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Farmed fish welfare practices: salmon farming as a case study.

OVERVIEW ON FISH WELFARE INDICATORS AND THEIR USE FOR BEST MANAGEMENT PRACTICES FOR SALMON FARMING

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FISH WELFARE

1. Introduction

Approximately 180 million salmonids (salmon and trout) eggs are produced each year in the UK making fish farming the largest livestock sector after broiler production (FAWC 2014). Fish farming is predicted to grow exponentially for the next 10 years and is projected to supply over 60 per cent of the global demand for fish for human consumption by 2030 (FAO 2018). There are still burning issues related to the welfare of farmed fish that have to be solved, not only for the benefit of the farmed fish, but also because good welfare throughout the life cycle should result in improved productivity and economic returns for farmers. Welfare is also important during transport, harvest and slaughter and it will impact on product quality (fish appearance and fillet quality).

The main objective of this overview is to review the state of the art of current farmed fish welfare practices, focusing on salmon farming as a model species. Cage farming of Atlantic salmon has been the focus of most welfare measures and practices implemented to date. By reviewing the current salmon welfare state of the art and the Operational Welfare Indicators (OWI) used in salmon farming we can identify areas of potential relevance for other farmed species (e.g. tilapia and catfish) as well as their role in best management practices (BMP).

This review aims to inform discussion of how enhanced welfare practices could be adopted by the sector through better understanding of the key issues by those involved and/or incorporation into BAP standards. It will support identification of problems to be addressed and opportunities to be assessed in the near future and outline how better monitoring and precision fish farming (PFF) could be implemented to improve fish welfare into the future.

2. What do we mean by welfare?

The simplest and most pragmatic definition of 'good welfare' is that an animal is healthy and has what it wants (Dawkins 2008). This definition encompasses the three alternative definitions of animal welfare (Fraser 1997): 1) a function-based definition, which states that animals should be raised under conditions that promote good biological functioning i.e.

health, growth and reproduction; 2) a feelings-based definition, which aims to minimise suffering but also to promote positive feelings (contentment, motivation, companionship, etc.) and freedom from negative experiences (*e.g.* pain or fear) and 3) a nature-based definition, where animals should be allowed to have natural positive experiences similar to that found in their natural habitat. However, the function-based definition has tended to dominate dialogue about fish welfare (Huntingford *et al.* 2006), especially in food-production aquaculture during the growing phase. The functional benefits are also of value to farmers at harvest and slaughter. Fish with better appearance sells best, and stress-free animals taste better and have better fillet quality (Poli, 2009). Arguably, although a function-based definition is enough for basic physiological parameters and health status, it is not sufficient to assure overall good welfare. For example, an isolated salmon could grow and be free of parasites and disease but lack the social interaction needed for their good mental health (definition 2 and 3 for good welfare).

Alternatively, the five freedoms approach provides valuable guidance to improve animal welfare. The concept of the five freedoms was outlined by the Farm Animal Welfare Council, UK (FAWC, 2010) and have been adopted by many welfare organisations i.e. the Royal Society for the Prevention of Cruelty to Animals (RSPCA), American Society for the Prevention of Cruelty to Animals (ASPCA), World Organisation for Animal Health (OIE).

The five freedoms contend that animals should be:

1) free from hunger and thirst (good osmotic regulation in the case of fish)

2) free from environmental challenge (proper water quality, appropriate temperature ranges according to the species, etc.)

3) free from pain, injury and disease

4) free from behavioural restriction (including lack of space and isolation, depending on species)

5) free from fear and distress (avoidance of mental suffering).

Although widely adopted, currently there is concern that they focus on the negative aspects of welfare i.e. "*free from*", rather than improving an animal's quality of life. Further, some researchers claim that focussing on creating stable conditions to maintain an animal's internal stability (homeostasis) may not be ideal for good welfare and we should be incorporating the concept of allostasis (stability through change). Increasingly the capacity of fish to respond to changes and biologically relevant challenges that promote good health and welfare should be the key indicator, rather than trying to minimise any changes (Korte et al. 2007).

