et al. (2022).

A workshop, focused on developing a standardised framework for sea lice dispersal modelling (Murray et al. 2022a), was initiated with funding from the Marine Alliance for Science and Technology for Scotland (MASTS 2017). Following on from this, the views from international sea lice modellers and interested stakeholders brought together for a virtual workshop on October 7, 2021, at the MASTS 2021 Annual Science Conference are outlined herein. Research and knowledge gaps were identified by participants, including scientists directly involved in new model development, industry stakeholders, policy makers and non-governmental organisation managers concerned with ensuring standards for models used to review and identify sea lice modelling challenges. We aimed to: (1) summarise the knowledge gaps identified and ranked at the international workshop; and (2) highlight possible synergies for future research collaborations within the international research community.

Reflection on knowledge strengths and gaps is important in the context of the blue economy, as adaptive management is a cornerstone of this vision (Scottish Government 2022a). It is apparent that different countries prioritise different aspects of salmon lice research, and therefore the knowledge gaps might vary by country. As this workshop was organised by authors based in Scotland, the research gaps in Scotland are at the fore. We investigated the data to see if it was possible to provide granularity for the various nations represented, but due to some countries only having 1 representative at the workshop it would have been statistically meaningless to weight the research gaps in this way. However, this paper provides a valuable resource for researchers, end users and funding bodies internationally. Here, we focused on the bio-physical scientific approach in addressing knowledge gaps and solutions. However, we acknowledge that social science approaches are important for shaping a sustainable response to sea lice: conservation thinking, policy decisions and management practices for all ecology–human interactions (Rüegg et al. 2018). Thus, we strongly encourage a socio-ecological analysis in response to this paper.

2. METHODOLOGY — IDENTIFICATION OF RESEARCH GAPS

The virtual workshop identified gaps in sea lice dispersal modelling and population assessment research. It aimed to ensure that participants had an opportunity to identify the research gaps. Organisations and their sectors represented are listed in Table S1 in the Supplement at www.int-res.com/articles/suppl/q016p027_supp.pdf. The various sectors were not equally represented across all nations at the workshop, therefore the data could not be meaningfully weighted by sector within countries.

The workshop was split into 2 sessions: (1) sea lice distribution and dispersal modelling; and (2) sea lice population modelling and monitoring sea lice in the water column. Each session included a keynote speech outlining the state of the science for the respective area, followed by short presentations on areas for improvement from various national and international experts representing different stakeholders. In breakout groups (6 to 8 people per group), participants were asked to identify and score sea lice research gaps according to their perceived: (1) immediacy of concern, i.e. 'the need to prioritise the gap'; and (2) magnitude of concern, i.e. 'the magnitude or seriousness of the issue' (1: very low, 2: low, 3: medium, 4: high, 5: very high). After the workshop, identified research gaps were circulated to all participants to ensure all gaps were captured, and to allow participants to refine their responses. Out of 74 workshop participants, 36 sent in responses and research gaps are listed in Table S2.

The average value of the metrics of (1) immediacy of concern and (2) magnitude of concern were calculated for each sector, giving a sector score mean value for each gap. For comparison, the overall average gap value across all sectors was calculated by adding all sector score averages then dividing by number of sectors. The priorities were ranked for each sector, running from 1 for the highest to 47 for the lowest value. These sectoral rankings were compared to the overall rankings by plotting a regression of sector against overall ranking. A simple pair of criteria were used to assess the key priorities as identified by workshop participants: (1) Is the priority gap identified as being in the top 10 of at least 3 sectors? This criterion was intended to identify those gaps generally assessed as being of high priority. This group is sub-divided into those with an overall average ranking in the top 10 (Fig. 1; meets Criterion 1A), and those whose overall average rank is outside the top 10, as a slightly lower priority (Fig. 1; meets Criterion 1B). (2) Is the gap identified in the top 5 priorities by 1 sector and in the top 15 by at least 2 other sectors? This criterion was intended to identify high priority gaps for individual sectors that have at least moderate support from some other sectors. These criteria were designed to give a transparent method for identification of priorities that were consistent with the opinions generated in the workshop. Inevitably, there was an arbitrary cut-off point for selection of priorities, but the cut-off was made transparent and final priority selection was objective (Fig. 1).

During the workshop, participants were asked to identify research gaps based on their expert knowledge to maximise coverage. Opinion was also sought from the participants to identify common institutional interest in specific areas of sea lice dispersal and population assessment research. To facilitate this approach, they were asked to score each of the gaps according to the relative value that it would represent to their organisation if the gap was filled. This allowed the research areas with the greatest value for end-user organisations to be identified and to provide some indication as to where the interests of end-user organisations overlap.

3. RESULTS

Workshop participants identified gaps based on the classifications shown in Fig. 2: 47 gaps were identified, which were discussed in breakout groups (Table S2). The overall highest ranking gap on immediacy and magnitude was A2.1 'For on farm lice counts, higher quality and frequency of data required along with better sharing of data'. When

