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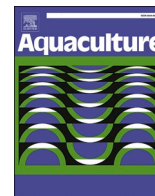
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# Prioritization of fish welfare issues in European salmonid aquaculture using the Delphi method

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## ABSTRACT

The European aquacultural sector is undergoing immense growth, and, generally, many more aquatic animals are farmed than land animals. However, the welfare of aquatic animals like fish has received less attention. This study focuses on the two largest contributors to Europe's aquaculture – Atlantic salmon and rainbow trout – farmed in cages in Northern Europe. An extensive literature review was conducted on potential welfare issues. These issues were grouped into five provisions / welfare aims according to an animal welfare framework adapted to fish. To set priorities among the issues, a Delphi assessment was performed, for which experts had to rate each issue based on the severity, duration, and prevalence. The participants were also asked to propose interventions to tackle the main issues. The three main welfare issues identified were ineffective prevention of diseases, sea lice treatment issues, and poor conditions during husbandry practices. Examples of interventions to improve the three main issues are lowering the stocking density, better monitoring, and specifically to prevent diseases, including sea lice, also developing more effective vaccines. This study provides valuable insights into which fish welfare issues should be tackled more urgently in European salmonid aquaculture. Future research could assess interventions more in depth and conduct similar studies for other aquatic farm animals and regions.

## 1. Introduction

Aquaculture is an important contributor to the global food supply. It is the fastest-growing food production system worldwide (Barreto et al., 2021). It can be considered as an alternative solution to the overfishing of fish stocks in the sea, which is the main driver of current biodiversity loss in the oceans (Emanuelsson et al., 2014). Besides, it can also be considered a substitution or complementation to land-based meat production, which has higher environmental impacts (Gentry et al., 2017). The mass of fish production is already higher than that of conventional livestock (Béné et al., 2015), and the number of individual animals farmed in aquaculture by far exceeds the number of animals in conventional agriculture. In 2018, it was estimated that the number of conventional livestock animals included approximately 1 billion pigs, 1.5 billion cattle, 2 billion sheep and goats, and over 30 billion chickens (FAO, 2022a), as compared to 59 to 129 billion farmed fish (Franks et al., 2021).

There are several frameworks on animal welfare that are developed for terrestrial animals but can potentially be adapted to aquatic animals. In general, the current key concepts, such as the Five Freedoms

framework, which are steering welfare guidelines of farmed animals, are inadequate to examine a complex and diverse taxonomic group such as fishes (Saraiva et al., 2018). However, available frameworks could serve as a basis for fish welfare studies when integrated with insights into fish morphology, physiology, and behavioural needs (Kristiansen et al., 2020).

In contrast to the welfare of terrestrial livestock, fish welfare has received only limited attention until recently (Barreto et al., 2021), although, from the early 1990s, the number of papers mentioning both welfare and aquaculture has been steadily increasing (Huntingford and Kadri, 2009). Not much research has been conducted on the nature and spread of fish welfare issues, and there is little insight into which issues are the most urgent to be solved and how these issues may be solved (Ashley, 2007; Kristiansen et al., 2020). Legislation to protect fish welfare exists in several countries or regions, such as the European Council Regulation on the Protection of Animals at the Time of Killing (European Commission, 2009). Also schemes to monitor fish welfare indicators are in use, such as the Royal Society for the Prevention of Cruelty to Animals (RSPCA) welfare standards (RSPCA, 2018). However, they seem to focus on describing a broad range of indicators or on how to measure these

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indicators (Kristiansen et al., 2020), instead of establishing the main welfare issues in the industry and focusing on potential ways to improve welfare.

Little research has been conducted on fish welfare in European aquaculture, even though the aquacultural sector has quadrupled in Europe in the past 30 years (Breuer and Dinkel, 2021). Since China has the highest farmed fish production in the world, much of the current literature focuses on China and is not accessible in English (Barreto et al., 2021). Furthermore, students in Europe seem to be less accepting of fish welfare issues than students in Asia, and more concerned about improving welfare (Phillips et al., 2012). At the same time, the welfare of farmed fish has become a growing concern for the general public, especially in Europe (Kristiansen et al., 2020). For this reason, it seems logical to raise awareness and invest into more studies on welfare issues and into implementation of welfare improvements for aquacultural fish in Europe. Subsequently, other countries may follow Europe, as Western countries have also acted as forerunners for societal concern about animal welfare in the past (Fraser, 2014). Moreover, the EU is the largest importer of seafood products, and they use their trade policies to support sustainable development in developing countries (Zhang and Tveterås, 2019). Similar trade policies could also be used to encourage better fish welfare.

Aquacultural production in Europe is biased to a selected set of countries and to a few core fish species. In 2019, Spain, France, the United Kingdom, Greece, and Italy were responsible for over 75% of the total EU's aquacultural production (when the United Kingdom was still part of the EU). However, Norway's production exceeds the total EU

production in volume (Fig. 1), and Norway is thereby the ninth largest producer globally (FAO, 2022b). Approximately 120 species of aquatic animals are farmed across Europe, of which more than half are finfish, and the five most common species comprise approximately 76% of the total aquaculture production (Fig. 1, Eurostat, 2022). The five main fish species farmed in Europe are Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*), European seabass (*Dicentrarchus labrax*), gilthead seabream (*Sparus aurata*) and common carp (*Cyprinus carpio*). Each species has different traits and is farmed in different conditions (Fig. 1), complicating generalisations about all fish species (Toni et al., 2019). However, a good overview of welfare issues and potential solutions for the two most common species, Atlantic salmon and rainbow trout, would already cover conditions for almost two thirds of aquacultural production in Europe.

Both Atlantic salmon and rainbow trout are part of the salmonids family, which means that similar results may be expected due to comparable physiological traits (Hvas et al., 2021). Atlantic salmon is mainly farmed in Norway, but a considerable amount is also farmed in the United Kingdom and on the Faroe Islands (FAO, 2022b), and some in Iceland, Ireland, and Denmark proper. Rainbow trout is farmed in 28 countries within Europe, with most production in Turkey and Norway, but also in France, Italy, Denmark, Spain, Finland and the United Kingdom. Atlantic salmon is mainly farmed in cages in the sea and brackish water, while rainbow trout is farmed in cages as well as tanks and raceways in both freshwater and salt or brackish water (Fig. 1). Both species include anadromous forms, which means under natural conditions they would migrate from freshwater to the sea and back to