Current research suggests that fish are sentient animals and can also feel pain and experience pleasure. Sentience is defined as the capacity to feel, perceive or experience subjectively. Fish possess receptors for detecting noxious stimulus and behavioural studies indicating that they can feel pain and, given the choice, will choose access to analgesics to alleviate pain (Ashley 2007, 2009; Braithwaite 2010; Nordgreen et al. 2009a, 2009b; Sneddon et al. 2003a, 2003b). Critics however argue against the behavioural studies because according to them fish lack the receptors and brain structure which are required to feel pain (Key 2015; Rose 2002, Rose et al. 2014). However, although the brain structure of fish is smaller and different structurally to mammals, there are areas that have similar functions. For example, within the mammal forebrain, the amygdala performs a primary role in the generation of emotions (such as fear, anxiety and aggression) and the hippocampus plays a role in learning. In contrast there are equivalent structures within the fish forebrain (Salas et al. 2006) indicated by impaired avoidance conditioning (as a response to fear) when lesions are present in the amygdala-equivalent area (Portavella et al. 2004), while lesions to the hippocampus-equivalent area impairs spatial learning (Rodriguez et al. 2006).
Whether fish can suffer or not is still being strongly debated, however collective evidence suggests that fish do have the capacity for pain and legislation within the EU currently reflects this view. From the point of view of fish as sentient animals, and assuming they can suffer pain, we should minimise any procedure that can potentially cause distress in fish and seek to implement integrated welfare assessment using Operational Welfare Indicators (Huntingford 2006, Turnbull et al. 2005).

3. Guidance and standards on finfish welfare

Several international independent and governmental organisations have issued recommendations or guidance on fish farmed health and welfare standards. The EU, Council Directive 98/58/EC ,lays down minimum standards for the protection of animals bred or kept for farming purposes, including fish.

The Council of Europe adopted a recommendation on the welfare of farmed fish in 2005. The *World Organisation for Animal Health (OIE*), which focuses mainly on health and welfare, has published an Aquatic Animal Health Code (http://www.oie.int) which emphasises standards related to fish transport and slaughter. The *European food safety authority (EFSA*) panel on Animal Health and Welfare (http://www.efsa.europa.eu/en/panels/ahaw) provides scientific advice and disseminates information on all aspects of food safety, animal disease and welfare for food production animals, including fish. EFSA's focuses on welfare during transport, production, stunning and slaughter. The *Aquaculture Stewardship Council (ASC, https://www.asc-aqua.org),GLOBALGAP aquaculture standard* (https://www.globalgap.org/uk_en/), *Best Aquaculture Practices (BAP*, https://bapcertification.org), *RSPCA Assured (Freedom Food*, https://www.rspcaassured.org.uk) are all certification programs to improve the environmental, social and economic performance of the aquaculture supply chain and most of them incorporate fish welfare into their certification schemes as one of a broader suite of sustainability issues. The *Code of Good Practice for Scottish fin fish culture (CoGP ,http://thecodeofgoodpractice.co.uk)* was developed by the Scottish Salmon Producers' Organisation (SSPO) (http://scottishsalmon.co.uk) to ensure high standards for Scottish finfish aquaculture. Some of these certification schemes are independently audited, and some provide product labelling. As of 2016, 99% of the Scottish salmon farming industry is accredited under the Code of Good Practice and 84% are current members of the SSPO. The RSPCA Farm Assured scheme certifies 70% of Scottish salmon farms (2018).

4. Stressors leading to poor welfare

Stressors are common in the daily life of farmed fish. From egg to adult, fish are under different environmental, physical and social challenges that can trigger a stress response. A stress response is an adaptive strategy for coping with a perceived threat to homeostasis; that is the stable equilibrium the internal body environment attempts to maintain. Animals respond to two different types of stress; acute and chronic. Whereas acute stress results from short term stressors, chronic stress is produced by a single or multiple long-term stressor occurring within the environment or the social group. An acute stress response is an adaptive mechanism which aids survival and should not be detrimental unless it repeats too often. In contrast chronic stress responses result from long-term unavoidable stress and become detrimental to the health and welfare of the animal. Chronic stress decreases the immune response and can lead to the death of the animals if it is not corrected. Allostasis, the process of achieving internal stability or homeostasis through physiological or behavioural change, can be overwhelmed by such stressors. The cumulative effect of several stressors (acute or chronic) can lead to failure in maintaining this stability and a loss of capacity to balance energy input and expenditure, resulting in compromised welfare. Allostatic overload has serious impacts on the health and welfare of the animals and can lead to pathologies and death if not corrected (Wingfield 2003).