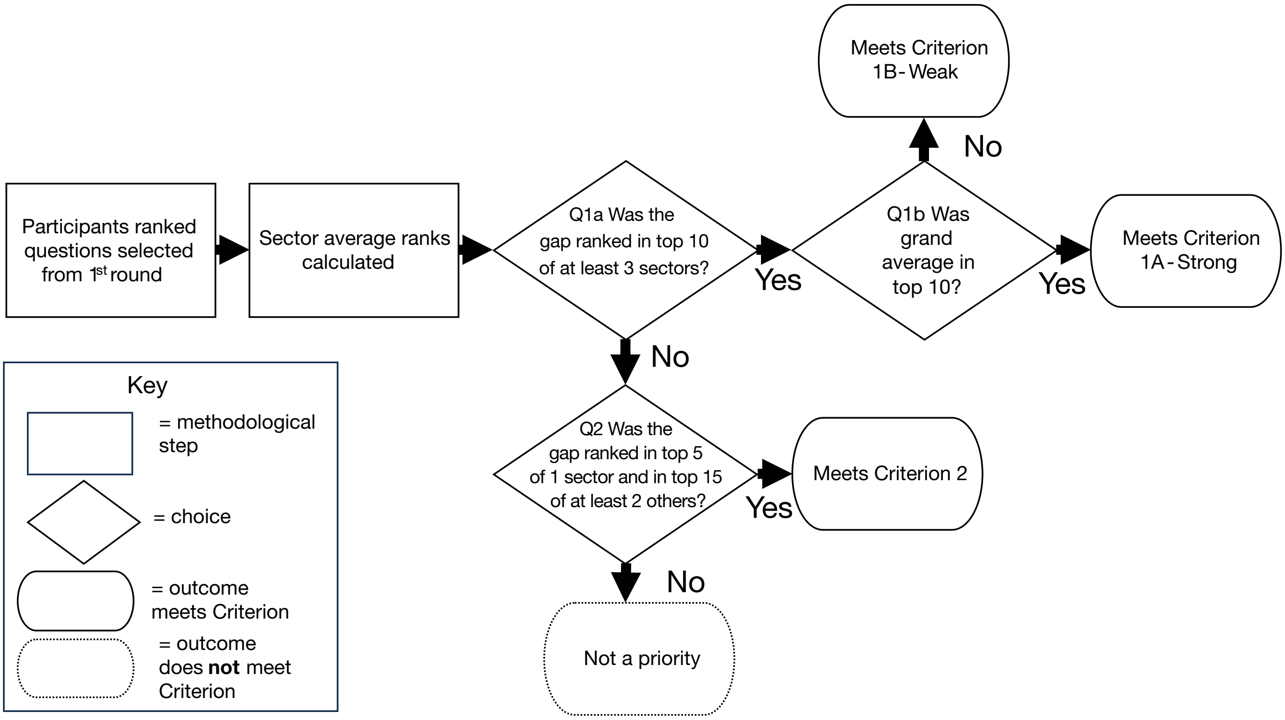

Fig. 1. Selection of priority knowledge gaps using the rankings given by workshop attendees from different sectors (Industry, Consultants, Academics, Government researchers and Policy makers). Criterion 1 identifies priorities with broad support (1A) and slightly weaker support (1B), while Criterion 2 identifies priorities ranked highly by at least 1 sector, with at least some support from other sectors

ranking of this gap is examined by sector, it can be seen to be of very high importance to consultants, government researchers and policy makers, and slightly lower to industry and university researchers (Table 1, Fig. 3). Looking at broad patterns in research question rankings (Figs. 3 & 4), there was a general agreement across sectors as to which questions were highest priority. However, there was considerable variation and difference in regression between overall average (across all sectors, not weighted for numbers in each sector) and the sector means (Table 2). A reasonable guide for the identification of top priority gaps is broad agreement on the ranking of research gap priority across sectors. Each sector had similar mean and variance in their scoring (see Table S3), so normal-

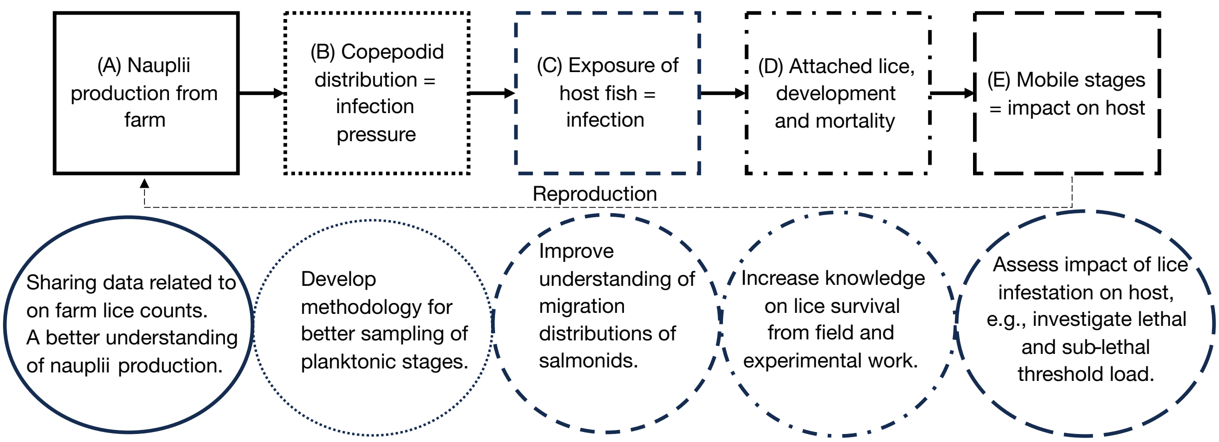

Fig. 2. Relating modelling stages (boxes) modified from Moriarty et al. (2024) to summarised priority research solutions (ellipses) arising from the workshop

Table 1. Key gaps in sea lice dispersal and population modelling research as identified by workshop participants. Each gap was ranked by participants working in various organisations and roles, thus the metrics 'immediacy of concern' and 'magnitude of concern' were averaged across all participants and then broken down by participant role. The letters A to E relate to the 5 stages described in Fig. 2. Shading highlights the score given, the lighter the shade the higher the score