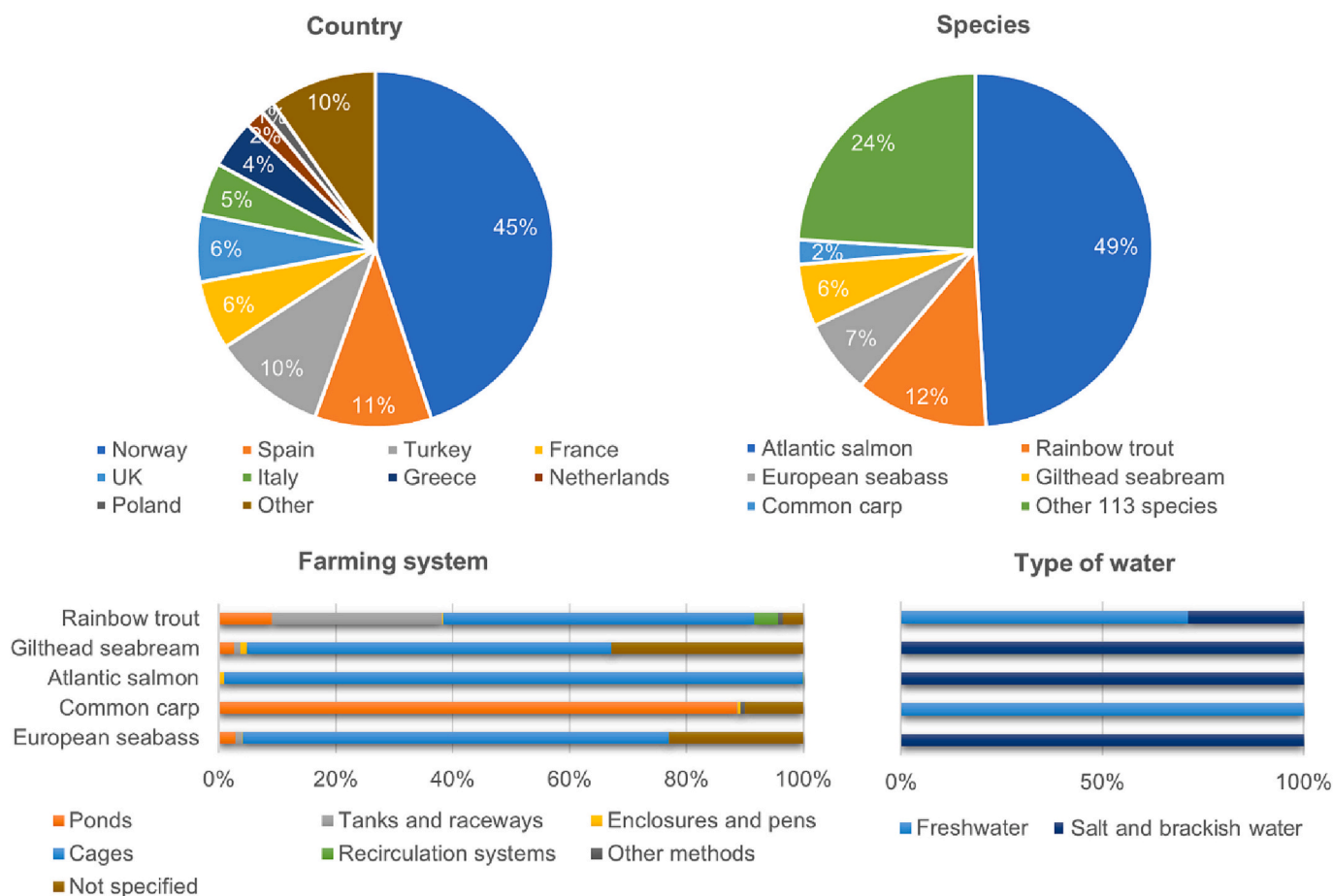


Fig. 1. Profile of European aquaculture, with spread across countries (top left) and species (top right, other 113 species include fish and other aquatic animals), and the core characteristics of farming systems (bottom left) and water type (bottom right) for the five most widely farmed fish species. The species were measured in tonnes of live weight and represent the year 2018 (Eurostat, 2022). Note that the data represent the EU, candidates for accession, and EFTA countries, but not all of Europe. For example, the Faroe Islands are missing despite their considerable farming of Atlantic Salmon (FAO, 2022b).

freshwater for spawning. Salmon smolt hatcheries are usually based in freshwater single-pass flow-through farms close to the coast or, in some cases, in lakes, from which smolts are transferred to grow-out facilities, usually cages at sea (Bergheim et al., 2009). For rainbow trout, some natural populations stay in freshwater their whole life, while others (steelhead) migrate for a period at sea. This is also reflected in farmed rainbow trout, which are partly farmed in freshwater and partly in salt or brackish water. In Norway and the United Kingdom, similarly to the Atlantic salmon, the Rainbow trout is mainly farmed in cages in the sea and brackish water (Eurostat, 2022). Due to the more limited resource of freshwater, further growth in the European aquacultural sector is expected in coastal farming, for both salmon and trout, instead of in freshwater ponds and indoor facilities (Lundebye, 2013).

In this study, we aim to identify the most pressing welfare issues of Atlantic salmon and rainbow trout farmed in cages in Northern Europe (including Denmark, Finland, Iceland, Ireland, Norway, Sweden, the UK, etc.) and to explore potential interventions to mitigate these issues. To do so, we conducted a Delphi assessment, in which experts rated welfare issues based on severity, duration, and prevalence and suggested potential interventions to mitigate the main welfare issues. This article provides an overview of fish welfare issues, summarizes the results of the Delphi assessment, including a ranking of the issues, and discusses potential interventions for the three highest-ranked issues.

## 2. Material and methods

### 2.1. General approach

We used the animal welfare framework proposed by Mellor (2016b), the Five Provisions/Welfare Aims paradigm, as a basis for our research. It resembles the more well-known Five Freedoms framework but solves multiple of its issues by avoiding the term “freedom” (which wrongly assumes that they are completely achievable) and including positive experiences. The framework had to be adapted to fish (Table 1), as it was designed just for terrestrial animals. The adapted framework for fish is a combination of the Five Provisions/Welfare Aims paradigm by Mellor (2016b) and the fish welfare needs as indicated by Kristiansen et al. (2020). We reviewed the literature for potential fish welfare issues, and all issues were grouped into categories following the adapted animal welfare framework. Subsequently, these issues were used in three rounds of Delphi surveys to determine the main issues. Delphi assessments have been used before in the fields of aquaculture sustainability (Bunting, 2010; Valderrama et al., 2014) and animal welfare (Garcia de Leaniz et al., 2021; Rioja-Lang et al., 2020). We followed Webster (1998), when addressing the magnitude of animal welfare issues with respect to three criteria – (1) severity, (2) duration, and (3) incidence or prevalence – reflecting how much, how long, and how often an issue affects animals. These criteria have been used in several animal welfare issue studies before (Brujinis et al., 2012; Rioja-Lang et al., 2020; Nielsen

et al., 2021). In the third survey round, participants were also asked about interventions to solve these issues. The responses were integrated with another round of literature review on mitigation efforts and success (Fig. 2).

### 2.2. Literature review

We searched the scientific and grey literature using Web of Science and Google Scholar. Search terms included initially general terms like “fish welfare issues”, “farmed fish welfare”, “fish welfare in aquaculture” and “fish welfare indicators”, and later more specific terms like “fish welfare feeding”, “fish welfare water quality”, “fish welfare light/dark regime”, “fish welfare of Atlantic salmon” and “fish welfare of rainbow trout”. We listed potential fish welfare issues, grouped into the Five Provisions (Table 1). Similar issues were combined to shorten the list for the Delphi surveys. Issues regarding the slaughter process were excluded from the list, as they depend on various aspects, such as the type of methods, pre-slaughter handling and pre-slaughter chilling (Huntingford et al., 2006; Santurtun et al., 2018), which were beyond the current scope, as other studies have already dealt with the slaughter process (Poli et al., 2005; Lines and Spence, 2012; Grimsbø, 2016). After the Delphi assessment, we explored potential fish welfare interventions to solve the three main fish welfare issues, that would come out of the Delphi assessment. Another, shorter follow-up literature review was conducted, in which we selected search terms based on the comments made by the participants in the final round of the Delphi assessment, to clarify or confirm their suggested interventions.

### 2.3. Delphi assessment

#### 2.3.1. Survey design

A Delphi assessment (Dalkey and Helmer, 1963) is an iterative survey carried out with an expert panel, where the multiple iterations allow to approach consensus. The survey was designed using the software Qualtrics. It was conducted within three rounds with two weeks to fill out each survey and one week in between. It took the participants about 10 min to one hour to fill out each survey. The participants were asked to give scores on each criterion (severity, duration, and prevalence) for each fish welfare issue. This was done on a 6-point Likert scale. An even-numbered scale means that the participants were obliged to make a decision on the importance of the issue (Rioja-Lang et al., 2020). Besides, they were encouraged to justify their scores for each issue. In the next round, they were given a similar survey but received an anonymous summary with the average, minimum and maximum of each criterion for each welfare issue and the justifications. The justifications were grouped by the average of the given scores across the three criteria (1–2 as low score, 3–4 as medium score, 5–6 as high score). This feedback process encouraged the participants to reassess their initial scores and possibly adjust them (Hsu and Sandford, 2007).

