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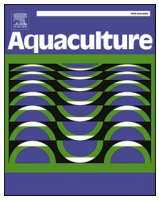

Concerns and research priorities for Scottish farmed salmon welfare – An industry perspective

Timothy Robert Wiese [a,*], Marie Haskell [b], Susan Jarvis [c], Sonia Rey-Planellas [a], Jimmy Turnbull [a]

[a] Institute of Aquaculture, University of Stirling, Stirling FK9 4LA, UK
[b] SRUC (Scotland's Rural College), West Mains Road, Edinburgh EH9 3JG, UK
[c] Global Academy of Agriculture and Food Systems, University of Edinburgh, Midlothian EH25 9RG, UK

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ABSTRACT

The intensification of Scottish salmon farming has been associated with increasing demands for the monitoring and safeguarding of farmed salmon welfare. Continued growth of farm productivity, while avoiding adverse effects on salmon welfare, will require the development of effective welfare assessment tools.

This paper reports on a survey of the Scottish salmon farming industry, which was conducted to understand current salmon welfare concerns and priorities for research. As part of a broader aim for further developing tools for on-farm salmon welfare assessment, a total of 61 individuals working in the Scottish salmon farming industry took part. This survey intentionally focused on industry stakeholders to provide insights into current practices and challenges associated with monitoring and assessing salmon welfare. Participants were recruited through authors' industry contacts, online advertisements, and searches of company websites. In terms of production stages, survey participants believed that the seawater rearing stage is a major area of concern, largely due to the challenges presented by sea lice. Gill health and environmental challenges, mainly relating to water quality, were two other highly ranked welfare concerns. Methods to monitor salmon welfare during husbandry practices, where disturbances and contact with the salmon is unavoidable (particularly during crowding, grading, and interventions), were emphasised as a priority. Although these were identified as the major concerns, the survey indicated that there are other significant welfare concerns specific to each production stage that also require consideration.

Participants highlighted non-invasive, remote, and animal-based welfare measures as important areas for further development for on-farm welfare assessments. Behavioural measures were identified as having the potential to make a major contribution in this context.

This survey presents the first collection of opinions from professionals employed across the Scottish salmon farming industry regarding the current overall state of farmed salmon welfare. This study upholds the importance of using an integrated approach to welfare assessments, and that behavioural measures could play an important role in ensuring these assessments benefit both salmon welfare and farm productivity.

1. Introduction

Farmed salmon welfare is inextricably linked to the farming practices and conditions within the salmon farming industry (FAWC, 2014; Noble et al., 2018). Animal welfare encompasses the physical and emotional state of an animal, its ability to cope with external events, and its overall quality of life (as a cumulative result of those events) (Webster, 2016). Animal welfare is now one of the criteria used by the public when deciding whether a husbandry system's continued use is acceptable on ethical grounds, therefore establishing welfare as a necessary consideration for sustainability (Broom, 2011). In the UK, farmed fish are also protected with a duty of care requirement under the Animal Welfare Act (2006), with the majority of salmon farms (~70%) also being certified by the RSPCA Assured standards (Salmon Scotland, 2020). Additionally, stress and poor welfare are known to increase susceptibility to disease, increase mortality rates, and ultimately lead to poor production

* Corresponding author.
E-mail address: trw1@stir.ac.uk (T.R. Wiese).

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(Schreck and Tort, 2016). For reference, Scottish salmon farming generated a direct economic contribution of £468 million in gross value added in 2018 (Economics, 2020), placing Scotland as the third largest producer of Atlantic salmon in the world (Kenyon and Davies, 2018). Safeguarding salmon welfare should therefore be seen as a priority from a moral, economic, and legal perspective (Animal Welfare Act, 2006; Lafferty et al., 2015).

A detailed understanding of the current state of the industry, with regards to welfare, is then also required to make valid, industry-relevant contributions to farmed salmon welfare. This includes identifying current concerns facing farmed salmon welfare, along with having knowledge of relevant production stages, husbandry practices, and the practicalities of on-farm welfare monitoring and assessment. Such information plays a vital role in developing a framework for realistic improvements of welfare assessments that, when used, do not come at the cost of farm productivity.

Various frameworks have been designed to help form the basis of animal welfare management. The Five Domains model, developing upon the Five Freedoms (Mellor, 2016), was created to provide a more systematic method for identifying potential welfare impacts associated with events/situations (Mellor and Reid, 1994). These impacts were divided into four physical domains (nutrition, environment, health/functional status, behaviour) and one mental domain (overall mental state). Originally designed to assess "compromise" in the welfare state of an animal, recent extensions to the Five Domains now facilitate considerations of positive experiences that may enhance welfare (Mellor and Beausoleil, 2015). It is now widely accepted that emotional affected states are an essential consideration when promoting positive welfare (Dawkins, 2004, 2006; Fisher, 2009; Paul et al., 2020). The development of welfare assessment tools should then not only focus on physical well-being and avoiding 'negative' welfare, but also promoting emotional well-being and 'positive' welfare (Fife-Cook and Franks, 2019).

In order to capture these different aspects of animal welfare, current welfare assessments typically include a set of 'Operational Welfare Indicators' (OWIs) that are believed to be practical and appropriate for detecting changes to the animal's welfare status (Noble et al., 2018). Examples of such welfare assessments include the monitoring program for physical damage / deformities suggested in the RSPCA Assured welfare standards for farmed Atlantic salmon (RSPCA, 2018), and the Salmon Welfare Index Models (SWIM 1.0 and SWIM 2.0) (Stien et al., 2013; Pettersen et al., 2014). Selected OWIs range from environmental (e.g., water temperature, oxygen saturation, salinity) to animal-based indicators (e.g., fin/eye/snout damage, deformities, changes in behaviour, sea lice infestation) (Stien et al., 2013; Noble et al., 2018). As on-farm assessments are limited to including Welfare Indicators (WIs) that are currently practical and affordable to use (Noble et al., 2018), it is likely that the full potential for how we can monitor and safeguard farmed salmon welfare is not yet realised. Stien et al. (2013) anticipate that these assessments, including their SWIM 1.0 model, will need further "upgrading" either through the development of current WIs or inclusion of entirely new WIs.

Identifying where improvements should be made, either within on-farm assessments or the general management of salmon welfare, is no easy feat. Monitoring and safeguarding farmed salmon welfare presents various challenges due to their complex, anadromous life cycle (Marschall et al., 1998). There are rearing conditions, husbandry practices, responsibilities and welfare considerations that are specific to each production stage (Bergqvist and Gunnarsson, 2013; Noble et al., 2018). The total tonnage of seawater fish produced per employee has also increased over 10-fold since 1985 (Ellis et al., 2016). This increasing intensity of production means that work practices, including welfare assessment tools, have to be time-efficient in order to be practical in the commercial production environment. When forming opinions on welfare concerns within this context, on-site experience of the various production stages can provide important perspectives on both the current practices and the relevant challenges that are faced. Professionals employed in salmon farming may potentially have a better understanding of how the processes involved are linked with salmon welfare, particularly with what practical limitations there are when implementing welfare assessments into their farming routines. Including these considerations during any developments of welfare assessment tools or management therefore increases the likelihood of their adoption on-site. Production staff ultimately play an essential role in safeguarding salmon welfare, where they share knowledge and develop and execute routines to protect farmed fish (Størkersen et al., 2021). In this survey, we attempted to access the collective knowledge of these production staff with the assumption that it would provide valuable insights into where farmed salmon welfare can be further advanced.

To date, no study has been conducted which focuses solely on professionals directly employed in Scottish salmon farming to assess their opinions on the state of this industry with regards to salmon welfare. A broader gap-analysis study was carried out on stakeholders from the European aquaculture sector and research community in 2018, with an aim of investigating research priorities for overall farmed fish welfare (Manfrin et al., 2018). However, in this 2018 study, Atlantic salmon were just one of nine species investigated over several countries.

It has been suggested that taking into account different perspectives within a particular industry, and working towards building a clear consensus on future research priorities, provides the best foundation for progressing fish welfare (Manfrin et al., 2018). This approach should be no different when making progress in the monitoring and management of farmed salmon welfare. This could take the form of farm staff either helping to identify key areas of concern, or highlighting any considerations that need to be made when improving on-farm assessments or the overall management of salmon welfare. Hence, this survey aimed to answer the following research questions:

1) Investigate the relative importance that different production stages, husbandry practices, and specific welfare concerns have towards farmed salmon welfare, as perceived by farm staff.

1a) In addition, assess any potential differences in these opinions / perceptions between farm staff with different professional backgrounds.

2) Identify which research priorities have the most potential for further improving the practicality and efficacy of on-farm salmon welfare measures.

Through addressing these research questions, this study will have provided a substantial contribution towards developing the practicality and efficacy of on-farm welfare assessment and management.

2. Materials and methods

2.1. Recruitment and survey development

Ethical approval for the survey development, recruitment methods and final version of the survey was obtained from the General University Ethics Panel (GUEP) at the University of Stirling (Project identification code GUEP (19 20) 858).

Survey development began with a key informant interview with two staff from a local hatchery. The discussion was based on open-ended questions regarding salmon welfare, prepared in advance of the interviews. These questions acted as a starting point for discussing general welfare concerns, which allowed the 1st version of the survey questions to be drafted. The 1st survey draft was then piloted on 10 volunteers across different farming companies during a fish welfare course delivered at the Institute of Aquaculture, Stirling (February 2020). Responses and feedback from this 1st draft were gathered alongside a concurrent literature review, which focused partly on welfare assessment and factors influencing farmed salmon welfare to refine the focus of the final survey.

Following this 1st draft, these initial research questions were formulated for the survey:

- Determine the perceived importance of monitoring salmon welfare in the various production stages.
- Identify major areas of welfare concerns affecting farmed salmon.
- Identify which husbandry practices require the most attention to monitor and safeguard salmon welfare.
- Determine the practicality and efficacy for on-farm use of welfare measures.
- Determine salmon welfare research priorities.
- Identify which farming practices provide suitable opportunities for monitoring salmon welfare.