Top Ten Research gaps	Ranking Score							
	Immediacy Mean	Magnitude Mean	Overall Mean	Industry n=2 Sector score	Consultants n=3 Sector score	University n=13 Sector score	Gov. Research n=6 Sector score	Policy n=12 Sector score
A2.1 'For on farm lice counts, higher quality and frequency of data required along with better sharing of data'	4.53	4.63	4.58	4.25	5.00	4.04	5.00	4.63
B1.3 'Better tools and methodology in place to help make good choices for sea lice management'	4.43	4.43	4.43	5.00	4.00	5.00	4.25	5.00
E1.1 'Investigate the impact on host i.e. what threshold of lice in the environment will be deadly for host'	4.31	4.48	4.40	3.75	5.00	3.85	4.50	4.88
C1.7 'We need a better understanding of migration path of wild salmon/sea trout through new tracking studies'	4.11	4.37	4.24	4.75	3.83	3.80	4.20	4.63
A2.6 'Improved data sharing and provision must be made a priority'	4.31	4.07	4.19	2.50	4.67	4.27	4.50	5.00
B2 'Increased knowledge on lice survival from field and experimental work for parameter estimation'	4.00	4.34	4.17	4.25	4.67	4.13	3.80	4.00
E1.4 'Better understanding critical lice thresholds for fish, seasonal effects and interaction between sublethal lice impacts and other stressors'	3.94	4.13	4.03	2.75	4.50	3.86	4.40	4.67
A1.2 'Increased knowledge on production of nauplii'	3.97	4.04	4.01	4.25	4.17	3.90	3.83	3.88
E1.3 'There are gaps in information on response to high/low infestation for individual fish and populations. What information is needed to inform appropriate local management?'	3.91	4.09	4.00	2.75	5.00	3.65	4.10	4.50
B1.1 'Efficient methods for getting good samples of planktonic salmon lice are required'	3.92	4.07	3.99	5.00	4.00	3.96	2.75	4.25

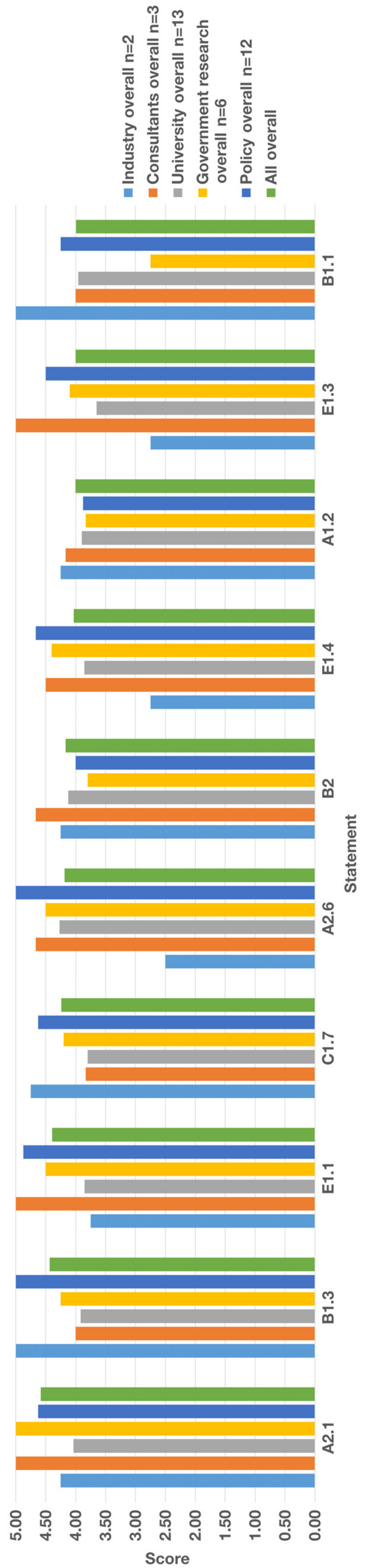

Fig. 3. The top 10 research priority gaps by sector (listed in Table 1). The y-axis score shows the sector average and the grand average for each gap

isation of results was not required. We thus ranked priorities by the overall average of sector average ratings for each research gap (general priorities).

However, gaps that were highly rated by a sector (sector priorities) might also be considered priority areas, even when there was a lack of agreement across all sectors (Fig. 1). Owing to the variation between sectors, we present the patterns for individual sectors in terms of the relationship between sector mean and overall average results (Fig. 4). These results confirm the general agreement in terms of ranking of questions. However, each sector has its own linear relationship of ranked priorities, and it is noted that industry stakeholders had relatively low agreement ($R^2 = 0.378$). Industry participants (n = 2) focused on specific priorities so scores tend to be either very high or very low, leading to scatter and hence the low agreement. Academic researchers (n = 13) differentiated less between low- and high-priority areas, and therefore the regression line is less steep, although agreement is similar to other sectors ($R^2 = 0.589$). Government researchers (n = 6) broadly agreed with the overall average for both low- and high-scoring questions, but scored the intermediate questions below the overall average. Policy makers (n = 12) agreed with the trend of the overall average but tended to score priorities higher than other sectors. The consultant (n = 3) scoring fitted the overall average trend well with no particular areas of deviation.

Due to the general agreement on high priority research gaps, we can use the responses with confidence to identify priority questions. Applying the criteria of 'Is the gap identified in the top 10 priorities by at least 3 sectors' and 'Is the gap identified in the top 5 priorities by 1 sector and in the top 15 by 2 other sectors' (Fig. 1), the first 7 research statements have the highest overall averages and satisfy both criteria, and can therefore be considered top priorities (Table 3). Statements ranked 11 and 13 using the overall average also fulfil Criterion 1, and, therefore, have priority support in at least 3 sectors.

Those ranked 9, 10, 14 and 23 additionally meet Criterion 2. Therefore, we have 13 ranked gaps that meet 1 or both criteria (Table 3). This selection of priorities differs relatively little from using the overall average, since only 2 of the top 14 ranked values are excluded, and only 1 gap outside the top 15 is selected. Objectives ranked by overall average as 9, 10, 11, 13, 14 and 23 trigger only 1 criterion for acceptance (Table 3); therefore, their consideration as priority gaps has lower confidence.