An important concept to be introduced in here is the concept of stress coping style (SCS). It is based on the individual differences and the way each fish will cope with a stressful situation (Koolhas et al. 1999). It has been a lot of interest on describing different stress coping styles for fish (wild and farmed) in order to understand how individual animals, perceive and react to threat or different challenges (environmental and social) and how this is related to their health, welfare and immunity. Production parameters of interest that are ultimately influenced by the SCS of each of the individuals within the population are growth, survival, FCR, appearance and disease resistance. By the study of this individual differences we can fully understand the group dynamics within our fish population and use it as a powerful selection tool to improve the health and welfare of the species.

A list of potential welfare stress related issues, over the life cycle of Atlantic salmon *(Salmo salar*), is shown in Table 1. Stressors can be acute that can be mitigated by best management practices or chronic and more difficult to detect and correct. An overview of each stressor is given in the following text.

***Table 1** Atlantic salmon life cycle assessment of stressors*

Life stages	**Farming Events*** **Atlantic salmon (*Salmo salar*)**	**Risk factors/Stressors**
Broodstock	Weight 10-20kg. Age 2-3 winters at sea Anaesthetised before stripping then killed. ~ 1500 eggs/kg of fish.	Same as one/two winter salmon, see below
Eggs	Mixed with sperm in hatchery. Infertile eggs removed. Kept in fresh water of highest quality. Up to 510 degree days to hatch.	Transport Handling Water quality Disturbance (removal of unviable eggs) Light levels
Young stock - Alevin	Yolk sac still attached, 0.1g to 0.3g. Kept in freshwater in indoor trays/tanks, in the dark. Loss of yolk sac just prior to first feeding. Time to first feeding depends on temperature.	Light Water quality Substrate access Weaning strategies (e.g. once yolk sac depleted transition to formulated feed)
Fry	Kept in indoor tanks. First sorted by size ('graded') at around 5g.	Transfer between tanks Netting/Handling Crowding Grading Water quality Water flow Access to food Food withdrawal Stocking density Predators Tank disturbance (cleaning) Light levels Social stress
Parr	Transferred to larger outdoor tanks or in freshwater lochs for 6-12 months, depending on conditions	*Same as fry with the addition of:* Vaccination Anaesthetic Transport to freshwater loch
Smolt (Salmon)	The stage of adaptation to salt water: S0: Smolting at 6 months induced by photoperiod and/or dietary constituents (e.g. increased salt content). S1: Smolting at 10-12 months, 75-120g S2(unusual): Smolting at 12-24 months, up to 400g Transferred to sea pens or seawater tanks.	*Same as fry (excluding tank transfer) with the addition of:* Transport to sea pens (loading, transport, unload) Salt water tolerance (osmoregulation)
One sea-winter salmon Two sea-winter salmon	Matured after one year at sea, 3-4kg. 18-24 months at sea, 5-10kg. Longer for broodstock, 10-20kg.	*Same as fry (excluding tank transfer) with the addition of:* Transport to slaughter Harvesting/Slaughter Sea lice / Amoebic Gill Disease Treatments for disease/parasites and toxicity levels of treatments Vaccinations Environment (weather, temperature, water quality, harmful algae)

*FAWC 2014 Opinion on the welfare of farmed animals

4.1 Feed (Access, Distribution and Quality)

Insufficient feed supply or poor-quality feed (including incomplete diets) will result in poor growth and low survival. Undernourished fish are stressed and less resilient to other problems, such as infectious disease, swimming performance, abnormal behaviours or deformities which may compromise welfare (Tacon, 1992; Lall & Lewis-McCrea, 2007). The use of automatic feeders is a common practise and malfunctions can result in hours or days of food withdrawal leading to an acute or chronic stress response. Aggression has been linked to food withdrawal and this can lead to fin damage (Cañon-Jones et al. 2012). Fin damaged animals are usually smaller in size in relation to the rest of the population and can suffer from chronic stress due to social pressure (Moutou et al. 1998; Noble et al. 2008). Appetite levels of fish are a good indicator of welfare status however water temperature has to be considered as it is also a variable that influences feeding. Sick or infected fish have reduced appetite, so it is a good warning system for fish welfare.