A 2nd draft, modified on the basis of these research questions, was developed and piloted with volunteers at the Institute of Aquaculture, along with several key informants in the industry ($n = 7$). This 2nd draft was piloted through in-person interviews and online formats (Microsoft Forms) to assess the effectiveness of the different styles and estimate the time for completion. Statistical analysis was not appropriate due to the small sample size, but essential feedback was gathered resulting in further refinement of the survey design.

2.2. Final questionnaire design

The final questionnaire, consisting of 53 questions, was divided into a section on participant's background followed by six question sections (see appendix). Background variables of participants (experience of specific production stage in salmon farming, current job title, and total years of experience in salmon farming) were recorded. Participants were informed about data security, and that any information they provided would remain anonymous. Due to the length of the questionnaire and inclusion of open-ended responses, constant and explicit signposts were used to emphasize the aim of each question section and prevent participants from drifting in their focus.

Section 1 asked participants to compare the relative importance of monitoring salmon welfare across the various production stages. Participants were provided with a list of the different production stages and asked to score each stage on a scale of 1 to 5 in terms of importance (1 = most important, 5 = least important).

Section 2 investigated the major areas of concern facing overall farmed salmon welfare. Section 3 examined which husbandry practices, due to their potential impacts, required the most attention towards monitoring salmon welfare. For these two sections, participants were asked to provide a minimum of 3 of their own examples in order of importance.

Section 4 examined what welfare measures were deemed most appropriate for on-farm use. Participants rated welfare measures, on a scale of 1 to 10, by their practicality and effectiveness (1 = completely impractical / ineffective, 5–6 = somewhat practical / effective, 10 = very practical/effective). 'Practicality' was defined as 'how easy the measure is to use on-site', and 'effectiveness' was defined as 'how much valuable information the measure provides regarding the welfare status of the salmon'. Participants were also able to comment on any practical considerations involved with the on-farm use of these measures. For the purpose of this paper, the term 'welfare measure' merely denotes a certain approach to assessing welfare, and is synonymous to 'welfare indicator'.

Section 5 asked participants to rate a list of research priorities, on a scale of 1 to 10, by the relevance and urgency of their development for on-farm welfare monitoring and assessment (1 = completely irrelevant / Not urgent at all, 5–6 = somewhat relevant / urgent, 10 = extremely relevant / urgent). 'Relevance' was defined as 'How relevant the need is for developing this group of welfare measures to allow for better monitoring and safeguarding of salmon welfare', whereas 'urgency' was defined as 'To what degree does this group of welfare measures need to be developed as soon as possible?'

Section 6 explored which parts of a salmon farmer's daily routine provide the best opportunity for monitoring salmon welfare. Participants were able to select a maximum of 3 husbandry routines from a list of 5 (feeding times, health checks, routine inspections, grading and/or transfer, during video monitoring) as well as add their own response in free text.

Participation was voluntary through an online version of the survey through Microsoft Forms. As of 2020, 1651 staff have been employed in Scottish salmon production (Munro, 2020). Efforts were made to ensure that as many of these staff as possible were at least informed of the opportunity to participate. This process began with colleagues forwarding the survey to potential participants, along with an introductory letter explaining the purpose of the survey. Advertisements and articles for the survey were shared across multiple media outlets, including fish farming news websites, Twitter and Facebook pages, community forums, accreditation sites, and company newsletters. A number of major Scottish salmon farming companies also agreed to support recruitment by forwarding the survey through their mailing lists. Individuals were also recruited directly via LinkedIn. The final survey was conducted from March–December 2020, where a total of 61 individuals directly employed within Scottish salmon production were consulted. Individuals who participated in the pilot studies were not included in the main survey.

2.3. Data processing and analysis

Data from the online survey were consolidated into Microsoft excel (2019), where figures were also produced. Statistical analysis was then carried out using IBM SPSS Statistics 28 for Windows 10.

2.3.1. Quantitative responses

For section 1, weighted scores were created to reflect participants' rankings, which gave more weight to participants' scores indicating a higher priority (e.g., each score of "1" = 5 points, score of "2" = 4 points, "3" = 3 points, etc.). Total weighted scores were then calculated for each production stage. For sections 2 and 3, responses encompassing the same topic of welfare concern or husbandry practice were compiled into categories to allow comparisons to be made between these categories. For example, welfare concerns that included *"AGD"*, "*Gill Disease*", and "*Gill Problems*" were placed into the category "*Gill Health*". Husbandry practices that included "*Treatments*", "*Mechanical / Chemical / Medicinal Treatments*", and "*Vaccinations*" were placed into the category "*Interventions*". The category *'Handling'* included husbandry practices such as *'Crowding', 'Grading', and '(Physical) Handling'*. Welfare concerns that included "Water quality" or "Environmental challenges" formed most of the category 'Environmental challenges'. However, a minority of more specific concerns such as "Tidal throughput", "Water temperature", and "Climate change effects on SW" were also included in this category. Weighted scores were then calculated for each category of responses in the same manner as section 1. For the open-ended responses in sections 2 and 3, weighted scores helped ensure that the order/priority of participants' responses would further reflect their significance, rather than assessing solely by the frequency of mentions. This would help distinguish categories that would have been referred to the same number of times, but at different "rankings" (first vs. last).

For the quantitative responses in Sections 1, 4 and 5, normality and homogeneity of variance were assessed (through histograms and descriptive statistics) before any parametric statistical analyses could be carried out. Log transformations were carried out on data sets to meet statistical assumptions when appropriate, but the degree of skewness for each data set (question sections 1, 4, and 5) did not allow for parametric tests. Therefore, Friedman's tests and Kruskal Wallis tests were used on ordinal and interval data sets respectively to test for significant differences between the categories of responses. Where appropriate (where $p < 0.05$), their corresponding post-hoc tests (Wilcoxon signed ranks test and Pairwise comparisons respectively) were then carried out with a Bonferroni correction. This allowed an assessment to identify where any statistically significant differences lay between categories of responses.

2.3.2. Qualitative responses

Participants' comments regarding practical considerations of using the listed welfare measures on-site were entered into Nvivo qualitative data analysis software (QSR International Pty Ltd., 2020). Certain words or phrases were then categorised into "sub-themes", based on mentions of a specific cost or benefit. These sub-themes were thematically coded into "nodes" to link the comments to their sub-theme. Based on their similar costs or benefits (i.e., whether they impacted farm practices or salmon welfare), sub-themes were grouped into 5 general themes. These were 'Advantages to using welfare measure', 'Practicalities regarding use of equipment & facilities', 'Limitations to using welfare measure effectively', 'Practical limitations to using welfare measure on-site', and 'Negative impacts of using welfare measure'. Separate matrix queries were then carried out against participants' comments for each group of welfare measures, which recorded the number of times each sub-theme/theme was mentioned for every welfare measure. The frequency of themes mentioned for each group of welfare measures helped in comparing the general sentiment of practicality involved between using the different welfare measures on-site.

2.3.3. Relationship between participants' professional backgrounds and their responses

Where there was no clear consensus in responses across all participants, we assessed whether any difference in responses were significantly correlated with participant's professional backgrounds.

For question sections 2, 3, and 6, participants were allowed to list and rank their own open-ended responses. Due to the lack of uniformity in the type of responses between participants, it was not possible to analyse the relationships between responses and backgrounds. Instead, these responses were examined separately for the different cohorts.

For question sections 1, 4, and 5, the homogeneity of responses/ratings between participants allowed for General Linear Models (GLM) to be used to examine potential relationships between the participant's background and the responses they provided. Separate GLMs were carried out for each background variable (specific production experience, current job title, or years of salmon farming experience) and the responses within each question section. Ratings and background variables were included as fixed factors. To avoid pseudo replication in the GLM tests, participant ID numbers were included as a random effect.

3. Results

3.1. Key characteristics of participants

There was considerable diversity between the 61 participants' professional backgrounds (see Fig. 1). Participants ranged from Farmer Trainees to Production Directors, with almost 50% of participants consisting of Farm Managers. Total on-farm experience ranged from <1 to 39 years, with an average of 14.5 years and more than half of the participants having more than a decade of experience in salmon farming. The majority of participants (82%) had some form of experience in the seawater rearing stage, whereas only 57% of participants had some form of freshwater experience. Where GLMs could be carried out, no relationship was found between these background variables (current position, years of experience, and production stage-specific experience) and the participants' responses ($p > 0.05$). Because of this, most question sections are described below with the responses from different cohorts combined.

3.2. Section 1- production stages; relative importance for monitoring salmon welfare

The seawater rearing stage received the highest numerical weighted score of relative importance. Significant differences were also found