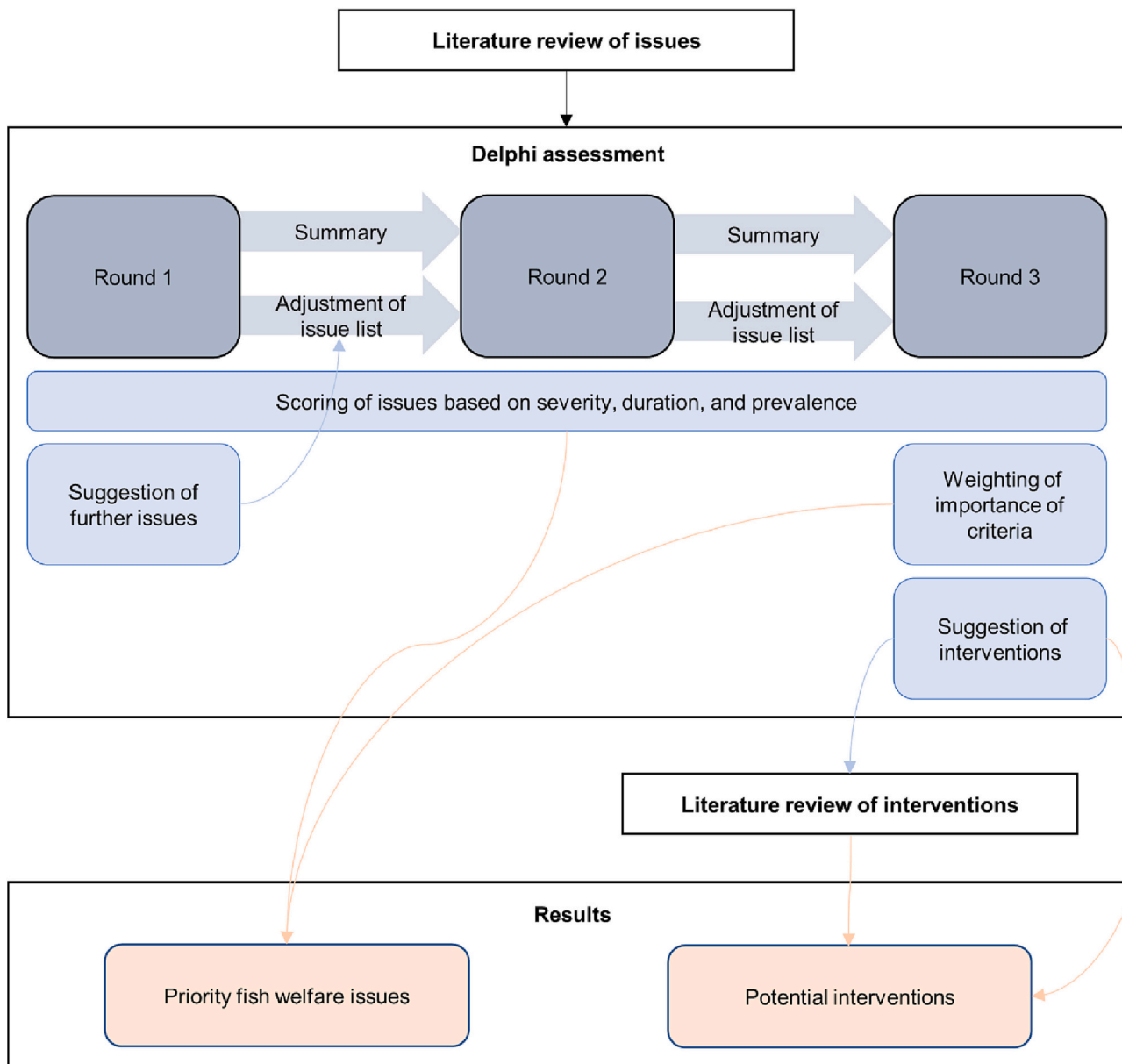
**Table 1**

Five Provisions/Welfare Aims paradigm for fish. Additions or substitutions compared to Mellor (2016b) are shown as underlined text, and removals are indicated in footnotes.

Provisions	Fish Welfare Aims
1. Good nutrition*: Provide ready access to a diet to maintain <u>growth, physiological functioning</u> and health	Minimise hunger and enable eating to be a pleasurable experience
2. Good environment: Provide an <u>appropriate water environment</u> including good <u>water</u> quality, shelter and resting areas	Minimise discomfort and exposure, and promote thermal, physical and other comforts
3. Good health: Prevent or rapidly diagnose and treat disease and injury, and foster <u>respiration and osmoregulation</u>	Minimise <u>gill problems</u> , pain and other aversive experiences, and promote <u>fitness</u> and the pleasures of physical activity
4. Appropriate behaviour**: Provide sufficient space, congenial company and appropriately varied conditions	Minimise threats and unpleasant restrictions on behaviour and promote <u>a sense of safety</u>
5. Positive mental experiences: Provide safe, congenial and species-appropriate opportunities to have pleasurable experiences	Promote various forms of comfort, pleasure, <u>exploration</u> , confidence and a sense of control

\* Provision of fresh water and the minimisation of thirst are not relevant to good nutrition of fish, as they live in water.

\*\* Proper facilities have been removed, as they are less relevant in a water environment.



**Fig. 2.** Overview of methods. The three-round Delphi assessment in grey boxes is at the core of the methods. The blue boxes below indicate what was done in each of the rounds. Orange arrows lead to orange boxes, which show the final outcomes of the study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the first survey round, the experts were additionally asked whether important fish welfare issues were missing in their view. Subsequently, the list of issues was adjusted for the second survey round (Table B1) by adding new or adjusting existing issues, following the participants' comments, and some issues were removed that consistently scored low to keep the list shorter. Due to the scope of the research, a few suggestions were excluded, such as sub-optimal genotype/ploidy/gender and issues regarding the slaughter process. An issue would be removed if it scored lower than 3 on each criterion. In the third round, the list was again slightly adjusted (Table B2) based on unclarities the participants commented on and removing further low-scoring issues. Additionally, participants were asked to weigh the importance of each criterion (severity, duration and prevalence). A total score of 60 had to be divided among these three criteria. An amount of 60 was chosen so the participants could easily distribute an equal amount when they considered all criteria equally important. Finally, the participants had to suggest potential interventions to improve the five highest-scoring issues

of round 2, aiming to still capture the three highest-scoring issues of round 3.

### 2.3.2. Participants

Potential participants were stakeholders and experts in the European aquacultural sector with different interests and roles. The participants were from universities, research institutes, the aquaculture industry, NGOs or the government with knowledge of Atlantic salmon and/or rainbow trout farmed in cages in Northern Europe. An invitation email was sent to over 100 experts and stakeholders. For example, researchers authoring papers on fish welfare were contacted. Companies related to aquaculture were found using [www.agriculture-xprt.com](http://www.agriculture-xprt.com). Such companies included those specialized in the farming of Atlantic salmon and/or rainbow trout or those related to fish farming, such as biotechnological companies specialized in fish diseases. The Google search engine was used to find NGOs and policymakers. Snowball sampling was also used through suggestions from invitees. Potential participants from

different countries were contacted, but since the Norwegian aquacultural sector is the largest in Europe, most of them were based in Norway. The goal was to reach between 10 and 20 participants. The first and second rounds were completed by 20 participants, and the third round was completed by only 18 participants. Especially researchers from universities or research institutes were willing to participate. Stakeholders from the industry or government were harder to find or less willing to participate (Fig. C4).

To check for attrition bias, the ranking of the issues of round two of the participants who completed the third round was compared to participants who did not complete the third round. Besides, the ranking in the third round was compared to those when adding the scores of the second round of the participants who did not complete the final survey (Table C1). As a larger sample size is generally favourable and the two participants who did not complete the final survey could at least consider the feedback after the first round, it was decided to add their scores from the second round to the results of the third round.

### 2.3.3. Analysis of Delphi results

The median value across participants of each criterion was used to estimate the central tendency, and the sum of the median values for the three criteria served as a basis for the prioritization of the welfare issues. The median was chosen due to the ordinal data type when using a Likert scale (Von der Gracht, 2012). As a sensitivity analysis, the weighted average of the median values for the three criteria was also used instead of the sum, with weights of importance of each criterion as indicated by the participants. Besides analysing the total results, an analysis of the results of round 3 per subgroup was also performed. However, as three of the subgroups only consist of 1 to 4 participants, the total was divided into two subgroups: research and non-research (including NGO, industry and government). In line with the median, the interquartile range (IQR) was used to measure consensus among the experts (Von der Gracht, 2012). An IQR of at most 1.5 was considered consensus. 1.5 for a Likert scale of 6 units was chosen, as other studies used an IQR of 2 or fewer units for a 10-unit scale and an IQR of 1 or less for a 4- or 5-unit scale (Von der Gracht, 2012). For the importance weights in the third round of a continuous data type, the coefficient of variation was used to measure the level of consensus, with <0.5 indicating an acceptable level of consensus. To assess the stability of the results, the convergence of group opinions between two subsequent rounds was measured. Using rounds 2 and 3 as an example, the convergence can be calculated based on the IQRs as follows (Von der Gracht, 2012):

$$CG_i = \frac{(IQR)_{2i} - IQR_{3i}}{(IQR)_{2i}}$$

Where  $0 < CG_i \leq 1$  if convergence takes place.

$CG_i$  = amount of convergence of group opinions for issue i.