4.2 Stocking Density

Some advocates of improving animal welfare, continue to link stocking density to poor welfare (Stevenson 2007; FAWC 2014). In previous studies the emphasis was on specifying maximum stocking densities, but more recent research has identified that maintaining water quality in the optimal range, for the cultured species, is more important (Soderberg & Meade 1987; Ellis et al. 2002; North et al. 2006; Person-LeRuyet et al. 2008; Hosfeld et al. 2009). The factors may of course be linked, as high stocking densities make maintenance of water quality more of a challenge i.e. ensuring adequate dissolved oxygen (DO), avoiding build-up of fish metabolites and carbon dioxide and any reduction in pH levels (Hosfeld *et al.* 2009). Increasing oxygenation (Colt & Watten 1988; Person-LeRuyet et al. 2008) and water flow (Ellis et al. 2002) allow stocking densities to be increased. In Atlantic salmon, as long as water quality, specific flow rates and feeding requirements can be met then rearing densities of up to 86kg.m-3 can be achieved without compromising production or most fish welfare indicators (Hosfeld et al. 2009; Calabrese et al. 2017). However, where the evaluation of fin damage has been included increasing density has had an adverse effect on fins (Ellis et al. 2002) even though growth rates and overall conditions remained favourable (Cañon-Jones et al. 2011). Social interactions such as hierarchy formation and concomitant aggression leading to chronic stress are believed to explain such fin damage at higher densities although they were well below the recommended stocking densities for salmon over 50g (Table 5). In the Cañon-Jones 2011 study stocking densities (mean fish weight 113g) ranged from 8- 30 kg/m^3.

4.3 Water Flow

In tank systems, water flow rates should be managed to allow the fish to at least 'hold station', a natural behaviour for salmon when they are pre-smolts or parr and live under natural conditions. Exercise in fish (swimming behaviour) has been considered as a good welfare practice for their potential benefits (EU FitFish cost action: https://www.fitfish.eu/en/fitfish.htm). Increasing the flow rate so that fish swim against the current has been used as a method to mitigate against fin damage as it reduces agonistic behaviours (Jobling et al. 1993). Improvements in growth in Atlantic salmon parr were highest when water flow rates allowed them to swim at their preferred speed of approximately 1-1.5 body lengths s^{-1} (Huntingford 1988). Too low a flow rate was related to increased stress in salmon (e.g. elevated plasma lactate levels) possibly due to agonistic behaviours. However, too high a flow rate causes the fish to expend more energy thereby reducing growth (Solstorm et al. 2015). In sea cages the natural water flow should also be sufficient to maintain water quality and this factor influences the location of fish farm sites. During the daytime, salmon smolts typically cruise at 0.3–0.9 body length s−1 (BL s−1) (e.g. review by Juell, 1995; Dempster et al., 2008 and 2009) while night speeds are slower at 0–0.4 BL s−1 (Korsøen et al., 2009). This differences in swimming speed preferences during day and night should also be considered for the flow rates for sea salmon cages close containment designs (CCD).

Off-shore conditions can compromise the fish welfare due to high currents that can drive them to exhaustion and storms that crowd fish inside the net pens and can potentially damage them through physical abrasion or trauma. Reduced water quality can also occur if animals become crowded (FAO,2018).

4.4 Water Quality

As fish are in constant contact with the environment through the gills and skin, water quality is an important factor in maintaining good welfare. Poor water quality is detrimental to fish health as demonstrated through slow growth and high mortalities. Key parameters include suspended solids, temperature, dissolved oxygen (DO), carbon dioxide (CO_2), ammonia, nitrite, nitrate and pH which should be monitored regularly. Optimal levels vary by species but are typically presented as a range: see Table 5 for Atlantic salmon (*Salmo salar*).

Monitoring of sea pens pose more logistic challenges than freshwater sites in general but temperature, DO and salinity should be monitored in any aquaculture facility where feasible and real-time monitoring is recommended. Suspended solids, even at commonly occurring sub-lethal levels, can negatively impact gill health and compromise fish health and welfare (Au et al, 2004).

Nitrogenous compounds produced either as excretory wastes of fish (via gills as ammonia or faeces) or as a decomposition product of uneaten feed and/or algae can be a major problem in aquaculture systems. Ammonia can be present in water in two forms: as un-ionised ammonia (NH_3) and ionised ammonium (NH_4), with NH_3 being highly toxic to fish. Low levels of dissolved oxygen exacerbate ammonia toxicity, (Thurston et al. 1981), as do increases in water pH and temperature (see MacIntyre et al. 2008).