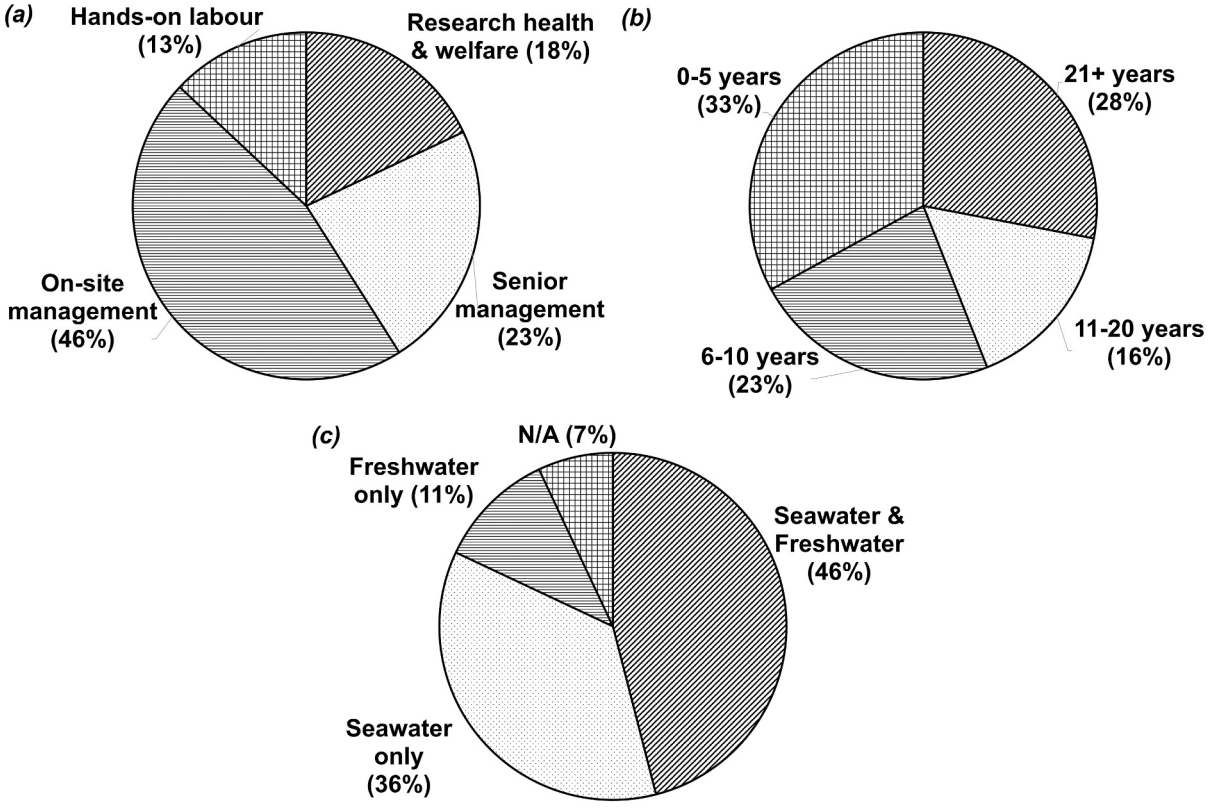

Fig. 1. Breakdown of participants' ($n = 61$) professional backgrounds, including (a) their current job title, (b) total years of experience in salmon farming, and (c) what specific experience they have had across the different production stages. Participants were categorised into 1 of the 4 different groups for each of the 3 different background factors recorded.

between some of these weighted scores ($X^2 = 10.25$, df = 3, $P < 0.05$, see Fig. 2). Seawater rearing and smoltification received comparable weighted scores. Although there were significant differences found between certain production stages, no single stage scored significantly different from all 3 other stages.

3.3. Section 2 - overall farmed salmon welfare concerns

Out of the 10 highest scoring categories of welfare concerns listed (see Fig. 3), 55% of the total weighted score was accounted for by the top 3 scoring categories ('Sea lice', 'Gill health', and 'Environmental challenges'). When listing 'sea lice' as a concern, 9 participants specifically referred to treatments for sea lice as one of their largest overall welfare concerns. A significant drop in the weighted scores followed, with 'Interventions' (largely relating to stress during and after treatments) being the next highest scoring welfare concern. Due to the open-ended nature of responses in this question section, statistical analysis could not be carried out to relate responses to participant backgrounds. However, qualitative differences in weighted scores between welfare concerns were recognised between participants with experience in different production stages (see Table 1).

3.4. Section 3 - husbandry practices requiring the most attention

In contrast to welfare concerns, there was far more of an agreement between participants regarding what husbandry practices they considered required the most attention in monitoring salmon welfare. Out of the 12 categories of husbandry practices mentioned by participants, 68% of the total weighted score was accounted for by the top 2 scoring categories ('Interventions', and 'Handling'). The next highest scoring category, 'Feeding', accounted for 9% of the total weighted score (see Fig. 4).

3.5. Section 4 - on-farm practicality and effectiveness of welfare measures

Numerically, the 4 highest overall scoring categories of welfare measures were '*Disease/health status of fish by prevalence of conditions during routine observations or sampling of individuals*', '*Changes in behaviour (both routine monitoring and husbandry practices)'*, and '*Changes in appetite'*. Significant differences were found between categories in their practicality ratings (Fig. 5; Kruskal Wallis test: H = 143.68, df = 11, $P < 0.001$). There was no significant difference found between the 7 highest numerical scoring categories of welfare measures ($P > 0.05$). Three of these categories, however, had the largest number of significant differences found compared to the remaining 9: '*Disease/health status of fish by prevalence of conditions during routine observations or sampling of individuals*', '*Changes in behaviour (routine monitoring)'*, and '*Changes in appetite after potentially disturbing husbandry practices'*.

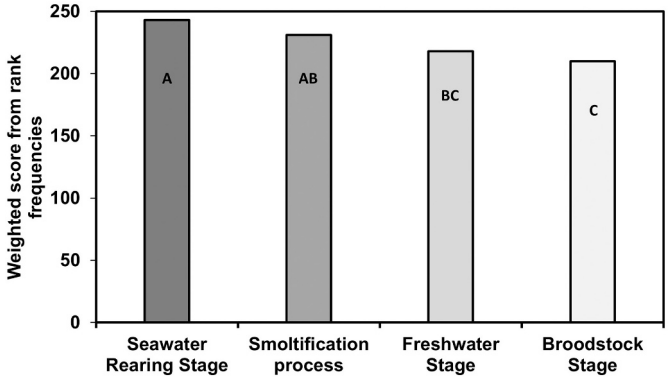

Fig. 2. Relative importance of monitoring and assessing salmon welfare during each production stage, based on weighted scores provided by participants (n = 61). Production stages without matching letters indicate a statistical difference ($P < 0.05$).

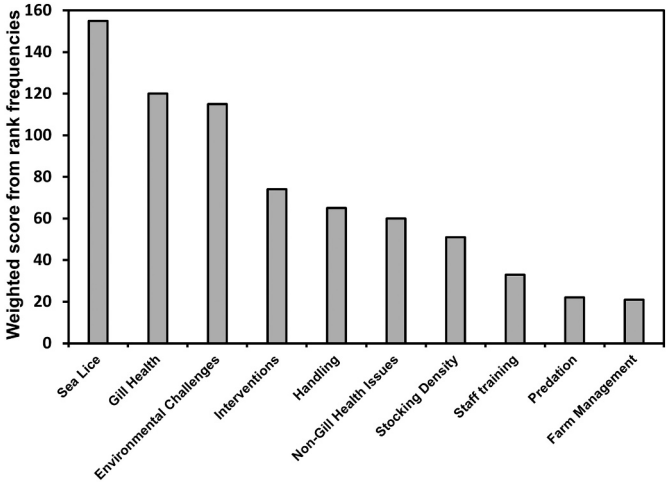

Fig. 3. Top 10 ranked categories of overall farmed salmon welfare concerns (out of 16 categories listed), based on weighted scores provided by participants (n = 61). The open-ended nature of this question meant that statistical differences between categories could not be tested for.

Table 1
Top 3 highest and lowest scoring welfare concerns, depending on participant's production stage-specific experience.

Production stage-specific experience:	Highest scoring welfare concerns:	Lowest scoring welfare concerns:
Freshwater only	Interventions, Handling, Stocking density	Sea lice, Predation, Farm management
Seawater only	Sea lice, Gill health, Environmental challenges	Predation, Interventions, Farm management
Both Freshwater & Seawater	Environmental challenges, Sea lice, Gill health	Farm management, Predation, Stocking density

Significant differences were found between categories in their effectiveness ratings (Fig. 6; Kruskal Wallis test: H = 79.57, df = 11, $P < 0.001$). There was no significant difference found between the 9 highest scoring categories of welfare measures ($P > 0.05$). The 3 aforementioned categories, along with '*Changes in behaviour (husbandry practices)'* were the highest numerical categories by effectiveness. These 4 categories had the largest number of significant differences found compared to the remaining 8 categories. Pairwise comparisons showed that, for practicality or effectiveness, no single category of welfare measures scored significantly differently from all the other 11 categories.

3.5.1. Participants' practical considerations for on-farm use of welfare measures – thematic analysis

A total of 384 comments were received regarding various considerations about using the listed welfare measures on-site (see Fig. 7). Comments on how these measures were either '*Already taken as part of farming routine'* or '*Easy to use and monitor on a consistent basis (if needed)'* accounted for 88 of the 96 statements regarding the '*Advantages to using welfare measures'*. With the exception of '*Assessing welfare by presence/absence of enrichment'*, these comments were made at least once for all other welfare measures listed. Out of the 8 remaining comments regarding advantages, 5 were exclusive to measures involved in '*Changes in behaviour'*, stating how such measures could act as early warning signs for arising issues. Conversely, 26 comments were made on '*Practicalities regarding use of equipment & facilities'*, all relating to concerns about the necessity for specialist equipment to either facilitate the use of, or even carry out, the listed welfare measures. Of the 188 comments regarding potential '*Limitations to using welfare measures effectively'*, 87 stated that

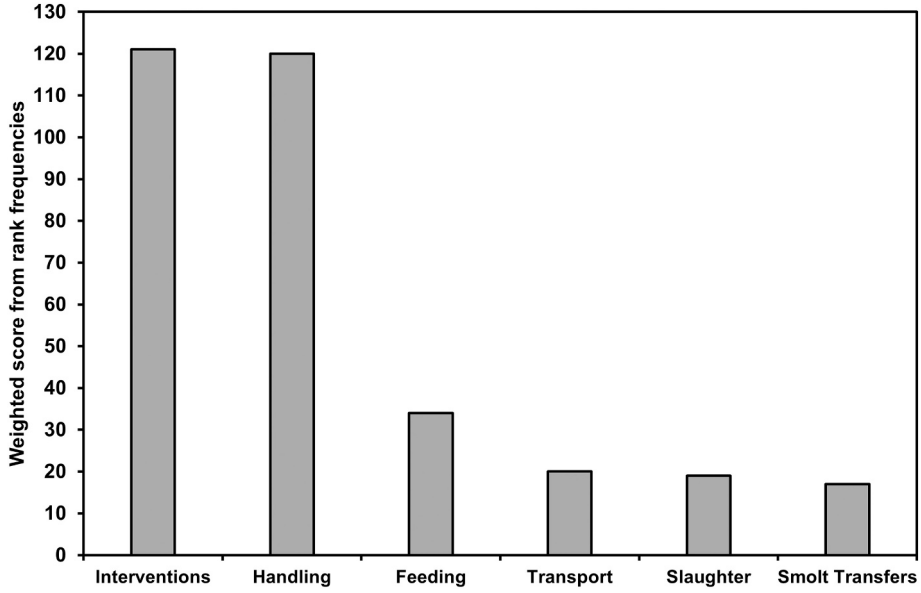

Fig. 4. Top 6 ranked categories of husbandry practices (out of 12 categories listed) that participants believed require the most attention in terms of monitoring salmon welfare, based on weighted scores provided ($n = 61$). The open-ended nature of this question meant that statistical differences between categories could not be tested for.