$IQR_{2i}$  = interquartile range in round 2 for issue i.

$IQR_{3i}$  = interquartile range in round 3 for issue i.

### 2.3.4. Ethical statement

The Delphi survey and all associated personalized data collection and processing were reviewed and approved by the Ethics Review Committee and the Privacy Officer of the Faculty of Science at Leiden University.

## 3. Results

### 3.1. Selection of the fish welfare issues

#### 3.1.1. Good nutrition

**3.1.1.1. Poor food quality or nutritional value.** It is important that the food has a high nutritional value and is not harmful to the animal (Noble et al., 2018). Besides, fish tend to show proactive behaviour for the type

of food they prefer, which suggests certain positive or negative emotions towards the quality of the food.

**3.1.1.2. Inappropriate food quantity.** When food-deprived, fish may develop negative emotions, such as hunger (Noble et al., 2018). This may also harm the other fish. For example, when hungry, the Atlantic salmon tends to become more competitive and fight more. Furthermore, the level of underfeeding may cause different effects on the fish (Noble et al., 2018). Complete withdrawal of feeding may cause less welfare loss than consistent underfeeding.

**3.1.1.3. Inappropriate feeding time.** Fish welfare may vary when feeding is either nocturnal or diurnal or either scheduled or random. For example, Atlantic salmon prefer diurnal feeding, but this can change during their lifecycle (López-Olmeda et al., 2012). A predictable feeding time may likely decrease aggressive behaviour (Cañon Jones et al., 2012).

**3.1.1.4. Food deprivation before husbandry practices (e.g. transportation, slaughter, or grading).** Food may often be withheld from the fish before certain farming practices, such as slaughter, transport, grading, or a health check. This may lead to health issues, such as dorsal fin erosion in rainbow trout and increased plasma glucose in Atlantic salmon (Huntingford et al., 2006). However, food deprivation may also benefit fish welfare, as it may lead to reduced metabolism, oxygen demand, and waste production (Ashley, 2007). The actual effects of food deprivation on the welfare of salmonids remain uncertain (Ashley, 2007). It may depend on the duration and the conditions of the food deprivation.

### 3.1.2. Good environment

**3.1.2.1. Inappropriate level of chemicals (e.g. salinity, pH, dissolved oxygen or toxic substances).** Many chemicals dissolve quickly in water, making them potential carriers of harmful substances (Huntingford and Kadri, 2014). Such water of poor quality may affect fish welfare. Water should contain the appropriate concentrations of substances and avoid abiotic adverse influences, such as certain gases, toxins, and metabolites (Tschirren et al., 2021). Moreover, aerated water with a sufficient oxygen level is essential for the health of salmonids (Huntingford et al., 2006). The proper parameters for good water quality are usually provided, for example, by a national authority (Noble et al., 2018). However, certain fish farms may not meet these conditions.

**3.1.2.2. Inappropriate water temperature.** Since fish are ectothermic, it is important to regulate the water temperature. Maintaining their body temperature affects their metabolism and influences the efficacy of their innate immune response (Tschirren et al., 2021; Huntingford and Kadri, 2014). Water temperature also affects the migration timing, the fish's growth rate, and smoltification (Noble et al., 2018). Besides, lower temperatures may positively impact fish welfare, as it reduces their energy and food needs (Huntingford and Kadri, 2014). Unfavourable thermal conditions may cause high stress depending on the severity and duration of the exposure. In sea cages, the Atlantic salmon are generally attracted by temperatures of at most 17 °C. However, this may depend on its lifecycle. Furthermore, climate change may cause milder winters, resulting in higher mortality (Moriarty et al., 2020). Acute thermal changes may harm fish welfare as well, which can be indicated by elevated oxygen consumption (Noble et al., 2018).

**3.1.2.3. Inappropriate water flow.** The water flow rate influences the number of substances dissolved in the water. It may also impact the speed of the current, which may exhaust, stress, or harm the fish (MacIntyre et al., 2008).

**3.1.2.4. Inappropriate light/dark regime (including insufficient resting opportunities).** Light intensity and colour, distance from the light source, shading, water temperature, and water clarity may impact the ideal light conditions for fish (Volpato et al., 2007; Noble et al., 2018). Light may positively or negatively influence the welfare of salmonids. Controlling the photoperiod regimes may influence smoltification and therefore affect the fish's adaptation to seawater, causing osmotic imbalance. Exposure to constant light may negatively affect the fish's neurological development and growth (Ebbesson et al., 2007). Potential positive effects of artificial light manipulation include the control of swimming behaviour to reduce lice. Salmon tend to swim deeper in the cage during daylight, which decreases the likelihood of infestations (Noble et al., 2018). A satisfactory light/dark regime also allows resting (Tschirren et al., 2021; Noble et al., 2018). During night time, salmonids have been observed almost motionless, less sensitive to acute changes, and moving away from lighting. This could indicate that they are resting. Resting is important since reducing activity levels maintains their body functions.

**3.1.2.5. Acute environmental changes (e.g. in water temperature, light, vibrations or sound).** Acute exposure to light may cause stress because of the sudden change in light intensity, which may result in panic behaviour or increased oxygen intake (Noble et al., 2018). Furthermore, fish's behaviour may be disturbed due to changes in vibrations in the water, like acute sound effects or background electrical fields (Huntingford and Kadri, 2014). This includes the production noise of the farming systems that may cause stress and other negative effects on the fish (Davidson et al., 2009). However, no long-term effects were found.

**3.1.2.6. Poor transport conditions (e.g. poor water quality or bad road and weather conditions).** Transportation may cause severe stress, which may take the fish a long time to recover. Stress can occur during the capture, loading, transport, unloading and stocking during either road or sea transport (Ashley, 2007). The water quality and the conditions during transportation, such as the weather or road conditions, may largely influence the severity of the impact on the fish (Santurtun et al., 2018). For example, vibration due to bad road quality or motion sickness due to a storm may play a role in this. Another issue is the introduction or spread of diseases due to live fish movements (Yatabe et al., 2015).

### 3.1.3. Good health

**3.1.3.1. Ineffective prevention of diseases (e.g. ineffective vaccines, prevention of sea lice infestation or prevention of diseases spread by wild fish stocks).** Diseases should be prevented, as they may cause pain or discomfort to the fish (Tschirren et al., 2021; Noble et al., 2018; Mellor, 2016a, 2016b). For example, sea lice can lead to multiple health issues, such as stress, skin damage, osmotic problems, and reduced immunity (Noble et al., 2018). While vaccines for some bacterial diseases are very effective, vaccines for viral diseases are not yet very effective (Ashley, 2007; Noble et al., 2018). To prevent fish from getting infected by biotic influences, such as viruses, bacteria and parasites, biosecurity standards should be assured (Tschirren et al., 2021). Fish in open cages, as usually used for farming salmonids in Northern Europe, are vulnerable since the current may spread organisms. Subsequently, wild fish may spread diseases to farmed fish (Noble et al., 2018; Huntingford et al., 2006). Besides, farmed fish in cages usually have high densities, creating an environment favourable for parasites or viruses. In addition, fish have an extra line of defence against pathogens that humans do not have, namely that their red blood cells are nucleated, which may cause immune responses. This has not yet been included in disease prevention (Huntingford and Kadri, 2014).

**3.1.3.2. Ineffective prevention of physical disturbance or injury (e.g. caused by selection/production process, such as handling and netting).** Injuries or other physical disturbances can cause fish pain or discomfort. Potential

permanent disturbances may occur due to the selection or production process, which could lead to deformities or increasing aggressiveness (Ashley, 2007; Huntingford et al., 2006). Increased aggressiveness among the fish could lead to fin damage and consequently cause infections (Ashley, 2007). Other types of damage may include eye damage, skin damage, and opercular injuries (Noble et al., 2018) and cause pain. This may arise from environmental factors, such as water quality, or other external factors. For example, handling and netting may cause stress, negatively impacting fish welfare (Huntingford et al., 2006; Noble et al., 2018).

**3.1.3.3. Inaccurate diagnosis or ineffective treatment of diseases or injuries.** For treatment, the right and rapid diagnosis are necessary (Noble et al., 2018). Besides, treatment needs to be and remain effective. However, for example, lice have developed resistance to chemical treatments over the past decades (Ashley, 2007), reducing their effectiveness.