Some fish have been shown to adapt to elevated levels of ammonia (Lang et al. 1987). Growth and visible lesions in rainbow trout (*Oncorhynchus mykiss*) were comparable to controls, after exposure to ammonia concentrations varying between lethal and sub-lethal levels over a number of weeks. However, fish still showed signs of distress with increased ventilation frequency. Ammonia can be converted to nitrite (NO_2) and elevated levels of nitrite are toxic to fish. In flow-through systems the risk of nitrite reaching toxicity levels is low, due to the continuous renewal and exchange of water. However, in recirculating aquaculture systems (RAS), malfunctioning biofilters has led to the build-up of toxic levels of nitrite. Biofiltration is a key feature of recirculation systems designed to remove ammonia, by converting it first to nitrite and then to nitrate. Fish also excrete CO_2 across the gills, which if allowed to accumulate in the water reduces pH. This in turn can increases the proportion of dissolved CO_2 in the water which in turn reduces the capacity for the fish to excrete endogenous carbon dioxide, resulting in declines in blood pH (MacIntyre et al. 2008). Hence degassing or CO_2 'stripping' is a key feature of intensive RAS, especially for marine systems (Moran, 2010 a and b).

The facility system design and husbandry quality can greatly impact on maintaining water quality. Some parameters such as dissolved oxygen, ammonia, CO_2, and nitrites may be more controllable by the farmer while others are more dependent on water source (i.e.

temperature, pH, pollutants) in conjunction with farm practices (i.e. nitrates, suspended solids) (MacIntyre et al. 2008). Management of water quality in ’closed’ (e.g. RAS) and open (e.g. cage) aquaculture systems to ensure high fish welfare are inevitably very different with the latter needing to accommodate seasonality and other water users.

Real-time environmental sensors are currently on the market for monitoring purposes in both tanks and cages. Continuous monitoring of water quality can greatly improve our understanding of changes in feeding or stress behavioural responses of fish. Scaling up and intensification of fish farming is typically associated with greater levels of investment in capital and risk management and continuous monitoring of water quality therefore becomes an essential measure to maintain the level of both profits and fish welfare.

4.5 Handling and Crowding

Both are important stressors for fish and are integral to many stages of the aquaculture process and are covered specifically within the following sections: transport, grading, vaccination, parasite monitoring, weighing, harvesting, etc. The core issue is to emphasise the need to avoid any unnecessary handling and crowding of fish as it can give rise to a range of negative welfare outcomes including poorer biosecurity, health problems, external injuries, degradation of the external environmental conditions (DO, stocking densities, etc). Any procedure that requires handling or can lead to crowding stress should be replaced, if possible, by a less stressful procedure and this will be discussed in each of the specific sections as mitigation measures to avoid handling and crowding of the animals. For example human handling can be replaced by mechanical pumping during transport and grading or other technologies such as use of underwater cameras to monitor the behaviour or feeding response, automatic biomass estimations, etc.

4.6 Transport

There are diverse methods to transport fish. Atlantic salmon for example is moved at different stages by land, sea and air using adapted trucks, well boats and helicopters respectively, but all require fish to be prepared prior to movement. In general food should be withdrawn for a period (for salmon the recommendation is to not exceed 48 hours for all fish stages) to allow fish to empty their digestive tracts (RSPCA, 2018) and thus help maintain water quality during subsequent transportation. Monitoring of dissolved oxygen (DO) is required to ensure appropriate levels are maintained throughout transport. During transportation and slaughter of terrestrial species, monitoring by a qualified person is a legal requirement (FAWC 2014). Transportation of fish is even more demanding; crowding and handling, two of the most stressful events for fish are required and observation of the environment and welfare when the stock is under water is more demanding. Fish pumps are generally used at the beginning and end of salmon transportation for moving fish from and into holding tanks. Fish becoming stuck in the pump lines is a major risk to good welfare along with deterioration in water quality during the journey. The monitoring of plasma cortisol (PC) suggests that the loading process is more stressful than the journey itself, as PC levels were observed to peak after loading but return to baseline on arrival at destination (Iversen et al. 2005). Transport companies have new tank designs that can be loaded onto the boat and avoid secondary transport (pumping again of the fish) to the sea pens (for example in Scotland Migdale Smolts Ltd.).