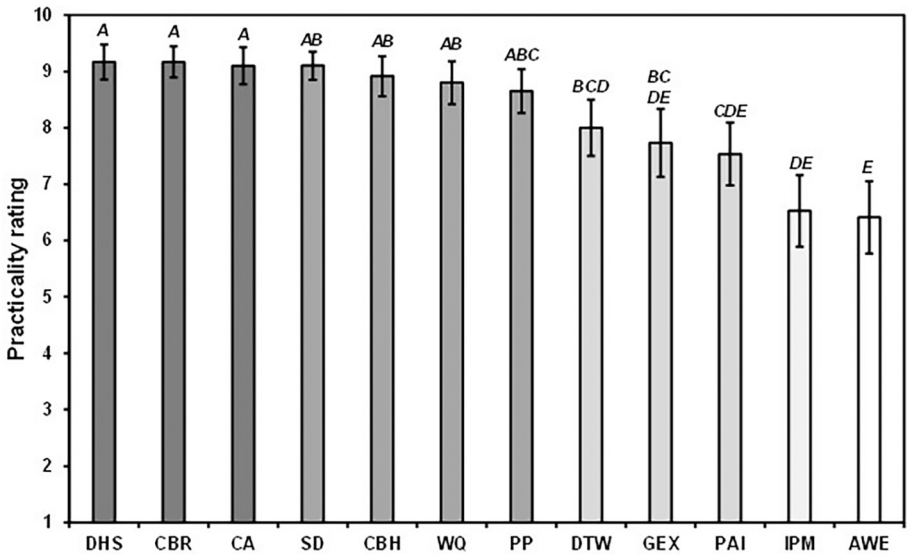

Fig. 5. Mean practicality ratings of the 12 ranked categories of salmon welfare measures listed, based on ratings provided by participants ($n = 60$). Error bars show 95% confidence intervals. Categories with no matching letters above the error bars indicate a statistical difference ($P < 0.05$).
DHS, 'Disease/Health status by prevalence of conditions; CBR, 'Changes in behaviour (routine monitoring)'; CA, 'Changes in appetite'; SD, 'Stocking density'; CBH, 'Changes in behaviour (husbandry practices)'; WQ, 'Water quality'; PP, 'Production parameters'; DTW, 'Duration of time out of water'; GEX, 'Grading by external abnormalities'; PAI, 'Presence of acute injuries'; IPM, 'Individual physiological measures of stress'; AWE, 'Assessing welfare by enrichment'.

'*the quality of information depends on the training and motivation of staff involved*'. Such comments were made across all measures, but particularly on those assessing physiological measures of stress, external abnormalities, and changes in behaviour during monitoring and husbandry practices (17, 11, 12, and 10 comments made respectively).

Another 32 comments regarding limitations involved the difficulty of '*ensuring a representative sample size*'; these comments were made at least once for all welfare measures that involved assessing the salmon directly. Other limitations mentioned included '*inherent subjectivity in the use of the welfare measure*', '*welfare measure cannot be used in isolation*', and difficulties in '*using the welfare measure to accurately reflect the salmons' welfare status*'.

There were 53 comments made on the '*Practical limitations to using welfare measures on-site*'. Twenty-nine of these stated that certain measures '*may require frequent monitoring, which could be costly or time consuming*'. The majority of the 29 comments (17) were specific to assessing physiological measures of stress, external abnormalities, and acute injuries during husbandry practices. Another 22 comments on practical limitations stated that the use of various measures '*requires good weather*'. Out of the 21 comments regarding potential '*Negative impacts of using welfare measures*', 15 were made about welfare measures that were likely to require invasive sampling to carry out (assessing physiological measures of stress, external abnormalities, and assessing disease/health status). All 15 of these comments specifically involved concerns about there being a '*Significant potential for damage, stress, or mortality to be caused*' to the salmon as a result of using these welfare measures.

3.6. Section 5 - relevance and urgency for R&D of welfare assessments

No significant differences were found between the relevance ratings of the different research priorities (Fig. 8; Kruskal Wallis test: $H = 6.56$, $df = 4$, $P = 0.161$). With regards to urgency ratings, one significant difference was found between the research priority '*Developing welfare*

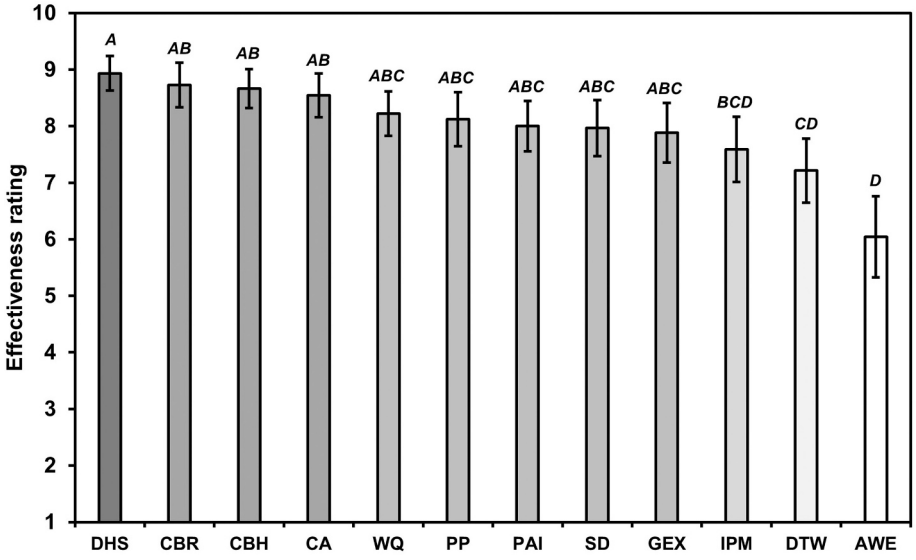

Fig. 6. Mean effectiveness rating of the 12 categories of salmon welfare measures listed, based on ratings provided by participants (n = 59). Error bars show 95% confidence intervals. Categories with no matching letters indicate a statistical difference ($P < 0.05$).
DHS, 'Disease/Health status by prevalence of conditions; CBR, 'Changes in behaviour (routine monitoring)'; CBH, 'Changes in behaviour (husbandry practices)'; CA, 'Changes in appetite'; WQ, 'Water quality'; PP, 'Production parameters'; PAI, 'Presence of acute injuries'; SD, 'Stocking density'; GEX, 'Grading by external abnormalities'; IPM, 'Individual physiological measures of stress'; DTW, 'Duration of time out of water'; AWE, 'Assessing welfare by enrichment'

indicators that allow for remote monitoring of salmon' and *'Developing more fish/user friendly methods for welfare indicators which currently require sampling of the fish'* (Fig. 8; Kruskal Wallis test: H = 13.374, df = 4, $P = 0.01$.

3.7. Section 6 - farming routines most practical for monitoring salmon welfare

Out of all routines, 'Health checks' and 'Feeding times' accounted for 61% of the total routines mentioned as being the most practical as an opportunity to assess welfare (see Fig. 9). In comparison, 'Routine cage/tank inspection', 'Video monitoring', and 'Grading and/or transfer' collectively accounted for 36% of the routines selected. Any mentions of routines by participants outside of the list provided ('Other') accounted for just 4% of total routines selected. Any mentions of routines by participants outside of the list provided ('Other') accounted for just 4% of total routines selected.

4. Discussion

Ascertaining what best approaches there are to the assessment and management of on-farm salmon welfare issues is, ultimately, one of the first steps towards addressing these issues. The results from this survey represent opinions on this matter from professionals across various production stages within the Scottish salmon farming industry. Owing to the sample size, this survey cannot claim to be representative of the industry's views as a whole. However, the variety of farming experience of the participants involved is an encouraging sign that the survey has succeeded in obtaining valuable insights from a diverse range of professionals directly involved with farmed salmon. Despite such variation in experience between participants, and some differences on what constitutes the largest overall concerns facing farmed salmon, there was a strong consensus on what areas of welfare monitoring and research priorities the industry must focus on to safeguard the future of farmed salmon welfare.

When participation in a survey is voluntary, it is important to reduce recruitment bias wherever possible (Fox et al., 2009). From the combination of the various recruitment methods, particularly with some of the largest salmon producers in Scotland agreeing to contact their entire production team to encourage participation, a reliable assumption can be made that as many of the Scottish salmon production staff as possible were at least informed of the opportunity to participate. In terms of reducing any systematic bias introduced by those individuals who chose to participate, the variety of professional backgrounds involved in the survey also suggests that this bias was limited.

4.1. Key areas of concern within salmon farming

Seawater rearing received one of the highest scores of relative importance, and this was not solely explained for by the largest proportion of respondents having seawater experience. Participants with only freshwater experience still scored the seawater rearing and freshwater stage almost identically (<1% difference in total weighted score). The relative importance of salmon welfare during seawater rearing may be partly due to this stage representing the largest portion of the salmon's overall life cycle (Superior Fresh, 2019; Scottish Sea Farms, 2021). There are also key welfare concerns specific to this stage which may further explain the participants' views on its importance. Sea lice, which received the highest numerical weighted score of welfare concerns in this survey, are also present exclusively in this production stage. Sea lice have a longstanding reputation as one of the largest welfare risks to farmed salmon in the marine environment, and as one of the most damaging parasites to the salmonid farming industry worldwide (Costello, 2006; Brown et al., 2008). Infestations are known to cause physical damage to the host's skin, potentially leading to reduced appetite and growth, as well as increased physiological stress through osmoregulatory dysfunction (Thorstad et al., 2015; Abolofia et al., 2017). A further indirect consequence of sea lice are delousing operations, particularly through mechanical and thermal methods, which have been known to impact salmon welfare and, in some cases, lead to increased mortality rates (Overton et al., 2018, 2019). This concern was also reflected by 9 of the participants in this survey.