**3.1.3.4. Painful treatment of diseases or injuries.** The treatment may negatively influence fish welfare (Noble et al., 2018; Overton et al., 2019). The treatment may even cause more welfare issues than the disease, such as potentially in the case of sea lice (Ashley, 2007; Overton et al., 2019). Similar to treatments, the side effects of vaccines may also negatively affect fish welfare. However, on average, welfare benefits from it (Noble et al., 2018; Huntingford et al., 2006).

**3.1.3.5. Osmotic regulation issues (e.g. due to inappropriate levels of salinity or pH, skin damage or inappropriate lifecycle stage of switching from fresh to seawater).** Osmotic regulation requires access to water with suitable salinities and pH values (Noble et al., 2018). This process is regulated by several organs, such as the skin, gills, and kidneys. Freshwater fish are hyper-osmotic, meaning their bodily fluids have higher salinity than the surrounding environment. For hypo-osmotic seawater fish, this is the opposite. Since Atlantic salmon and rainbow trout (specifically, steelhead trout) are anadromous, they have to switch between both states. Small salmon not transferred into seawater timely may suffer from dehydration and eventually die (Noble et al., 2018). Hence, multiple factors can cause osmotic stress, such as an inappropriate salinity level and damage to, for example, the skin (Stien et al., 2013).

**3.1.3.6. Respiration issues (e.g. due to gill damage, inappropriate levels of chemicals or air exposure).** If a fish cannot respire, it will die. The gills, needed for respiration, cannot perform an immune response themselves, which makes fish vulnerable to harmful substances in the water due to poor water quality (Huntingford and Kadri, 2014). When the gills are not functioning well due to injuries or diseases (Noguera et al., 2019), this may cause a serious threat to the fish's welfare. Exposure to air during husbandry practices may also limit respiration (Noble et al., 2018).

### 3.1.4. Appropriate behaviour

**3.1.4.1. Aggressive interactions (e.g. with other fish or predators, such as birds or seals).** Aggressive interactions among fish may cause damage or chronic social stress. Aggression may result from social hierarchies, which may be influenced by stocking density, feeding technique, and socio-biology (Huntingford et al., 2006; Ashley, 2007). Besides contact with conspecifics, farmed fish may be exposed to the aggression of predators, such as birds or seals. These animals may attack the fish farms and cause mortality or injury to the farmed fish. Simply exposure to predators may also cause welfare concerns, such as increased cortisol levels, increased ventilation rate, and suppressed feeding (Huntingford et al., 2006). Freezing behaviour is also common among fish when trying to avoid predators and is often shown as a fear response (Noble et al.,

2018).

**3.1.4.2. Insufficient social contact (e.g. sense of safety, sharing information or opportunities for reproductive behaviour).** Most fish need social contact. For example, being around other fish may give them a sense of safety. It also allows sharing of information about food or possible danger. Social contact also includes the opportunity to perform reproductive behaviour when sexually mature (Tschirren et al., 2021; Noble et al., 2018). The group behaviour of individual Atlantic salmon suggests that social contact is an important factor, as they seem to behave adversely to separating from the school (Noble et al., 2018).

**3.1.4.3. Inappropriate stocking densities.** Social behaviour may change during a lifecycle, for example, from more solitary and aggressive behaviour to forming schooling groups. The level of aggressiveness may also differ among group sizes or densities (Noble et al., 2018). Many fish live in big schools, so a high density is not necessarily disadvantageous (Huntingford and Kadri, 2014). However, particularly high densities may negatively affect the salmonids' welfare (Huntingford et al., 2006; Ashley, 2007).

### 3.1.5. Positive mental experiences

**3.1.5.1. Insufficient exploration opportunities.** Fish should be able to try to discover external stimuli (Tschirren et al., 2021). So, the fish should have exploration opportunities. The aquacultural environment shows less variation in factors such as temperature, light, and current speed than the fish would be exposed to in the wild (Noble et al., 2018). However, such natural and gradual variation may be important for the fish's ability to find and explore external stimuli. Although this may not be crucial for its survival, it may still negatively affect fish welfare (Noble et al., 2018).

## 3.2. Prioritization of fish welfare issues

### 3.2.1. Severity, duration, prevalence

In the third and final round of the Delphi assessment, issues related to health scored highest overall on severity and issues related to nutrition lowest (Table C5). Issues related to health scored highest overall also on duration, although it is less dominant, and behaviour scored lowest. Finally, issues related to the environment highest on prevalence, and behaviour scored again lowest. It shows clear differences in the ranking of fish welfare issues across the three criteria. This is even more obviously captured in the low Pearson correlation coefficients among the criteria between  $-0.12$  and  $0.15$  (Table 2). Although behaviour and nutrition issues generally scored low, individual issues can still score high for some of the criteria. Predatory interactions as a behaviour issue was among the five issues scoring highest on severity, poor food quality or nutritional value as a nutrition issue scored second-highest on duration, and food deprivation before husbandry practices as another nutrition issue scored highest on prevalence (Figs. C1–3).

The non-research group (NGO, industry, and government) tended to give higher scores, with differences in the median scores from 0 to 2 (Table C8). Some of their median scores also reached 6 as the maximum of the Likert scale, namely the severity of acute environmental changes and the prevalence of food deprivation before husbandry practices, which the research group instead assessed with a 4. In general, the

**Table 2**

Pearson correlation matrix among the criteria for the third and final round of the Delphi assessment.

	Severity	Duration	Prevalence
Severity	1		
Duration	0.15	1	
Prevalence	0.12	$-0.12$	1

largest differences occurred for prevalence.

### 3.2.2. Consensus and convergence

The Delphi participants reached consensus on the most fish welfare issues regarding severity, followed by duration, and finally prevalence (Table C7). For severity and duration, the number of issues where the Delphi participants reached consensus increased across the three Delphi rounds. However, for prevalence, it decreased from round 1 to round 2, after which it increased again but stayed lower than in round 1.

The number of issues where convergence of group opinions took place reduced between the last two rounds compared to the first two rounds for all three criteria, and it is below 50% between the last two rounds for all three criteria (Table C7). For severity, the lower convergence is mostly because several issues (9 out of 21) had already reached stability. For duration, it is also because of an increasing number of issues with diverging group opinions. For prevalence, there is hardly a change in convergence.

### 3.2.3. Aggregated scores

When summing the median scores across the three criteria, three fish welfare issues scored highest in the third and final round of the Delphi assessment: ineffective prevention of diseases, poor conditions during husbandry practices, and sea lice treatment issues (Fig. 3). As such, the top three issues cover two health and one environment issue. Subsequently, the combined scores of issues gradually decrease and reach a minimum at 25% of the maximum. Among the top three issues, ineffective prevention of diseases reached consensus on severity and prevalence, sea lice treatment issues only on severity, and poor conditions during husbandry practices on none of the criteria. Overall, health issues score highest, closely followed by environment issues, while nutrition and behaviour issues score relatively low, and the few issues regarding mental experiences scored so low that they were not even considered anymore in the final round.