4.7 Vaccination and Grading

During the freshwater phase salmon are graded and vaccinated prior to smoltification and transfer to sea. Vaccination is a preventative measure to protect fish against potential diseases whereas grading is a common management practice to group fish of similar size together to improve feed utilisation, remove small fish and reduce agonistic behaviours. The RSPCA farm assured guidelines (RSPCA 2018) recommend that grading be kept to a minimum by optimising feed ration and distribution to reduce size hierarchies. After grading, the smallest grades of fish get culled by an anaesthetic overdose. This is mainly during the freshwater stage. During the sea stage of salmon farming vaccination is very rare but grading remains a common practice, with the number of grading events dependent on fish size variation. Salmon are pumped out of the cage onto a boat and graded automatically by machine. In contrast to the freshwater stage, small fish are retained, and only moribund or deformed fish are culled at this stage. There is potential for improving these methods based on a better understanding of learned behaviour in fish to reduce stress. Such responses can be exploited to facilitate sorting and grading. For example, using a conditioned response to a light cue and how fish position themselves to face a water current, they can be encouraged to move through an underwater, size-grading grid (Fjæra & Skogesal, 1993). However, there appears to be little research into the practicalities of such methods at production levels.

Vaccinations can be administered orally (in the feed), by immersion (bath or dip) and by intra-peritoneal (IP) injection. Simultaneous vaccination by injection and grading can avoid the cumulative effect of stress due to handling and crowding (Iversen & Eliassen, 2014). Several measures can reduce the stress of vaccination by injection such as ensuring needles are compatible with fish size, anaesthetics are used to reduce handling stress and operators are trained and fully competent. Although injection is more stressful than other methods, benefits such as delivery of multivalent vaccines, ensuring exact dosages for variably sized fish and demonstrated greater subsequent protection over longer periods are achieved. Differences between Intraperitoneal (IP) oil and water-based vaccinations on the welfare of fish are still to be studied. Oil-based vaccines can result in pollution of water after vaccination, so water quality has to be checked after vaccination has taken place and measures to avoid it should be implemented (e.g. increase water flow, oxygenation, etc). Side effects of IP vaccinations can be local reactions and intra-abdominal tissue adhesions, deformities and impairment of growth. This is mostly due to adjuvants and can cause sickness or even death of the fish (Gudding et al. 2014)

4.8 Social stress

Social interactions, such as between dominant and subordinate individuals within a fish population can be a source of social stress. The outcome of aggressive interactions and access to feed, territories and breeding opportunities can change social behaviour and potentially negatively affect welfare, particularly for subordinate fish (Martins et al. 2012). Indicators of social stress include reduced food intake (thereby reducing growth), changes in swimming behaviour and skin colouration as well as elevated plasma cortisol. However, plasma cortisol levels can also be elevated in dominant fish after aggressive interactions (Øverli et al. 1999). Different parts of the life cycle are characterised by varying levels of aggression; Atlantic salmon parr being more territorial and aggressive than smolts for example (Keenleyside & Yamamoto 1962).

4.9 Predator Control

Fish can be exposed to a variety of predators including wild birds and mammals (e.g. seals, otters, mink). Globally, and especially in freshwater open systems, insects, reptiles and amphibia may, depending on life cycle stage, be important predators. The primary means of protecting fish is through physical exclusion. Both, the welfare of fish and the predator are of public concern. Non-lethal methods of controlling predators are preferred such as ensuring nets are adequately tightened, top nets are secure, dead fish are removed, animal deterrents deployed where permitted to do so and the use of predator nets/seal curtains/screens where appropriate. Net mesh should be sized to ensure that birds are not ensnared. The shooting of seals is permitted only as a last resort and only in exceptional circumstances, for example, where a seal has managed to gain access to an enclosure and is in the act of attacking the fish.

4. 10 Parasites and diseases

The impact of parasites and pathogens on fish health and welfare is determined by threshold values of their abundance in culture systems and can be signalled by a range of indicators. Various forms of prophylaxis and best management practices that can prevent or reduce parasites and pathogens from entering cages, are believed to be the way forward to improve the welfare of the animals and to reduce or eliminate the use of chemotherapeutants to treat the environment and/or the fish.

Questions remain over the availability of approved veterinary medicines and how to effectively administer medicines so that those fish severely affected can be most effectively treated. Farm design can incorporate methods to apply treatments without removing fish from the water. For example, tanks designed to ensure fish swim through an enclosure which contains the treatment, and remain there for a certain amount of time, before being released. Immersion methods are less stressful on the fish than injections and allow smaller fish to be treated, however, there are issues in ensuring that the correct dose has been applied and in general more frequent treatments are required (See section 4.5).