Regardless of how important participants believe that the seawater rearing stage is for overall salmon welfare, it is important to recognise that each production stage listed still scored relatively highly in terms of importance by each cohort of participants. Therefore, similar consideration must still be given to salmon welfare during all production stages.

Gill health was the second largest concern for welfare, concurring with the growing concern over poor welfare and increasing losses related to gill disease in Atlantic salmon worldwide (Mitchell and Rodger, 2011; Gjessing et al., 2017). A monthly mortality report by the SSPO in June (SSPO, 2021) showed that where a Scottish farm listed a mortality rate of 3.4% or higher, it was linked to either gill health, gill management (e.g., treatments for gill health) or viral challenges. The three highest mortality rates listed (9.5%, 7.2%, and 5.7%) were all related to gill health issues. Gills are naturally exposed to the constantly

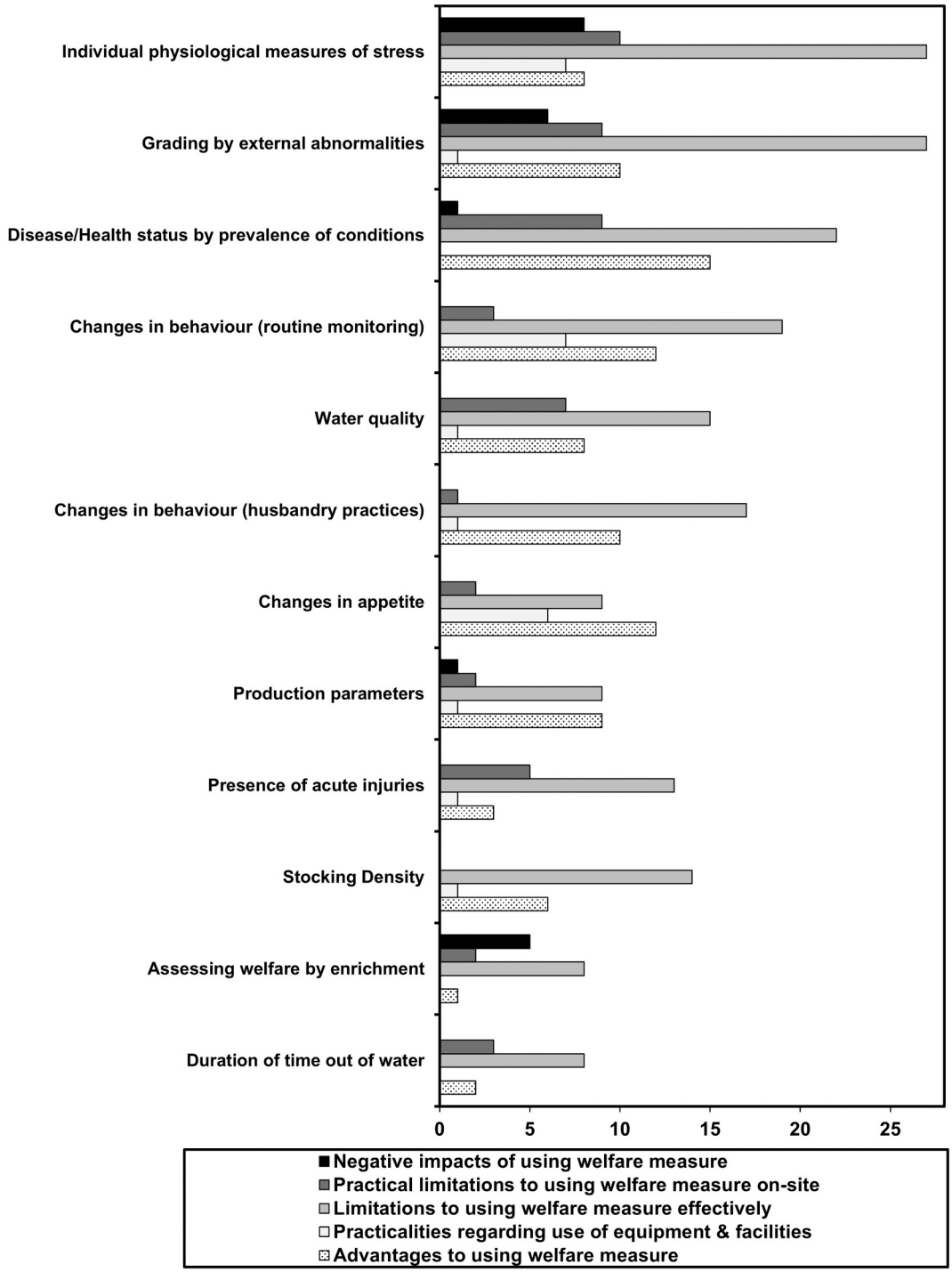

Fig. 7. Coding frequency for main themes of practicality mentioned by participants (n = 53) when given the option for providing comments on the practical considerations of the welfare measures listed.

changing physico-chemical properties of the surrounding water, as well as to numerous aetiological agents such as algal blooms, jellyfish swarms, viruses, and bacteria that can compromise gill health (Steinum et al., 2010; Baxter et al., 2011; Mitchell and Rodger, 2011; Rodger et al., 2011; Gjessing et al., 2017). 'Complex gill disease' has also become a growing issue for farmed salmon, particularly in the marine environment over the past few years (Herrero et al., 2018; Boerlage et al., 2020).

The degree of concern relating to environmental challenges was comparable to that of gill health. In a welfare risk assessment carried out for EFSA, abiotic hazards (mainly water quality) were a concern across all life stages of Atlantic salmon (Brown et al., 2008). Welfare concerns relating to environmental challenges in both this survey and the EFSA risk assessment mostly included concerns about water quality, as well as the issue of ensuring that appropriate enclosures were used and maintained. This includes selecting suitable site locations for sea cages. With sea cages being exposed to uncontrollable environments, water currents and low water O_2 content have previously been identified as the abiotic hazards with the most potential to affect the physiology, behaviour, and ultimately welfare of farmed salmon (Brown et al., 2008; Hvas et al.,

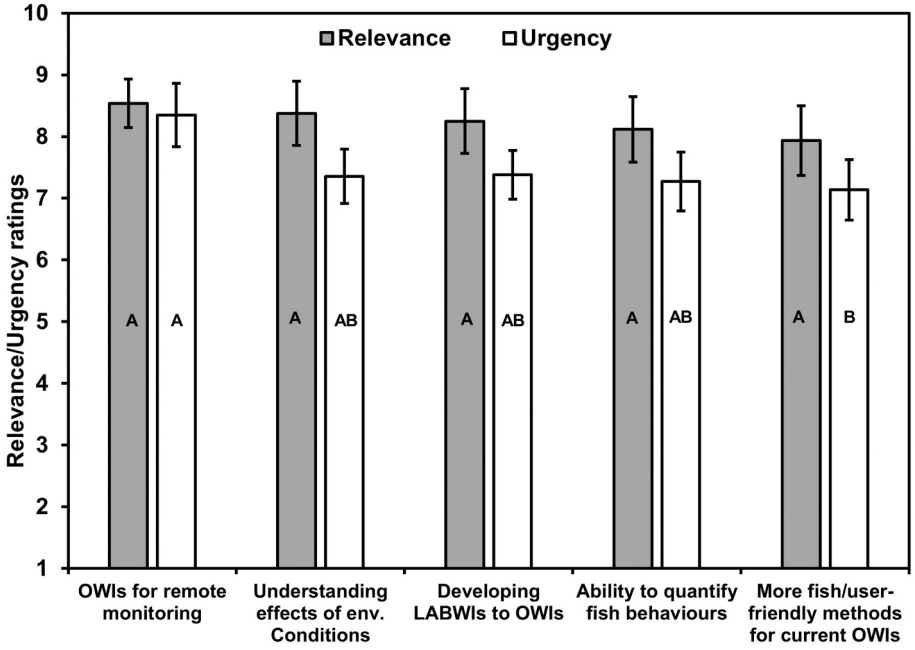

Fig. 8. Mean relevance and urgency ratings of the 5 research priorities listed, based on ratings provided by participants ($n = 59$). Error bars show 95% confidence intervals. Research priorities with no matching letters indicate a statistical difference ($P < 0.05$), with relevance and urgency ratings being compared separately. LABWI = Laboratory-Based Welfare Indicator, OWI = Operational Welfare Indicator.

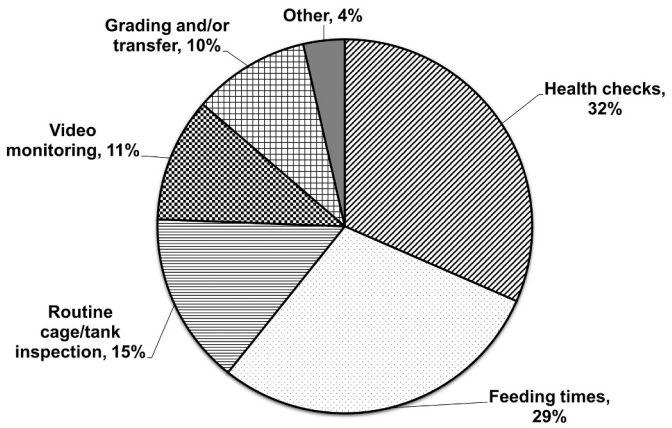

Fig. 9. Most suitable opportunities for monitoring welfare measures on site during a farm's daily routine, based on the relative proportion of times they have been mentioned by participants ($n = 60$) as a suitable opportunity for monitoring certain welfare measures on-site.

2021).