### 3.2.4. Criteria importance

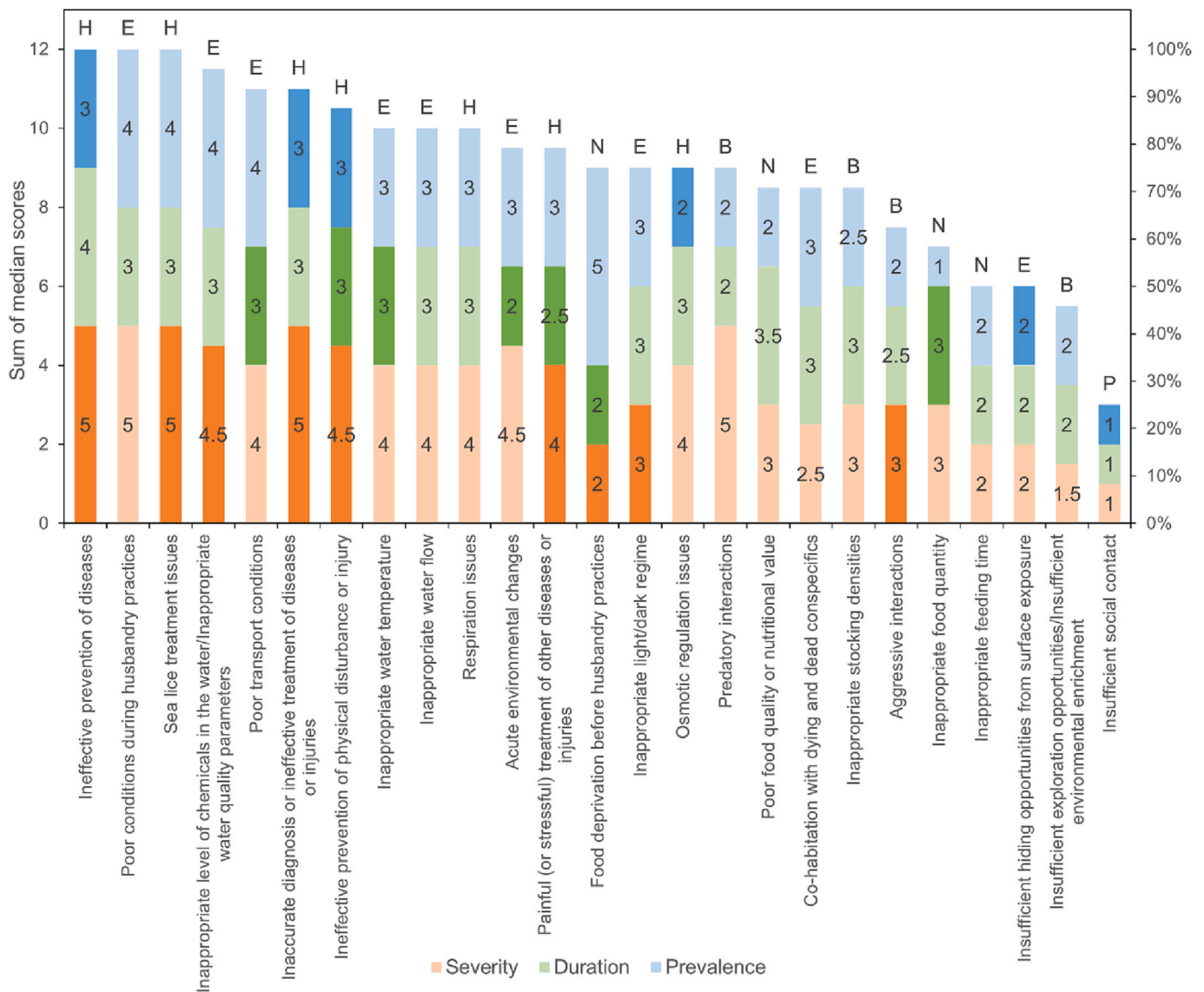
The Delphi participants assigned, on average, severity the highest importance, followed by duration and, at a similar level, prevalence (Table 3). Despite some variation among the participants, they reached consensus on the importance of all three criteria (Table C9). The average of the median scores across the issues is also considerably higher for severity but similar for duration and prevalence, although the order between the latter two switches. This similarity between the importance assigned by experts and the average of the median scores could have resulted from the participants already considering the importance among the criteria when assigning the scores, as one of the participants also pointed out as a possibility. The Pearson correlation of the scores for the individual criteria and the combined scores shows that severity influenced the final results the most, in line with the higher importance and average (Table 3). Prevalence follows it now with a more significant difference to duration, which is due to a combination of the slightly higher average and a higher variation among the participants.

Considering the importance assigned by the Delphi participants as a weight when averaging the median scores across the three criteria leads to a similar ranking of the fish welfare issues as when summing the scores (Fig. 4). There are, above all, less ties when using the weighted average. For example, the top three issues remained the same but did not all score equally anymore. Instead, the ineffective prevention of diseases scored higher than poor conditions during husbandry practices and sea lice treatment issues. The most notable difference in ranking was for predatory interactions that reduced from rank 14.5 (together with three other issues) to 18.

## 3.3. Potential interventions to improve the main fish welfare issues

### 3.3.1. Ineffective prevention of diseases

The participants proposed various interventions to improve the



**Fig. 3.** Combined scores of fish welfare issues in the third and final round of the Delphi assessment. Only the last four issues represent scores from previous rounds because they were excluded in the final round. Sample size: 20 participants. Darker colours indicate that the participants reached consensus. N = good nutrition, E = good environment, H = good health, B = appropriate behaviour, P = positive mental experiences. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

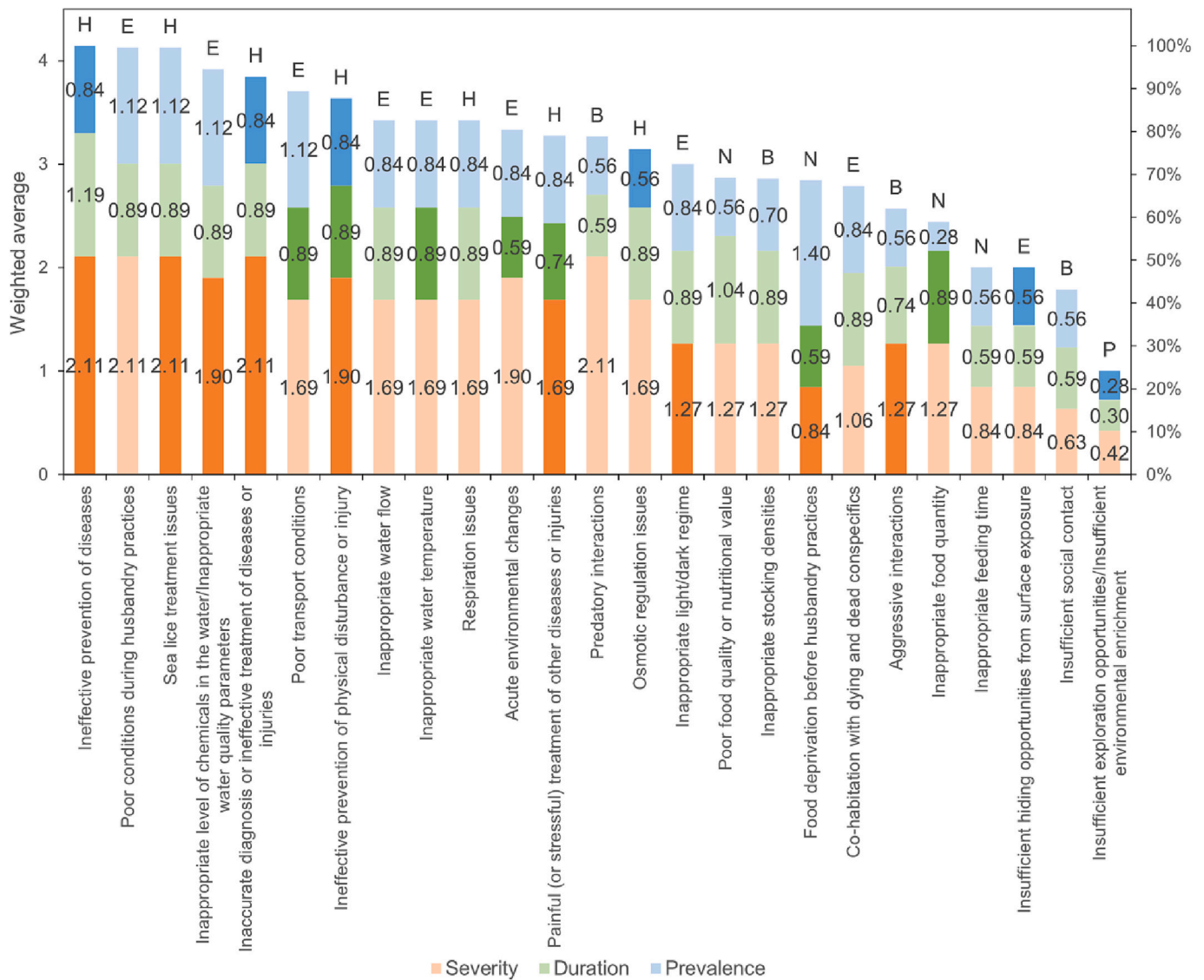
**Table 3**  
Comparison of the three welfare criteria.

	Severity	Duration	Prevalence
Importance by experts (%)	42.2	29.7	28.1
Average of median scores	3.90	2.88	2.98
Correlation with total scores	0.77	0.40	0.60

prevention of diseases, such as the use of vaccines, which corresponds to some recent statements in the literature. [Assefa and Abunna \(2018\)](#) even state that vaccines should be the top priority in disease prevention in aquaculture. Effective vaccines already exist to prevent bacterial diseases. However, this does not apply to many viruses and parasitic diseases. Many participants mentioned the importance of creating new or more effective vaccines; however, some also indicated that there is insufficient money to realize it. Furthermore, more frequent reviews of existing vaccines can ensure the right vaccine choice. The ineffectiveness of vaccines should be documented and reported. Another participant also proposed the possibility of genetic selection and the

application of gene editing approaches.