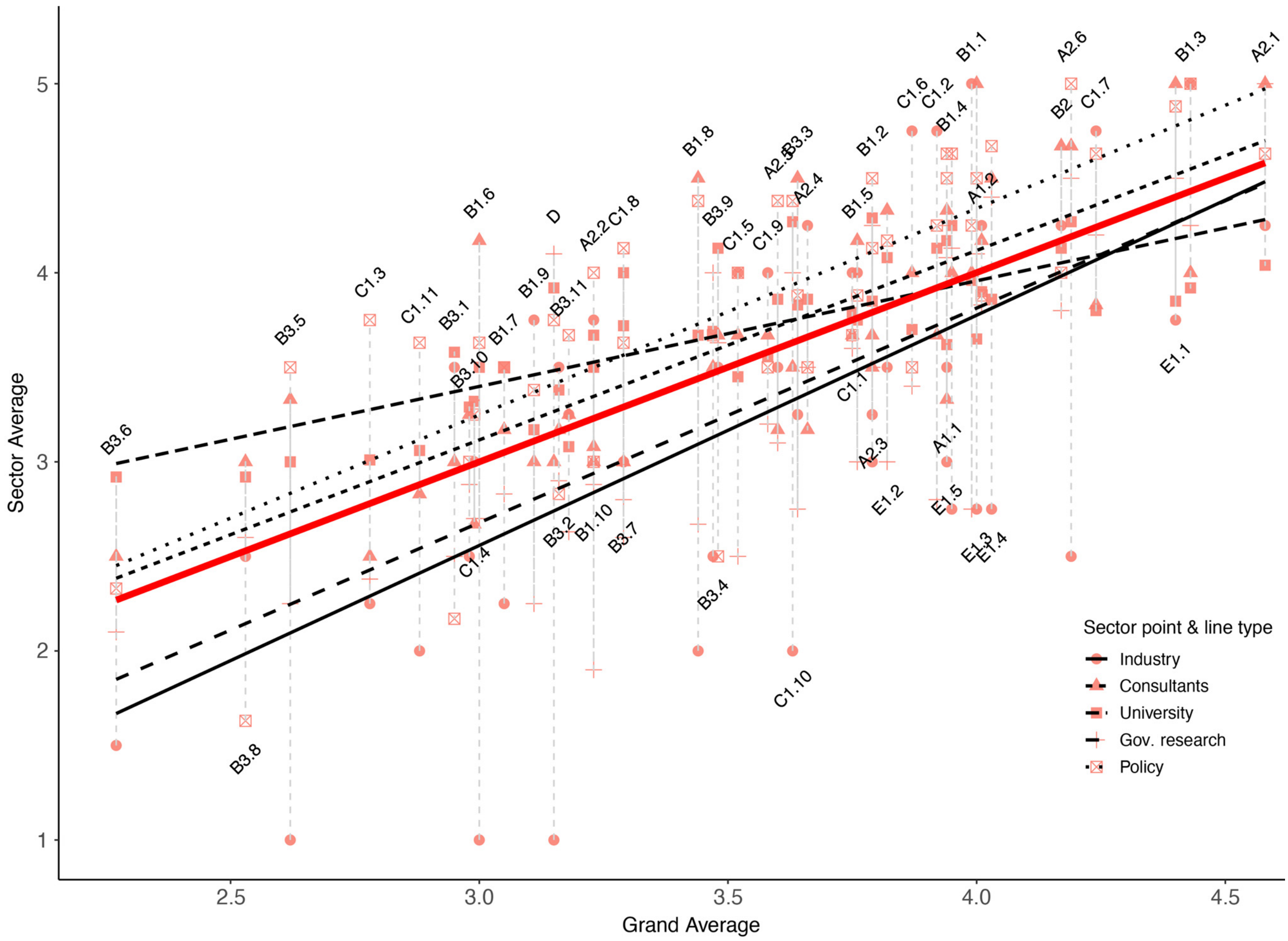

Fig. 4. Sector score values for gap ranking versus overall average gap values. Solid red line: overall average gap value; black lines: linear regressions of sector scores on the overall average (Table 2). Letters A to E refer to the processes to which the research gaps relate (described in Fig. 2)

4. DISCUSSION

Sea lice dispersal and population models are operational and effective in national management plans (e.g. Norway) and are currently being integrated into other national management plans (e.g. Scotland). The identified research gaps vary in 2 aspects: the areas of science and data gathering required for their support, and the amount of work required to address these gaps. The prioritisation exercise identified 13 gaps that meet 1 or both selection criteria (Fig. 1). These gaps are important for different sectors. Industry showed a relatively low agreement (R^2 = 0.378) (Fig. 4, Table 2), but this appeared to be because of focused priorities, so that lower priorities were downgraded and higher were raised — hence greater scatter and lower agreement than other sectors. Alternatively, this relatively low agreement may be due to the low number of representatives (n = 2) in this category — thus narrowing the range of different interests in comparison with a larger category. University researchers, perhaps because of broad interests in this sector, differentiated less between low-priority and high-priority areas. Perhaps this was due, in part, to them being the largest group (n = 13), with more variability in interests than other groups.