4.1.1. Freshwater production staff highlighted the importance of interventions & handling

Responses regarding welfare concerns were the most varied in this survey when compared against participants' experience in specific production stages. Considering that the survey had significantly more participants with seawater experience, the overall scores for welfare concerns may have represented concerns that can be found more within seawater rearing. Therefore, concerns listed by participants with only freshwater experience have been considered separately.

In contrast to other participants, freshwater production staff ranked sea lice as one of the three lowest concerns for salmon welfare. Since sea lice exclusively affect the seawater stage, staff lacking first-hand experience in dealing with this parasite may not appreciate the true extent of their impacts. Environmental challenges were also far less of a concern to freshwater staff, potentially due to environmental parameters being easier to control in freshwater systems compared to seawater cages (Brown et al., 2008). Instead, interventions (largely relating to treatments) of salmon were their highest overall welfare concern, followed by handling and stocking density. The immediate impacts from invasive events such as treatments, vaccinations, and handling may be more visible to freshwater production staff, and could potentially explain why they ranked these welfare concerns much higher.

The importance of interventions and handling was also reflected in which husbandry practices participants believed required the most attention in terms of monitoring salmon welfare. Across all groups of participants, interventions and handling were of the highest priority. Various handling procedures can lead to acute stress, injury, weakened osmoregulatory abilities, and increased disease incidence in salmon (Ashley, 2007; Brown et al., 2008; Powell et al., 2015). Fish suffering from disease or injury are already under physiological stress, and are therefore susceptible to the cumulative stress that can occur during certain treatments (Marcos-López et al., 2017). Careful monitoring of salmon welfare is therefore required during interventions and any handling prior to these practices must be minimised due to the high risk of impact to health and welfare at these times.

4.1.2. Discrepancies in perceived importance of husbandry practices and concerns; staff knowledge, staff training, slaughter, and transport

The importance of staff training and biosecurity for salmon welfare across all life stages has been frequently mentioned in previous studies (Brown et al., 2008). Through interviews of employees at various company levels, Størkersen et al. (2021) concluded that daily tasks on-site were considered to make the most positive contribution to fish welfare. Production staff play an important role by sharing knowledge, developing, and executing routines to protect farmed fish (Størkersen et al., 2021). However, participants in this survey were more concerned with the issues mentioned above (sea lice, gill health, environmental challenges, risks associated with interventions) than with staff training and farm management. This discrepancy may partially be the result of participants being limited to listing only 3–5 of their most significant welfare concerns *facing* salmon welfare. Rather than dismissing the

importance of training and management, these may have simply been less important to the participants than animal-based concerns that directly affect the salmon. In addition, handling and environmental challenges potentially overlap with concerns relating to staff training and farm management, which could further explain their underrepresentation in these results.

Overall, participants in this survey also scored transport and slaughter far lower than interventions, handling, or even feeding. This is in stark contrast to the literature, which have often considered processes relating to slaughter and transport as serious threats to welfare (Poli et al., 2005; Erikson et al., 2016). Participants in this survey may have treated any of the handling, crowding, or grading that occurs prior to these two practices as separate to the actual slaughter/transport process themselves. The procedures immediately prior to slaughter/transport could potentially account for a large portion of the concern associated with them. This difference in opinion may also be partially explained by the fact that transport and slaughter represent a relatively small fraction of the salmon's overall life cycle. In comparison, examples of interventions or handling can occur many times over, leading to a larger cumulative effect on the salmon's overall welfare status.

Variation was also found in welfare concerns between participants with different farming experience, and this in turn may be related to the specific challenges faced in each stage of production (Noble et al., 2018). When concerns vary between stakeholders and even within the industry, identifying welfare priorities becomes complex. Although certain welfare concerns have been identified in this survey as the "largest" concerns by participants (e.g., sea lice, gill health, environmental challenges, risks associated with interventions), this serves mainly to inform on some of the major concerns present in Scottish salmon farming. At the very least, equal consideration must still be given to any of the welfare concerns from each production stage and husbandry practice for which participants have repeatedly mentioned.

4.2. Welfare monitoring and assessment - key areas of focus

4.2.1. Suitability of on-farm welfare measures for non-invasive, remote monitoring

Participant responses indicated that, for the majority of welfare measures, there was no difference between their practicality or effectiveness. No single category was statistically different from all remaining 11 categories in either rating. However, welfare measures relating to monitoring changes in behaviour, appetite, or the disease/health status of the salmon were found within the highest scoring group of categories. Collectively, these categories of welfare measures had significant differences with the largest number of other categories in both practicality and effectiveness ratings. Out of the categories listed, these welfare measures also constitute a broader class of animal-based, non-invasive measures that can be monitored remotely.

While the ratings produced some quantifiable indication of how appropriate these measures are for on-farm use, additional comments gave participants' the opportunity to give further detail on this topic. With the exception to assessing welfare by the presence/absence of enrichment, all remaining measures listed were mentioned at least once as having the advantage of either already being recorded on-site or able to be readily measured as part of the farming routine. This is reflected in the high practicality scores across the majority of measures listed. The group of animal-based, non-invasive measures that can be monitored remotely continued to maintain a more positive sentiment around their use on-site. More than half of the remaining comments regarding advantages to using these welfare measures were exclusive to monitoring changes in behaviour. Participants also believed that the use of these measures posed fewer risks for salmon welfare compared with other animal-based measures. This is in accordance with the previously mentioned sentiment (in 4.1.1) that handling of the salmon must be minimised. Additionally, monitoring changes in behaviour may also provide early warning signs for issues that arise on-site (Huntingford et al., 2006; Oppedal et al., 2011). When compared with other direct animal-based measures of salmon welfare, the frequent monitoring that may be required for non-invasive measures (monitoring changes in behaviour or appetite) were seen as not being as costly or time-consuming.

Participants' responses suggest that welfare measures that involve handling or invasive procedures of the salmon (e.g., sampling individuals for physiological measures of stress) should be limited, unless they are an essential part of the production process. Regular health checks are now regarded as a crucial aspect of farming routines for protecting health and welfare for salmon (Rey et al., 2019; RSPCA, 2021). This likely explains why participants deemed health checks as one of the most suitable opportunities for monitoring welfare, due to the valuable welfare-relevant information they already provide. As health checks are already required, they provide an opportunity to use valuable animal-based measures (e.g., fin damage, sea lice infestation, body/skin condition) without causing unnecessary stress. For all animal-based welfare measures, however, participants noted a number of limitations. Any measures involving a direct assessment of the salmon face the challenge of obtaining a representative sample of the fish. Specialist equipment may also often be required. The most frequently mentioned limitation when using these animal-based measures was their dependency on the motivation and training of staff. This is in contrast to the low ratings that staff knowledge and training received as an overall welfare concern. This suggests that, while participants appreciated the importance of staff training and knowledge relating to monitoring and safeguarding salmon welfare, they did not believe that this was currently a major concern to farmed salmon welfare. Participants also recognised the importance of using multiple measures to avoid the subjective bias that may arise from any single measure (Sneddon et al., 2003).

Practicality and effectiveness ratings did not provide any information on the need for further developments. In order to identify areas of welfare assessment that are both appropriate for on-farm use, and require further development, these ratings have to be considered with the identified research priorities.

4.2.2. Key areas of development in welfare monitoring and assessment

All research priorities were deemed equally relevant for improving the monitoring and safeguarding of salmon welfare. Given their equal relevance, they can only be differentiated by their urgency ratings. The development of remote monitoring was seen as the most urgent, which may have been highlighted to participants by the restricted access to sites for farm staff during the 2020 COVID-19 pandemic (Murray et al., 2021). These restrictions would have likely had a significant impact on the degree of active surveillance that was possible during the lockdown period, with in-person audits being replaced with virtual assessments for 2 months (FishFarmingExpert, 2020; Murray et al., 2021). Relying on virtual assessments could hinder the ability for certification bodies to safeguard salmon welfare due to the limited amount of information that can be obtained. These events have likely demonstrated the necessity of having welfare measures that can be used without requiring staff on-site. This would include passive, non-invasive measures that could be recorded through the use of remote sensors, or video/acoustic monitoring (Føre et al., 2011; Brijs et al., 2021; Bell et al., 2022). High urgency ratings for remote monitoring as a research priority suggest that measures currently available may not yet be developed enough to fulfil this role.

4.2.3. Improving non-invasive, animal-based and remote welfare monitoring on-site – a case for behavioural welfare measures

Behavioural measures were identified as a promising candidate for non-invasive and remote welfare monitoring. The potential benefits of their implementation into practical farm-management strategies have already been acknowledged (Dawkins, 2003; Huntingford et al., 2006; Oppedal et al., 2011; Martins et al., 2012; Miller et al., 2020; Barreto et al., 2021; O'Donncha et al., 2021). Although direct measures of

animal welfare tend to be the most informative, their use often comes with the cost of either being time-consuming, technically complex, or causing disturbances to the fish (Huntingford et al., 2006). In contrast, behavioural indicators are one of the few animal-based measures that benefit from being comparatively fast and easy to observe (Huntingford et al., 2006; Martins et al., 2012). Effective inclusion of behavioural indicators with other evidence of an animal's health could help to identify pre-clinical signs of health problems (Dawkins, 2003). Improving the ability for farm staff to recognise and prevent problems before they can severely impact stock is beneficial not only to the fish, but for farm production. Further innovations in camera technology and image processing may allow for significantly improved on-farm surveillance of salmon behaviour (Saberioon et al., 2017).