Multiple participants proposed reducing the stocking density and increasing the distance to other farms to reduce the spread of diseases among fish. Besides, the fish should be tested for as many diseases as possible, going beyond the more likely ones. When detecting a disease early, the further spread can be prevented. A disease outbreak may require depopulation in the infected zone, in which case compensation funds ideally support the farmers ([Palić et al., 2015](#)); however, compensation is not always provided ([Pettersen et al., 2015](#)). Better biosecurity protocols or control programs and further restrictions on moving fish, such as closed well boats or slaughter on the farm, may prevent diseases from entering the system. Moreover, the fish and water surveillance could be increased by, for example, taking e-DNA water samples. [Assefa and Abunna \(2018\)](#) explain that surveillance could identify the possible route of a disease and the emergence of new diseases. New fish with an unknown health status could also be placed in quarantine before adding them to the existing stock ([Assefa and Abunna, 2018](#)). Particles and uneaten pellets should be collected so that wild fish will not be tempted to approach the farms, thereby spreading diseases.



**Fig. 4.** Weighted average scores of fish welfare issues in the third and final round of the Delphi assessment, weighted by importance. Only the last four issues represent scores from previous rounds because they were excluded in the final round. Sample size: 20 participants. Darker colours indicate that the participants reached consensus. N = good nutrition, E = good environment, H = good health, B = appropriate behaviour, P = positive mental experiences. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A participant commented that monitoring water through sensors and fish through sensors or point-of-care analysis of important biological parameters, such as pathogens, stress, homeostasis and osmoregulation, can be very useful for preventing diseases. Moreover, another participant mentioned that after the fish is cured, it should be monitored for a longer period to ensure the pathogens are gone after a disease outbreak. The accumulation of sediments under the cage may serve as a long-term reservoir of pathogens, which is why accumulation should be avoided, as suggested by one of the participants. Moreover, a participant proposed improving water quality and the implementation of a health and welfare plan developed by an aquatic animal veterinarian. Another participant stated that more research, innovation, and access to new diagnostic tools are needed.

**3.3.2. Sea lice treatment issues**

According to some participants, for a few years, sea lice treatment issues have been gaining more attention, and the industry is increasingly putting more resources into trying to improve these issues. One participant explained that treatment is important to keep the lice levels low and save the fish. However, the farmed fish can be treated

approximately every ten days and may also be affected by other diseases in the meantime. The fish cannot handle this amount of treatment or diseases, which results in poor welfare and high mortality. If treatment continues at the same scale, the treatment methods should become less harmful, and infestation should be prevented.

Closed or semi-closed aquacultural systems could help with prevention. In a semi-closed sea cage, the fish may be protected from the upper waters, and deep sea water can be pumped into the cage. Barrett et al. (2020) also named barrier technologies such as skirts, snorkels and closed containment and even concluded that barrier technologies may be the most effective method to prevent sea lice. Besides, reducing the number of farmed fish or cages in an area may also reduce sea lice infestations. One participant commented that farmers should collaborate within zones to administer sea lice treatments simultaneously. According to Arriagada et al. (2017), lice levels five to seven weeks after the treatment synchronization were significantly lower than before collaboration. Especially high-risk locations may require additional regulation and management (Barrett et al., 2020).

Some participants and Barrett et al. (2020) pointed out the importance of new technologies, as well as more rigorous testing of new

methods during the development stage. Another intervention proposed by the participants and Barrett et al. (2020) was the introduction of an effective vaccine. Furthermore, companies have started breeding salmon resistant to sea lice (Barrett et al., 2020). Such selective breeding may be a cheap and effective solution, especially when resistance to treatments is becoming a problem (Gharbi et al., 2015).

When the infestation cannot be prevented, it is important to remove the lice early to prevent rapid spread. The lice larvae should be shielded from the fish. Ideally, the fish should be sorted out when they need treatment by using underwater cameras to detect lice. Access to improved treatment options should be established by gaining more knowledge on sea lice treatment. More research is needed on treatments and their effects on the fish's different lifecycle stages (Aaen et al., 2015), considering also a major shift from chemotherapeutics to mechanical and thermal treatment due to the growing resistance to medicinal delousing, causing new welfare issues (Overton et al., 2019). Besides, training and guidelines for the industry should be established if this is not yet the case. For example, fish handling may be done more carefully. One participant also noted that sedation during treatment might lower undesirable welfare effects. A central platform should be created where farmers may report their observations, such as the adverse effects of certain medications.

### 3.3.3. Poor conditions during husbandry practices

Some participants proposed fewer fish handlings along with shorter crowding time and a lower water flow speed for the fish in pipes. Multiple participants advised against sharp bends in these pipes or any other features where fish may collide with equipment. Solutions could also be lower stocking densities during these practices or better monitoring during crowding with an underwater camera. Oxygen levels should also be monitored (Southgate and Wall, 2001).

Multiple participants mentioned better technology as a potential for improvements and that the development of new technologies or equipment should focus on more animal-friendly practices. For example, the design of pumps should focus on not harming the fish (Southgate and Wall, 2001) and requires testing on fish before using them on a larger scale. One stated that new technologies or production systems are moving fast and often do not focus on the needs of the fish. Other participants stated that more research is needed on comparing the different methods or developing milder methods and routines. For example, new technologies with internal physiological tags may reveal how the fish perceive changes in methods, equipment, or systems. One also stated that humans are currently guessing what is best for the fish instead of focussing on the fish's perception by researching this subject.

Another solution could be focussing more on the fish's natural behaviour to get them in the desired direction. This could be done by implementing a light source or using the water current. Some participants also suggested sedation during these stressful events. One mentioned that fish could potentially be trained to tolerate stressors by positive conditions in the freshwater stage. Another participant mentioned focusing on variability in growth to reduce the need for grading. Besides, the use of an all-in-all-out approach could be beneficial.

Some participants also mentioned improving or increasing the training or guidance of employees. Implementing improved best-practice standards that the farmers should follow could help. Standards for husbandry practices exist, for example, within the RSPCA welfare standards (RSPCA, 2018) or the code of conduct for European aquaculture (FEAP, 2008).

## 4. Discussion

### 4.1. Main findings in context

The fish welfare issues ranking highest are ineffective prevention of diseases, sea lice treatment issues, and poor conditions during

husbandry practices. The first two issues are related to health, while the latter is related to the environment. In a similar study on various farm animals, including pigs, poultry, sheep, beef cattle, dairy cows, and dairy goats, Rioja-Lang et al. (2020) identified a few common crucial issues across all species, of which many were also health-related. In contrast, according to Rioja-Lang et al. (2020), inappropriate nutrition is a big issue among farmed land animals, but for farmed fish, this does not seem to apply, with poor food quality or nutritional value scoring relatively low. Differences can be expected, given the very different types of species. However, it seems as if health-related issues receive more attention by researchers (Rey et al., 2019) and the media (Holen et al., 2019) and, thus, could be perceived as more important, although the same does not apply to poor conditions during husbandry practices. It was estimated that 10% of all farmed aquatic animals are lost because of diseases (Adams, 2019), which underlines the importance of health-related issues.

According to Oppedal et al. (2017), sea lice infestations are even the most problematic parasitic disease for salmonids in Northern Europe, which may explain its high ranking. Over twenty years ago, sea lice infestations were already recognized as a problem. In 1997, the Norwegian National Action Plan Against Salmon Lice on Salmonids was introduced to reduce harm to farmed and wild fish. This included limits for the maximum number of lice per farmed fish and rules for reporting these numbers, monitoring lice infections in wild fish, and the implementation of regional treatment strategies (Johansen et al., 2011). However, by 2009, the average number of lice per farmed fish still remained similar.

Although the Five Provisions/Welfare Aims paradigm was created to direct greater attention to positive welfare states, the fifth provision (Mellor, 2016b), this emphasis was not reflected in the study results. The only welfare issue related to this provision was insufficient environmental enrichment (e.g. exploration opportunities or encouragement of natural behaviour), which scored relatively low and was excluded after the second round.

Some of the interventions mentioned by the experts could alleviate multiple key welfare issues. For example, a lower stocking density can reduce the spread of diseases, including sea lice, and issues during husbandry practices. Monitoring is also relevant to all three main issues, demonstrating the value of intelligent fish farms (Wang et al., 2021). By using automatic systems instead of the observations of the technicians, the detection of diseases and issues during husbandry practices will become less subjective and slow.