As a useful framework to examine more specific gaps, we looked at them in the context of the 5 modelling stages discussed in Moriarty et al. (2024) and shown in Fig. 2. Models act as a representation of a system that can define, analyse and communicate important concepts to manage our environment in a sustainable way. Moriarty et al. (2024) detail how the modelling of salmon lice production, transmission and impact are used extensively to advise on the management of lice in many salmon-producing countries. Moriarty et al. (2024) conclude that knowledge underpinning sea lice modelling has advanced,

Table 2. Sector question rank average values relative to overall average values showing intercept, slope and R^2 value for each sector

Sector	Intercept	Slope	R^2
Industry	−1.096	1.218	0.378
Consultants	0.11	1.002	0.602
University	1.753	0.559	0.589
Government research	−0.728	1.135	0.594
Policy	−0.027	1.092	0.593

but there are areas where further research and sustained data collection could help to reduce, or remove, key uncertainties and provide more accurate model predictions. Here we focus on the perception of the workshop participants in identifying key areas for improvement. The gaps identified should be considered alongside the review of the knowledge set out in our companion paper (Moriarty et al. 2024). They can be used as a guide for researchers in the areas where increased data collection/sharing, or model development, can help to improve farm management strategies and develop understanding of sea lice impacts on wild fish populations in the context of other pressures, such as climate change.

4.1. Nauplii production from farms

The highest ranked priority gap, particularly by government representatives and consultants, was A2.1 'For on farm lice counts, higher quality and frequency of data, required along with better sharing of data'. Also highly ranked was A1.2 'Increased knowledge on production of nauplii' (ranked 8th overall), which relates directly to nauplii production from farms.

Sea lice reporting differs by country (see Moriarty et al. 2024), so there is an opportunity to learn by comparison of different national systems. Potential refinements may include reporting of a wider range of sea lice life stages, sampling larger numbers of fish, or reducing the lag between observation and reporting. This has proven feasible in the Faroe Islands where the number of fish farms in operation are around 20 at any given time (Moriarty et al. 2024). More detailed reporting is not without operational challenges, as rapid turnaround of highly detailed data for publication can be very onerous for farm site staff, and divert resources from work with more immediate impacts on fish husbandry. If resources are to be used with the aim of supporting sea lice management, these must be fit-for-purpose, i.e. data collection must return reliable information that is cost-effective and of use in managing problems (Moran & Fofana 2007). Effective data collection requires the buy-in of those collecting the data (Brugere et al. 2017), but inadequate data can lead to poor decision making (Jeong et al. 2021). Other issues may include commercial sensitivity and the utility of such information for management decisions. There may need to be scope to revise data collection protocols, particularly in relation to statistical significance if lower prevalence lice counts are required under evolving regulations, if farms become larger. The potential improvement in understanding of lice population and dispersal patterns must be weighed against what is realistic operationally. However, a future automatic system for detecting lice on farmed fish might address this gap (Benfield et al. 2007).

4.2. Copepodid distribution

The statement 'Efficient methods for getting good samples of planktonic salmon lice are required', priority B1.1, was ranked 10th overall. Obtaining representative samples of larval sea lice is problematic given the rather low density of sea lice larvae, high densities of other planktonic organisms and impacts of, e.g., weather conditions on sampling success (Skarðhamar et al. 2019). The patchiness of sea lice larvae in the water limits the value of currently used methodologies as a monitoring tool unless numerous samples are processed in time and space (Moriarty et al. 2023b). New technologies such as machine learning for particle recognition applied to zooplankton larvae, fluorescence microscopy (Bui et al. 2021, Thompson et al. 2021) and DNA-based sampling methods (Pert et al. 2022) may potentially offer opportunities to improve identification and quantification of sea lice larvae while reducing the need for costly and time-consuming manual taxonomic identification (McBeath et al. 2006, Jacobs et al. 2018).

Priority C1.10 'Investigate ways for farms to avoid cross infecting' (Table 3) was the lowest priority gap that satisfied the prioritisation selection criteria. This gap may be addressed by modelling farm lice dispersal to identify how to minimise interaction between farms and wild salmonids, or through development of methods for farm shielding, such as snorkel technologies (Stien et al. 2016, Geitung et al. 2019). This priority relates to the more general gap calling for

Table 3. Priority gaps, sorted by overall average ranking across sectors, that meet priority Criteria 1 (weak, strong or no) and/or 2 (see Fig. 1). All gaps are listed in Table S2 with the top 10 in Table 1

Rank	Gap	Criterion 1	Criterion 2	Comment
1	A2.1 'For on farm lice counts, higher quality and frequency of data required along with better sharing of data'	Yes (strong)	Yes	Agrees with ranking in Table 1
2	B1.3 'Better tools and methodology in place to help make good choices for sea lice management'	Yes (strong)	Yes	Agrees with ranking in Table 1
3	E1.1 'Investigate the impact on host, i.e. what threshold of lice in the environment will be deadly for host'	Yes (strong)	Yes	Agrees with ranking in Table 1
4	C1.7 'We need a better understanding of migration path of wild salmon/sea trout through new tracking studies'	Yes (strong)	Yes	Agrees with ranking in Table 1
5	A2.6 'Improved data sharing and provision'	Yes (strong)	Yes	Agrees with ranking in Table 1
6	B2 'Increased knowledge on lice survival from field and experimental work for parameter estimation'	Yes (strong)	Yes	Agrees with ranking in Table 1
7	E1.4 'Better understanding critical lice thresholds for fish, seasonal effects and interaction between sublethal lice impacts and other stressors'	Yes (strong)	Yes	Agrees with ranking in Table 1
9	E1.3 'Information on response to high/low infestation for individual fish and populations'. What information is needed to inform appropriate local management?	No	Yes	In the top 5 for consultants (4) and top 15 for 2 others, and ranked in the bottom half for industry and academia
10	B1.1 'Efficient methods for getting good samples of planktonic salmon lice are required'	No	Yes	Meets Criterion 2, rated high priority by industry (2), and rated weakly by government researchers (33)
11	B1.4 'Development of appropriate sensitivity analyses for coupled hydrodynamic−dispersal models'	Yes (weak)	Yes	Meets Criteria 1 and 2, ranks as 11 overall. Ranks 5 for universities, 9 for government researchers and 7 for policy makers. Overall ranking is reduced, low ranking (34) by industry and indifferent (17) for consultants
13	E1.5 'Climate change impact on lice, predators, and hosts'	Yes (weak)	No	While ranking 13 in overall listing, is in the top 10 sector ranks for consultants (10), government researchers (7) and policy makers (9) and so meets Criterion 1
14	C1.2 'Better empirical data on infective dose (distribution of copepodids in water) including updating the parameter values for lice contact with hosts, and lice attachment rates, including data on lice age, water temperature'	No	Yes	Meets Criterion 2, as ranked by industries (5), university researchers (8) and policy (15), so is ranked 14 in the overall response. Therefore, this is a gap that is at the lower boundary of top priority gaps
23	C1.10 'Investigate ways for farms to avoid cross infecting'	No	Yes	Meets Criterion 2, because it is ranked highly by universities (3). However, with the overall average (23) and the next highest other sector ranking of 12 (policy), this is not supported by other sectors as a priority