While video monitoring accounted for just 11% of the routines mentioned as most suitable for monitoring salmon welfare, it is important to consider that camera systems are already routinely used to monitor feeding and swimming behaviours in commercial aquaculture facilities (Pinkiewicz et al., 2011). Feeding times, which accounted for 29% of the routines mentioned, also provide opportunities for assessing behavioural patterns either through video or acoustic devices (Martins et al., 2012; Hassan et al., 2019). It is not clear if scientific research could ever provide a robust measure of salmon's subjective experiences (Mason and Mendl, 1993; Fraser et al., 1997; Broom, 1998; Dawkins, 1998; Jarvis et al., 2021). Behavioural analysis is currently the only tool which provides any relevant insights (Turnbull and Kadri, 2007; Folkedal et al., 2012; Martins et al., 2012; Zhao et al., 2018; Hassan et al., 2019). A promising approach for gaining such insights is Qualitative Behavioural Assessment (QBA), which describes and quantifies expressive qualities of an animal's dynamic body language using qualitative behavioural terms (Jarvis et al., 2021). There are, however, risks of misinterpreting changes in behaviours (Weary and Fraser, 1995; Dawkins, 2003). Welfare assessments should therefore not rely solely on behaviour or any single welfare measure, and rather use an integrated approach of various measures (Jarvis et al., 2021).

5. Conclusion

In terms of key areas of focus for salmon welfare, seawater rearing and sea lice are of particular importance. Gill health and environmental challenges (mainly relating to water quality) are two other key welfare concerns perceived to threaten salmon welfare. Participants emphasised the importance of monitoring salmon welfare during husbandry practices where contact and disturbance to the fish is unavoidable, particularly during handling and interventions. Further reflecting the importance of minimised handling, this survey has identified that non-invasive, animal-based welfare measures (particularly those involving behavioural assessment) as one of the most opportune areas for further developing the practicality and efficacy of on-farm salmon welfare assessments.

The results from this survey have also exemplified that no single measure allows for a comprehensive assessment of farmed salmon welfare, and that there are significant welfare concerns which can be unique to a husbandry stage or practice. Protecting farmed salmon welfare will therefore depend on the industry's ability to address the major concerns specific to each of these. This reflects the importance of using an integrated approach to welfare assessments that combines behavioural, physiological, and production-based parameters. Future research should examine potential relationships between behavioural and physiological welfare measures to help validate the use of behavioural assessments when interpreting the welfare status of salmon.

The economic and social aspects of any industry are well established dimensions of its sustainability (UN General Assembly, 2015). With regards to the Scottish salmon farming industry, the public's perception of welfare issues are central to both of these pillars. This survey has helped provide direction for further developing the practicality and efficacy of on-farm welfare assessment and management, and has therefore contributed one step further to advancing farmed salmon welfare. As a result of aiding social acceptance through improved salmon welfare, this work will further add to the potential sustainability of salmon aquaculture.

CRediT authorship contribution statement

Timothy Robert Wiese: Conceptualization, Visualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Investigation, Formal analysis. **Marie Haskell:** Supervision, Conceptualization, Visualization, Methodology, Writing – review & editing, Validation. **Susan Jarvis:** Supervision, Conceptualization, Visualization, Methodology, Writing – review & editing, Validation. **Sonia Rey-Planellas:** Supervision, Conceptualization, Visualization, Methodology, Writing – review & editing, Validation. **Jimmy Turnbull:** Supervision, Conceptualization, Visualization, Methodology, Writing – review & editing, Validation.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2023.739235.

References

Abolofia, J., Asche, F., Wilen, J.E., 2017. The cost of lice: quantifying the impacts of parasitic sea lice on farmed Salmon. Mar. Resour. Econ. 32 (3) https://doi.org/10.1086/691981.

Animal Welfare Act 2006, 2006. Animal Welfare Act 2006, The National Archives. Available at: https://www.legislation.gov.uk/ukpga/2006/45/contents (Accessed: 27 June 2022).

Ashley, P.J., 2007. Fish welfare: current issues in aquaculture. Appl. Anim. Behav. Sci. 104 (3–4), 199–235. https://doi.org/10.1016/j.applanim.2006.09.001.

Barreto, M.O., et al., 2021. Emerging indicators of fish welfare in aquaculture. Rev. Aquac. 1–19. https://doi.org/10.1111/raq.12601 (December 2020).

Baxter, E.J., et al., 2011. Gill damage to Atlantic Salmon (Salmo salar) caused by the common jellyfish (Aurelia aurita) under experimental challenge. PLoS One 6 (4), 4–9. https://doi.org/10.1371/journal.pone.0018529.

Bell, J.L., et al., 2022. Environmental monitoring tools and strategies in salmon net-pen aquaculture. Integr. Environ. Assess. Manag. 18 (4), 950–963. https://doi.org/10.1002/ieam.4622.

Bergqvist, J., Gunnarsson, S., 2013. Finfish aquaculture: animal welfare, the environment, and ethical implications. J. Agric. Environ. Ethics 26 (1), 75–99. https://doi.org/10.1007/s10806-011-9346-y.

Boerlage, A.S., et al., 2020. Epidemiology of marine gill diseases in Atlantic salmon (Salmo salar) aquaculture: a review. Rev. Aquac. 12 (4), 2140–2159. https://doi.org/10.1111/raq.12426.

Brijs, J., et al., 2021. Bio-sensing technologies in aquaculture: how remote monitoring can bring us closer to our farm animals. Philos. Trans. R. Soc. B 376 (1830). https://doi.org/10.1098/rstb.2020.0218.

Broom, D.M., 1998. Welfare, stress, and the evolution of feelings. In: Advances in the Study of Behavior, pp. 317–403.

Broom, D.M., 2011. A history of animal welfare science. Acta Biotheor. 59 (2), 121–137. https://doi.org/10.1007/s10441-011-9123-3.