The experts highlighted vaccines as important for preventing diseases, including sea lice, of salmonids. This is even though research on fish vaccines has mainly focussed on salmonids, and vaccines were quite a success in Norway (Gudding and Van Muiswinkel, 2013). This could imply that the current situation of effective vaccines is even worse for other fish species, where vaccinations are indeed used less routinely or not at all (Adams, 2019). Besides differences in vaccine use among species, differences also exist among regions (Adams, 2019). Nevertheless, the development of fish vaccines made remarkable progress in the past decades and further progress is expected due to continued cost reductions, changes in European regulations, and the use of new technologies (Adams, 2019).

### 4.2. Reflection on Delphi assessment

When prioritizing welfare issues, the selection of issues included in such an assessment is crucial. This was done through a literature review supported by suggestions from participants in the first round of the Delphi assessment. Involving the participants in the selection proved important, as two out of the three main issues were added because of them. When issues are interpreted differently, this may give biased results. When unclarity was noted, the phrasing of issues was adjusted in a subsequent round. Overlaps between issues were difficult to avoid. For example, the handling of fish before delousing, which may be done

roughly or cause damage, can be considered a sea lice treatment issue and an issue of poor conditions during husbandry practices.

While a sufficient number of participants could quickly be reached, the stakeholder groups were not evenly distributed. An underrepresentation of NGOs, industry, and the government may have resulted in biased outcomes. One participant commented on the negative formulation of the welfare “issues”. For future research, it may be better to take a more positive approach to avoid farmers feeling criticized and discourage them from participating. Most participants were based in Norway, but this may still be representative of Northern Europe, as most aquaculture is also based in Norway. Not all participants completed the entire Delphi assessment, but the attrition was rather low, with only two participants in the final round. Some participants who completed the final round late indicated that they were on holiday. So, carefully timing a Delphi assessment may reduce the risk of attrition.

The Delphi assessment consisted of three rounds, which usually suffices (Hsu and Sandford, 2007). The convergence of group opinions decreased over the rounds, so an additional iteration might not have improved the level of consensus further. Among the three main issues, a consensus was only reached on the severity of ineffective prevention of diseases and sea lice treatment issues and on the prevalence of ineffective prevention of diseases. The partial lack of consensus might partly be due to the breadth of some of the issues. For example, the ineffective prevention of diseases covers various diseases, and participants might have had different diseases in their minds during the assessment. However, even if no consensus may be reached, a Delphi assessment can still give interesting insights into a problem or trend and highlight issues that require further research because of the lack of consensus (Von der Gracht, 2012). Making justifications for the scoring mandatory may have helped to reach consensus, but it could also have increased attrition due to the higher effort.

Variation in the median scores of welfare issues was typically modest. Increasing the Likert scale from 6 to 10 points may allow for more pronounced variation among the issues. The wider scale may also allow the use of the average instead of the median despite the ordinal data type (Von der Gracht, 2012), which would further increase the granularity. To get more reliable results and avoid that some participants consider personal importance weights when evaluating issues across the three criteria (severity, duration, and prevalence), the participants could also be instructed that the most important issue regarding each criterion separately should receive the maximum score, and other issues should be evaluated relative to it (Bottomley and Doyle, 2001).

#### 4.3. Societal implications

Animal welfare is one of the main concerns consumers have about the current food production systems (De Passillé and Rushen, 2005). The welfare of farmed fish has also become a growing concern for the general public, especially in Europe (Kristiansen et al., 2020). Consumers in Norway are willing to pay more for fish products that promise good welfare (Ellingsen et al., 2015). However, they also think the main responsibility lies with the government and the farmers. This study identified which welfare issues are currently the most threatening to salmonids in Northern European aquaculture and can guide the government, farmers, NGOs, and researchers in their attention to improving welfare. Besides, drawing more attention to fish welfare in Northern Europe is important, as Western countries often acted as forerunners for societal concern about animal welfare in the past (Fraser, 2014), which could also induce improvements in other regions of the world.

Many factors that may impact fish welfare also affect the economic sustainability of aquacultural production. Both welfare and the profitability of the farming industry would benefit when issues, such as diseases and injuries, were tackled (Lines and Spence, 2012; Yavuzcan Yildiz et al., 2017; Rey et al., 2019). For example, sea lice treatments cause stress and injury, which may lead to production losses from higher

mortality, reduced growth, and lower quality of the farmed fish (Barrett et al., 2020). Besides, lice control methods account for 10% of all production costs (Oppedal et al., 2017).

Improving fish welfare may also have environmental advantages. Lower mortality would reduce the environmental footprint due to less feed demand and waste production (Ellis et al., 2012). Besides, the prevention or rapid treatment of diseases, such as sea lice, in farmed fish would reduce the transmission to wild fish stocks (Taranger et al., 2015). As another example, good water quality contributes to better fish welfare and healthy ecosystems (Taranger et al., 2015).

#### 4.4. Recommendations for future research

The findings from this study could be considered in the development or revision of fish welfare indices, which enable fish farmers to measure the welfare of their salmon. An existing example is the Salmon Welfare Index Model (SWIM 1.0), for which the developers determined a list of welfare indicators, their weighting factors, and positive or negative contributions to the overall welfare index (Stien et al., 2013). Similarly, the SWIM 2.0 was designed for application by fish health professionals (Pettersen et al., 2014).

While this study has elicited the main welfare issues for salmonids from experts and suggested some interventions, knowledge gaps remain, especially for other species. Welfare can already be improved by adapting or adopting existing procedures from the experiences with the farming procedures of other fish species or farming systems so that new concepts or methods may not be necessary (Lines and Spence, 2012). Yet, differences may exist among fish species and regions, and it would be interesting to conduct similar studies on different species or in different regions. For example, European seabass, gilthead seabream, and common carp could be interesting subjects, as they also belong to the top five fish species farmed in Europe (Eurostat, 2022). Besides, European seabass and gilthead seabream are mainly farmed in Southern Europe instead of Northern Europe, and common carp are mainly farmed in freshwater ponds instead of sea cages (Eurostat, 2022), making some differences likely. Where additional fish species are used within the production systems, their welfare may also be affected and should, thus, also be addressed. For example, cleaner fish used for fighting sea lice of Atlantic salmon face poor welfare and high mortality in sea cages, mandatory reporting of mortality is rare, and they are often wild-caught, putting pressure on wild fish stocks (Overton et al., 2020).

The main welfare issues may change over time, so the identification and ranking of issues require updates. The industry is moving towards new production systems, such as recirculating aquaculture systems, implying closed or semi-closed containments (Ytrestoyl et al., 2020; Lazado et al., 2022). The industry may also be affected by future challenges, such as climate change and increased fish production (Rey et al., 2019). Other issues may emerge, or currently lower-scoring issues may become more important. For example, the growing number of wind farms may negatively affect farmed fish through noise pollution (Thomsen et al., 2006; Kikuchi, 2010). As the study only included explorative research on the interventions, a similar Delphi survey could focus on potential interventions.

## 5. Conclusions

The most critical fish welfare issues for the Atlantic salmon and rainbow trout in Northern European aquaculture are ineffective prevention of diseases, sea lice treatment issues, and poor conditions during husbandry practices. A consensus was reached on the severity and prevalence of ineffective prevention of diseases and the severity of sea lice treatment issues. Examples of interventions to improve the three main issues are lowering the stocking density, better monitoring, and specifically to prevent diseases (including sea lice), also developing more effective vaccines. In the future, new issues may emerge, or other issues may become more important, requiring updates of such an

assessment. While some of the results may apply to other regions and fish species, one can also expect differences. Overall, more research on fish welfare and drawing more attention to fish welfare issues remain highly important to stimulate tackling the most pressing fish welfare issues identified here and fill remaining knowledge gaps.

### CRedit authorship contribution statement

**Lucia van den Boogaart:** Methodology, Investigation, Formal analysis, Visualization, Writing – original draft. **Hans Slabbekoorn:** Writing – review & editing. **Laura Scherer:** Conceptualization, Methodology, Supervision, Writing – review & editing.

### 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

The anonymized scores from the Delphi assessment are available in the article's supplementary material. Statements from the Delphi assessment are not publicly available due to privacy restrictions.

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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.2023.739557>.

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