'Better tools and methodology in place to help make good choices for sea lice management' (B1.3). Data describing the location, density and population structure of sea lice larvae in the water column are needed for better modelling of the process of infection and these may be issues that can, at least in part, be addressed by relatively small-scale experimental work. This was highlighted as an area for improvement at the workshop as 'Better empirical data on infective dose (distribution of copepodids in water)' (C1.2; Table 3). Fulfilling this gap requires various inputs, including, but not limited to, updating the parameter values for lice contact with hosts; better understanding of sea lice attachment rates; data on age and fecundity; water temperature; and salinity.

A wide range of commercial and bespoke hydrodynamic and particle tracking simulation packages are used within the aquaculture industry. These simulation packages rely on a range of different computational solvers to resolve hydrodynamic currents and the distribution of lice within 3D space. The workshop highlighted the 'Development of appropriate sensitivity analyses for coupled hydrodynamic–dispersal models' as the 11th highest priority overall (B1.4; Table 3). Work to address this is already being undertaken in various formats, for example in the Salmon Parasite Interactions in Linnhe, Lorn and Shuna (SPILLS) project (Moriarty et al. 2023b), as well as independent work by industry and other research organisations (e.g. AquaDEEP; https://aquacultureuk.com/news/bmt-supports-the-scottish-seafood-industry-with-innovative-solutions/). Sensitivity analysis is frequently incorporated into modelling work; however, it often focusses on the impact of specific parameters or the time window simulated (Moriarty et al. 2023b). Some studies have considered the impact of key biological processes (Johnsen et al. 2014, 2016, Sandvik et al. 2020, James et al. 2023), though the impact of such effects also depends on local physical conditions (Myksvoll et al. 2020) and climate change (Sandvik et al. 2021b).

4.3. Exposure of host fish

Further inference on realised impact may be addressed in the 4th highest ranked priority overall (C1.7) in Table 3, 'We need a better understanding of migration path of wild salmon/sea trout through new tracking studies'. Development of acoustic telemetry using tags implanted into salmon and sea trout smolts has enabled several studies to elucidate emigration patterns (Thorstad et al. 2012, 2015, Middlemas et al. 2017, Halttunen et al. 2018, Bjerck et al. 2021, Jensen et al. 2022). Such tags can be detected by strategically placed receivers to estimate the movement rates of individual salmon and hence the times that they are exposed to areas of high lice infestation pressure. Various studies are currently underway to increase the knowledge base on salmonid movements in relation to assessment of lice impacts, including intensive study of small-scale sea trout movements in Loch Torridon (Marine Scotland Science, https://blogs.gov.scot/marine-scotland/2020/03/18/acoustic-tracking-of-salmon-and-sea-trout-in-torridon), and larger-scale movements of salmon through sea lochs and the Minch (https://atlanticsalmontrust.org/our-work/west-coast-tracking-project/). These projects link to other tracking initiatives such as SeaMonitor (www.loughs-agency.org/managing-our-loughs/funded-programmes/current-programmes/sea-monitor/) and COMPASS (https://compass-oceanscience.eu/), which, through using compatible equipment to enable data sharing and collaboration, effectively increases the overall range of coverage by adding to the receiver network.

4.4. Attached lice development and mortality

An explicit call for more observational data on sea lice survival was ranked as the 6th highest priority, 'Increased knowledge on lice survival from field and experimental work for parameter estimation' (B2; Table 3). This is important for better parameterisation of sea lice models and will require large-scale field studies and aquarium-based experimental work. Any experimentation should include observation of variables relating to behaviours of relevance to sea lice modelling, as this will strengthen understanding of lice survival. Each life stage requires different experiments, as the survival of planktonic larval lice in the water is impacted by different processes to that of lice on a host. At present, larval sea lice survival in the water is of most concern to dispersal modellers. Key unknown parameters for modelling are grazing losses of larval lice and temperature effects (which could make mortality rates vary seasonally), whereas others, such as salinity effects on lice survival, are much better described in the existing data. While modelling is important, so too is reducing the sea lice numbers in areas of aquaculture production, which requires effective sea lice control (Treasurer & Bravo 2022). Farm operators are interested in the control of sea lice, where interrupting the life cycle before eggs are produced and larvae released into the environment is preferable for both wild and farmed fish populations. Thus, understanding survival of attached stages is a key priority from this perspective.