Brown, D.M., et al., 2008. Animal welfare aspects of husbandry systems for farmed Atlantic salmon - scientific opinion of the panel on animal health and welfare. EFSA J. https://doi.org/10.2903/j.efsa.2008.796.
Costello, M.J., 2006. Ecology of sea lice parasitic on farmed and wild fish. Trends Parasitol. 22, 475–483. https://doi.org/10.1016/j.pt.2006.08.006.
Dawkins, M.S., 1998. Evolution and animal welfare. Q. Rev. Biol. 73 (3), 305–328.
Dawkins, M.S., 2003. Behaviour as a tool in the assessment of animal welfare. Zoology 106 (4), 383–387. https://doi.org/10.1078/0944-2006-00122.
Dawkins, M.S., 2004. Using behaviour to assess animal welfare. Anim. Welf. 13 (SUPPL), 3–7.
Dawkins, M.S., 2006. A user's guide to animal welfare science. Trends Ecol. Evol. 21 (2), 77–82. https://doi.org/10.1016/j.tree.2005.10.017.
Economics, B., 2020. Aquaculture Sector - Wider Economic Impacts: Estimates. Available at: https://www.gov.scot/publications/estimation-wider-economic-impacts-aquaculture-sector-scotland/.
Ellis, T., et al., 2016. Trends during development of Scottish salmon farming: an example of sustainable intensification? Aquaculture. Elsevier B.V. 458, 82–99. https://doi.org/10.1016/j.aquaculture.2016.02.012.
Erikson, U., et al., 2016. Crowding of Atlantic salmon in net-pen before slaughter. Aquaculture. Elsevier B.V. 465, 395–400. https://doi.org/10.1016/j.aquaculture.2016.09.018.
FAWC, 2014. Opinion on the Welfare of Farmed Fish.
Fife-Cook, I., Franks, B., 2019. Positive welfare for fishes: rationale and areas for future study. Fishes 4 (2), 31. https://doi.org/10.3390/fishes4020031.
Fisher, M.W., 2009. Defining animal welfare — does consistency matter? N. Z. Vet. J. 57 (2), 71–73. https://doi.org/10.1080/00480169.2009.36880.
FishFarmingExpert, 2020. RSPCA Assured targets return of farm visits, FishFarmingExpert News. Available at: https://www.fishfarmingexpert.com/article/rspca-assured-takes-first-step-towards-normal-assessments/ (Accessed: 11 October 2021).
Folkedal, O., et al., 2012. Food anticipatory behaviour as an indicator of stress response and recovery in Atlantic salmon post-smolt after exposure to acute temperature fluctuation. Physiol. Behav. Elsevier Inc. 105 (2), 350–356. https://doi.org/10.1016/j.physbeh.2011.08.008.
Føre, M., Alfredsen, J.A., Gronningsater, A., 2011. Development of two telemetry-based systems for monitoring the feeding behaviour of Atlantic salmon (Salmo salar L.) in aquaculture sea-cages. Comput. Electron. Agric. Elsevier B.V 76 (2), 240–251. https://doi.org/10.1016/j.compag.2011.02.003.
Fox, N., Hunn, A., Mathers, N., 2009. Sampling and sample size calculation. In: The NIHR RDS for the East Midlands / Yorkshire & the Humber, 1(1), pp. 1–41. Available at. https://www.gov.scot/publications/scottish-fish-farm-production-survey-2019/pages/5/.
Fraser, D., et al., 1997. A scientific conception of animal welfare that reflects ethical concerns. Anim. Welf. 6 (3), 1–19.
Gjessing, M.C., et al., 2017. Salmon gill poxvirus, a recently characterized infectious agent of multifactorial gill disease in freshwater- and seawater-reared Atlantic salmon. J. Fish Dis. 40 (10), 1253–1265. https://doi.org/10.1111/jfd.12608.
Hassan, W., et al., 2019. Internet of fish: integration of acoustic telemetry with LPWAN for efficient real-time monitoring of fish in marine farms. Comput. Electron. Agric. Elsevier 163 (September 2018), 1–9. https://doi.org/10.1016/j.compag.2019.06.005.
Herrero, A., et al., 2018. Complex gill disease: an emerging syndrome in farmed Atlantic Salmon (Salmo salar L.). J. Comp. Pathol. Elsevier Ltd. 163, 23–28. https://doi.org/10.1016/j.jcpa.2018.07.004.
Huntingford, F.A., et al., 2006. Current issues in fish welfare. J. Fish Biol. 68 (January), 332–372. https://doi.org/10.1111/j.1095-8649.2005.01046.x.
Hvas, M., Folkedal, O., Oppedal, F., 2021. Fish welfare in offshore salmon aquaculture. Rev. Aquac. 13 (2), 836–852. https://doi.org/10.1111/raq.12501.
Jarvis, S., et al., 2021. Qualitative behavioral assessment in juvenile farmed Atlantic Salmon (Salmo salar): potential for on-farm welfare assessment. Front. Vet. Sci. 8 (September), 1–11. https://doi.org/10.3389/fvets.2021.702783.
Kenyon, W., Davies, D., 2018. Salmon Farming in Scotland. Available at. https://digitalpublications.parliament.scot/ResearchBriefings/Report/2018/2/13/Salmon-Farming-in-Scotland.
Lafferty, K.D., et al., 2015. Infectious diseases affect marine fisheries and aquaculture economics. Annu. Rev. Mar. Sci. 7, 471–496. https://doi.org/10.1146/annurev-marine-010814-015646.
Manfrin, A., Messori, S., Arcangel, G., 2018. Strengthening fish welfare research through a gap analysis study.
Marcos-López, M., et al., 2017. Oxidative stress is associated with late-stage amoebic gill disease in farmed Atlantic salmon (Salmo salar L.). J. Fish Dis. 1–6. https://doi.org/10.1111/jfd.12699.
Marschall, E.A., et al., 1998. A framework for understanding Atlantic salmon (Salmo salar) life history. Can. J. Fish. Aquat. Sci. 55 (SUPPL.1), 48–58. https://doi.org/10.1139/cjfas-55-s1-48.
Martins, C.I.M., et al., 2012. Behavioural indicators of welfare in farmed fish. Fish Physiol. Biochem. 38 (1), 17–41. https://doi.org/10.1007/s10695-011-9518-8.
Mason, G., Mendl, M., 1993. Why is there no simple way of measuring animal welfare? Anim. Welf. 2 (4), 301–319.
Mellor, D.J., 2016. Updating animal welfare thinking: moving beyond the "five freedoms" towards "a life worth living". Animals 6 (3), 1–20. https://doi.org/10.3390/ani6030021.
Mellor, D.J., Beausoleil, N.J., 2015. Extending the "five domains" model for animal welfare assessment to incorporate positive welfare states. Anim. Welf. 24 (3), 241–253. https://doi.org/10.7120/09627286.24.3.241.
Mellor, D.J., Reid, C.S.W., 1994. Concepts of animal well-being and predicting the impact of procedures on experimental animals. In: Improving the Well-Being of Animals in the Research Environment, pp. 3–18. Available at. http://org.uib.no/dyreavd/harm-benefit/Concepts of animal well-beingand predicting.pdf.
Miller, L.J., et al., 2020. Behavioral diversity as a potential indicator of positive animal welfare. Animals 10 (7), 1–17. https://doi.org/10.3390/ani10071211.
Mitchell, S.O., Rodger, H.D., 2011. A review of infectious gill disease in marine salmonid fish. J. Fish Dis. 34 (6), 411–432. https://doi.org/10.1111/j.1365-2761.2011.01251.x.
Munro, L.A., 2020. Scottish Fish Farm Production Survey 2019. Available at: https://www.gov.scot/publications/scottish-fish-farm-production-survey-2019/pages/5/.
Murray, A.G., et al., 2021. A preliminary assessment of indirect impacts on aquaculture species health and welfare in Scotland during COVID-19 lockdown. Vet. Anim. Sci. Elsevier Ltd. 11, 1–5. https://doi.org/10.1016/j.vas.2021.100167.
Noble, C., et al., 2018. Welfare indicators for farmed Atlantic Salmon: Tools for assessing fish welfare.
O'Donncha, F., et al., 2021. Data driven insight into fish behaviour and their use for precision aquaculture. Front. Anim. Sci. 2 (July), 1–18. https://doi.org/10.3389/fanim.2021.695054.
Oppedal, F., Dempster, T., Stien, L.H., 2011. Environmental drivers of Atlantic salmon behaviour in sea-cages: a review. Aquaculture. Elsevier B.V. 311 (1–4), 1–18. https://doi.org/10.1016/j.aquaculture.2010.11.020.
Overton, K., et al., 2018. The use and effects of hydrogen peroxide on salmon lice and post-smolt Atlantic salmon. Aquaculture. Elsevier 486 (December 2017), 246–252. https://doi.org/10.1016/j.aquaculture.2017.12.041.
Overton, K., et al., 2019. Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review. Rev. Aquac. 11 (4), 1398–1417. https://doi.org/10.1111/raq.12299.
Paul, E.S., et al., 2020. Towards a comparative science of emotion: affect and consciousness in humans and animals. Neurosci. Biobehav. Rev. 108 (May 2019), 749–770. https://doi.org/10.1016/j.neubiorev.2019.11.014.
Pettersen, J.M., et al., 2014. Salmon welfare index model 2.0: an extended model for overall welfare assessment of caged Atlantic salmon, based on a review of selected welfare indicators and intended for fish health professionals. Rev. Aquac. 6 (3), 162–179. https://doi.org/10.1111/raq.12039.
Pinkiewicz, T.H., Purser, G.J., Williams, R.N., 2011. A computer vision system to analyse the swimming behaviour of farmed fish in commercial aquaculture facilities: a case study using cage-held Atlantic salmon. Aquacult. Eng. Elsevier B.V. 45 (1), 20–27. https://doi.org/10.1016/j.aquaeng.2011.05.002.
Poli, B.M., et al., 2005. Fish welfare and quality as affected by pre-slaughter and slaughter management. Aquac. Int. 13 (1–2), 29–49. https://doi.org/10.1007/s10499-004-9035-1.
Powell, M.D., Reynolds, P., Kristensen, T., 2015. Freshwater treatment of amoebic gill disease and sea-lice in seawater salmon production: considerations of water chemistry and fish welfare in Norway. Aquaculture. Elsevier B.V. 448, 18–28. https://doi.org/10.1016/j.aquaculture.2015.05.027.
QSR International Pty Ltd, 2020. Nvivo qualitative data analysis software (March 2020 ed.).
Rey, S., Little, D., Ellis, M., 2019. Farmed fish welfare practices: Salmon farming as a case study. GAA publications.
Rodger, H.D., Henry, L., Mitchell, S.O., 2011. Non-infectious gill disorders of marine salmonid fish. Rev. Fish Biol. Fish. 21 (3), 423–440. https://doi.org/10.1007/s11160-010-9182-6.
RSPCA, 2018. RSPCA welfare standards for farmed Atlantic salmon. Available at: https://science.rspca.org.uk/sciencegroup/farmanimals/standards/salmon.
RSPCA, 2021. RSPCA welfare standards for Farmed Atlantic Salmon. In: RSPCA Welfare Standards for Farmed Atlantic Salmon, pp. 1–80 (February). Available at: http://industry.freedomfood.co.uk/media/96636/RSPCA-welfare-standards-for-farmed-Atlantic-salmon-web-version.pdf.
Saberioon, M., et al., 2017. Application of machine vision systems in aquaculture with emphasis on fish: state-of-the-art and key issues. Rev. Aquac. 9 (4), 369–387. https://doi.org/10.1111/raq.12143.
Salmon Scotland, 2020. What is RSPCA Assured? Available at: https://www.salmonscotland.co.uk/facts/fish-health-welfare/what-is-rspca-assured (Accessed: 30 October 2022).
Schreck, C.B., Tort, L., 2016. The concept of stress in fish. In: Fish Physiology. Academic Press, pp. 1–34. https://doi.org/10.1016/B978-0-12-802728-8.00001-1.
Scottish Sea Farms, 2021. Salmon lifecycle - From egg to harvest. Available at: https://www.scottishseafarms.com/sustainability/salmon-lifecycle/ (Accessed: 14 September 2021).
Sneddon, L.U., Braithwaite, V.A., Gentle, M.J., 2003. Novel object test: examining nociception and fear in the rainbow trout. J. Pain 4 (8), 431–440. https://doi.org/10.1067/S1526-5900(03)00717-X.
SSPO, 2021. Monthly Mortality Rate: June 2021, SSPO Lice & Survival Reports. https://doi.org/10.1016/j.ajodo.2021.04.004.
Steinum, T., et al., 2010. Microbial and pathological findings in farmed Atlantic salmon Salmo salar with proliferative gill inflammation. Dis. Aquat. Org. 91 (3), 201–211. https://doi.org/10.3354/dao02266.
Stien, L.H., et al., 2013. Salmon welfare index model (SWIM 1.0): a semantic model for overall welfare assessment of caged Atlantic salmon: review of the selected welfare indicators and model presentation. Rev. Aquac. 5 (1), 33–57. https://doi.org/10.1111/j.1753-5131.2012.01083.x.
Størkersen, K.V., et al., 2021. Fish protection during fish production. Organizational conditions for fish welfare. Mar. Policy 129 (October 2020), 1–11. https://doi.org/10.1016/j.marpol.2021.104530.

Superior Fresh, 2019. What's the story behind your supermarket salmon? Available at: https://www.superiorfresh.com/blog-reference/whats-the-story-behind-your-supermarket-salmon (Accessed: 14 September 2021).
Thorstad, E.B., et al., 2015. Effects of salmon lice Lepeophtheirus salmonis on wild sea trout salmo trutta - a literature review. Aquacult. Environ. Interact. 7 (2), 91–113. https://doi.org/10.3354/aei00142.
Turnbull, J.F., Kadri, S., 2007. Safeguarding the many guises of farmed fish welfare. Dis. Aquat. Org. 75 (2), 173–182. https://doi.org/10.3354/dao075173.
UN General Assembly, 2015. Transforming our world: the 2030 Agenda for Sustainable Development, A/RES/70/1. https://doi.org/10.1163/15718093-12341375.
Weary, D.M., Fraser, D., 1995. Calling by domestic piglets: reliable signals of need? Anim. Behav. 50 (4), 1047–1055. https://doi.org/10.1016/0003-3472(95)80105-7.
Webster, J., 2016. Animal welfare: freedoms, dominions and "a life worth living". Animals 6 (6), 2–7. https://doi.org/10.3390/ani6060035.
Zhao, J., et al., 2018. Modified motion influence map and recurrent neural network-based monitoring of the local unusual behaviors for fish school in intensive aquaculture. Aquaculture. Elsevier 493 (January), 165–175. https://doi.org/10.1016/j.aquaculture.2018.04.064.