4.5. Mobile stages

Having high-quality data for on-farm salmon lice numbers allows modellers to provide an estimate of infection pressure, which can be validated in part using observations of sea lice numbers in the environment, including on wild fish. However, to equate this to realised impact on wild fish populations, more detailed information is required on the wild fish component (migration time and route). This is partially addressed in the 9th highest ranked priority overall (E1.3) 'Information on response to high/low infestation for individual fish and populations. What information is needed to inform appropriate local management?' This requires sampling of wild fish to assess lice variation among fish and populations, coupled with lice dispersal simulation modelling with appropriate and relevant releases to define threshold conditions. An attempt to do so can be found in Bøhn et al. (2022).

Increased data collection in various areas including, but not limited to, those listed above may allow detailed investigation of the lice infestation pressure and associated impacts on fish in the wild. The 3rd highest ranked gap, 'Investigate the impact on host i.e. what threshold of lice in the environment will be deadly for host' (E1.1), highlights that this is important across multiple sectors. This is a complex issue to resolve and requires linking observational data from the field or experiments on sea lice loads and fish health, plus data on larval concentrations in the water (linking larval density to numbers of attached stages on fish and impact on fish health). Currently, the only pragmatic approach to estimating larval concentrations in the wild is using model outputs, as measuring larval lice in the environment is highly labour and capital intensive, and has shown very variable results (Adams et al. 2012, 2021, Skarðhamar et al. 2018). In a recent study carried out in Norway, the sea lice-induced mortality on out-migrating salmon post-smolts was estimated based on calibration of the infestation level on virtual post-smolts against observations of wild post-smolts genetically assigned to their rivers of origin (Johnsen et al. 2021). The sensitivity to thresholds for mortality was investigated by increasing or decreasing these thresholds (Taranger et al. 2015). Impact of attached lice levels on the health of host fish has been investigated previously, see the meta-analysis of Ives et al. (2023).

Sea trout, unlike salmon smolts, can return to rivers or brackish waters to rid themselves of lice. With this difference in behaviour, sea trout need an alternative management option to salmon smolts. Biophysical modelling can be used to predict potential consequences of lice densities on marine feeding space and residence time by developing proxy values for risk assessments. Finstad et al. (2021) describe 2 metrics for this: reduced marine living area and reduced marine feeding time. There is a need for more investigation of lethal and sub-lethal impacts on sea trout for a range of host sizes (Moriarty et al. 2023a).

Some work has been done on linking sea lice infestation pressure to realised mortality of fish in the wild (Vollset et al. 2016a). Until recently, no correlation was found between model estimates of infestation pressure and impact on host as measured in randomised control trials (Vollset et al. 2016a, 2018). However, a new meta-analysis indicates a clearer link between infestation pressure on wild fish and the return rates of released smolts (Vollset et al. 2023). Gaining an improved understanding of linkages between the complex physical and biological processes governing sea lice interactions with wild fish is essential, as is empirical work that allows comparison of lethal and sub-lethal impacts between farmed and unfarmed areas. This issue is further highlighted as an important gap 'Better understanding critical lice thresholds for fish, seasonal effects and interaction between sublethal lice impacts and other stressors' (E1.4, ranked 7th; Table 3). This gap covers a similar theme to E1.1, but extends the scope to more complex interactions that may cause thresholds to vary, and to long-term sublethal effects on wild salmonid populations (e.g. reduced fecundity). These effects may be subtle, complex and long-term, making research into them particularly challenging. When considering the impact on host populations, 'Climate change impact on lice, predators, and hosts' (E1.5) was ranked in the top 10 priorities by at least 3 sectors. Sea lice are sensitive to climate change (Sandvik et al. 2021b) and so it is appropriate that their thermal responses be considered in assessing climate change impacts on aquaculture. This may be through sea lice-specific work or broader climate change work, e.g. the Marine Climate Change Impact Partnership (Murray et al. 2022b). This aspect is important to facilitate the resilience and long-term sustainability of the aquaculture industry in changing climates.

4.6. Gaps that apply across all areas

Some highly ranked gaps are general in tone, and could be applied to many areas of sea lice research and adaptive management. The workshop participants identified the theme of model application as being important, and discussions were centred around the need for agreed methods and determination of how models are to be used for management/regulation (see gaps B1.3, B1.4; Table 3). This is an essential component of any environmental management scheme, and Norway has led the way in generating modelling outputs and ensuring understandable information is available to stakeholders. In other nations, a lack of agreed methodology, or outputs, means that the approach taken differs on a case-by-case basis. Thus, each sector recognised the need for 'Better tools and methodology in place to help make good choices for sea lice management' (B1.3, ranked 2nd highest priority; Table 3). This is a requirement to make model outputs applicable to policy or industry decision-making, and to develop an agreed standard methodology for producing and presenting model outputs. Focused projects with innovative solutions, such as AquaDEEP, are being developed by consulting firm BMT to support the Scottish seafood industry with various aspects of sea lice management, site selection, etc., while innovations such as BarentsWatch (www.barentswatch.no/en/services/) provide the Norwegian seafood industry with real-time information on aspects of fish health, wave forecasting, etc. These projects require dedicated funding and cross-sectoral co-operation, and may focus on ways to make model outputs align with regulatory and planning needs for decision makers, using graphical or other means of presenting models and their uncertainties.

At present, the application of lice population modelling within the Scottish industry is not consistent across companies, which means that operators differ in their capability and implementation of these methods. As the application of these modern simulation techniques becomes more widespread, approaches to frame model outputs to readily support management decisions will develop. For example, models are an important source of information in the Norwegian Traffic Light System (Eliasen et al. 2021). The decision-making process incorporates expert interpretation of data and modelling output. There is less requirement for fundamental research, but more for appropriate networking and possibly future workshops with focused scope and outputs.

The theme of data collection (both *in situ* and experimental) was central to the discussion on key gaps identified by workshop participants, discussed in Sections 4.1 to 4.5 above. Dialogue in breakout groups covered various components of data provision. In particular, pelagic larvae data from wild and experimental sources, on-farm lice data, host-impact data and population impact data were all ranked highly across multiple sectors. High quality, consistent data are a crucial component for any assessment of impact. Long-term monitoring programmes on the effects of sea lice *in situ* on hosts, such as the randomised control trials carried out in Norwegian rivers, provide valuable data on the impacts of farms on wild salmon populations that may help to address the data needs for sustainable aquaculture (Vollset et al. 2016a,b, 2023). A wide-ranging call for 'Improved data sharing and provision' (A2.6) ranked 5th in Table 3. This refers to the general collection and sharing of data to support modelling and management development. It can be addressed by consistent publication of data and associated modelling, and through workshop and conference discussions. Improved collaboration between modellers from different sectors and countries will also support the closing of this gap. Existing research projects, such as the Crown Estate Scotland funded SPILLS (Moriarty et al. 2023b), can provide a space for facilitation of data sharing for model development, while protecting commercially sensitive data. Also, the Scottish Fish Farm Production Surveys (Munro 2022), an annual survey questionnaire sent to all active authorised fish-farming businesses in Scotland since 1979, consistently has a 100% response rate from industry. This highlights willingness to provide data when it is collated in a consistent and systematic manner. Outward-facing graphical user interfaces such as Scotland's Aquaculture Website and Scottish Aquaculture Production Surveys shiny app (https://scotland.shinyapps.io/sg-aquaculture-production-surveys/) have been developed to increase the accessibility of these data.

The selected priority gaps identified are not definitive, and we can continue to look at other objectives for which there is significant interest. The complete rankings of all the statements are shown in Table S2. However, for a prioritisation exercise, the identification of the top research gaps is a valuable step that is inevitably somewhat arbitrary in terms of its lower cut-off point. In the workshop, most participants came from a modelling perspective; therefore, the starting point was how to identify gaps that could improve sea lice modelling and management. However, aquaculture is an example of a complex social–ecological system (Berkes et al. 2000) that has the capacity to adapt to environmental changes. Given that climate emergency is causing major changes in the marine environment, it is important to consider this complexity, potential vulnerabilities and adaptive capacity within a management system (Hughes 2021, Refulio-Coronado et al. 2021).

5. CONCLUSIONS

Much of the modelling of sea lice production, transmission and impact is already well developed and models are widely used in many salmon-producing countries to advise on the management of lice. Models have been developed for Scotland (Salama et al. 2018, Murray & Moriarty 2021, Moriarty et al. 2023a), the Faroe Islands (Kragesteen et al. 2018), Canada (Stucchi et al. 2011), but primarily for Norway (Johnsen et al. 2016, Myksvoll et al. 2018, Sandvik et al. 2020), where they are firmly integrated into salmon lice management (Taranger et al. 2015, Johnsen et al. 2021, Sandvik et al. 2021a). Fundamentally, sea lice models are well described, and the breadth of literature is extensive (Brooker et al. 2018, Moriarty et al. 2024). However, it is clear from the workshop that there are gaps that underlie the use of modelling in sea lice impact mitigation. It determined that tools are being developed to ensure models can be applied and understood when used in sea lice management, and it was recognised that these models need to be adapted to include climate change scenarios.

In summary, the workshop identified that the developments in modelling sea lice should now be underpinned with an improved empirical basis in Scotland. In Norway, better inference could arguably be directly linked to the resource applied to the question, resulting in a much higher researcher headcount working on the topic. The long-standing data collection on wild fish populations and lice infestation has allowed development of a variety of novel statistical methods to inform model validation and wild fish impact. International scientific collaborations will facilitate an improvement in national surveillance and management regimes in areas where data may be lacking. The connections made through this workshop have led to the set up of a technical working group of government researchers among Scotland, Norway and the Faroe Islands: Communication of Knowledge Strength in Sea Lice Dispersal Modelling – Technical Working Group | Marine Scotland Information. This recognises the shared research questions relating to the management of sea lice among salmon-producing countries in the North Atlantic. Broadly, the responses highlighted the need for better empirical data on the infection level, mortality response and key parameters used to drive model predictions (see Pert et al. 2022). Such data are critical for understanding how well models represent realised larval distributions, and for defining host behaviour and sensitivity to infection. Coupled with adequate information sharing and clear guidance on model output application, this will allow the models to be more readily applied to practical problems of sea lice management.

Acknowledgements. The authors thank the reviewers and editors for their comments which have helped to shape the manuscript. The authors acknowledge the support of the MASTS pooling initiative (Marine Alliance for Science and Technology for Scotland) in the completion of the workshop. MASTS is funded by the Scottish Funding Council (grant reference HR09011) and contributing institutions. Participants, speakers and facilitators are also acknowledged for their input and support in the workshop and development of the manuscript. Funding for authors M.M., B.R., J.M., S.I. and A.G.M. was provided under Scottish Government project FW0050. M.L. acknowledges the support of the VSCORES project funded by EPSRC Supergen-ORE, the Smart Efficient Energy Centre (SEEC) at Bangor University part-funded by the European Regional Development Fund (ERDF), administered by the Welsh Government, and the EPSRC METRIC fellowship (grant no. EP/R034664/1). H.C.R. and K.L. were funded through the Crown Estate Scotland SPILLS project (03604). J.P., as part of a PhD studentship, was funded by the Sustainable Aquaculture Innovation Centre and the Data Lab.

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Editorial responsibility: Kate S. Hutson, Nelson, New Zealand
Reviewed by: M. D. Fast and 1 anonymous referee

Submitted: May 10, 2023
Accepted: October 18, 2023
Proofs received from author(s): December 21, 2023