4.10.1 Sea lice (L. Salmonis) control

Sea lice is only a problem within the marine environment and in the UK, it is a legal requirement to maintain specific records on their occurrence in farm stocks. Sites are sampled weekly and information shared between Farm Management Areas (CoGP) so that efforts to manage sea lice are co-ordinated between farms within defined management areas. Treatment is guided by monitoring the build-up of pre-adults to prevent the development of gravid females and is dependent on the time of year. Earlier in the season (1^{st} Feb-30^{th} June) trigger levels requiring treatment are an average of 0.5 female sea lice per fish, which increase to an average of 1.0 female sea lice per fish from 1^{st} July-31^{st} January. All stages of the life cycle of sea lice require enumeration. Sites are left fallow for a period of time after a production run as part of the management strategy to reduce sea lice outbreaks.

Sea lice can cause injury to the fish itself as well as lowering the immune system making the fish more susceptible to disease and increasing mortalities (Grimnes & Jakobsen, 1996; Wagner et al. 2008). Methods of control can include medicinal (based on chemotherapeutants) and non-medicinal, however, the efficacy of medicinal treatments has reduced recently due the sea lice developing resistance. There is therefore increasing emphasis on alternative approaches (Helgesen et al. 2018). Bath treatments using sea lice chemotherapeutants are typically managed either by surrounding the sea pen with a tarpaulin or transferring the fish to a well boat. The key points for fish welfare impacts occur prior to, during and after treatment. When using a tarpaulin, the sea pen is raised nearer to the surface causing crowding which can be a major cause of stress as can the application of the medicine. Water quality, especially levels of dissolved oxygen (DO) need to be continuously monitored to ensure they remain within safe limits. If using a well boat, the fish have the added stress of being loaded on and off the boat. Fish cannot be harvested for a number of weeks after any application of chemotherapeutants.

Non-medicinal approaches to sea lice management include the use of hydrogen peroxide baths, however there are reports of sea lice developing resistance to hydrogen peroxide (Treasurer et al. 2000). Other treatments based on physical removal include brushing and using jets of water to flush lice off fish (e.g. hydrolicer) or passing fish through lukewarm water to kill the lice (thermolicer). However, all these methods require moving fish onto a well boat or the use of a special tarpaulin, exposing fish to many of the same stressors as chemotherapeutants. Alternative methods that do not require chemical use, handling or transfer of fish outside of the culture environment include the use light to manipulate swimming behaviour of salmon and make them go to water layers where sea lice are not present, barriers to deter sea lice from entering pens (e.g. bubble curtains or tarpaulins) and lasers that kill lice after detection by an underwater camera. It can operate 24/7 within a pen and is not supposed to harm fish as fish skin is reflective. More recently farms have been stocking cleaner fish such as wrasse (Labridae) and lumpfish *(Cyclopterus lumpus),* that predate on sea lice living on cage-reared salmon. Cultured or wild wrasse have been shown to be efficient at removing lice from salmon (Skiftesvik et al. 2013) resulting in Improvements in salmon welfare due to the reduced need to handle or crowd the fish. However, continued reliance on harvesting wild wrasse and lumpfish is unsustainable and there is large-scale investment in farming wrasse and lumpfish to support the salmon industry. There is also the issue of the welfare of the cleaner fish themselves, particularly during harvesting of the salmon, and the effect of introducing another species, with the potential to harbour pathogens or diseases that could be harmful to salmon (Brooker et al. 2018). Cleaner fish are also translocated long distances to fish farms and the effect of escapees to the local environment is under-researched (Faust et al. 2018).

4.11 Humane slaughter

Historically, fish were slaughtered through asphyxiation in air or on ice, or by cutting of the gills while still conscious and allowed to bleed out. These methods are considered inhumane although are still practiced within the EU and elsewhere e.g. asphyxia in ice of sea bass and sea bream is still routinely used to slaughter fish in Greece, Spain and Italy (COM (2018) 87). The killing method must render the fish immediately unconscious, and unaware of any pain and this condition should persist until death to be considered humane. Within the UK salmon industry automated percussive and electrical stunning systems are commonly used. During percussive stunning a piston driven by compressed air hits the fish head to kill the fish outright. Electrical stunning occurs after fish are placed on an electrically conductive conveyer belt passing under an electrode; the potential difference generated between the electrode and conveyor belt renders the fish unconscious. Batches of fish can be electrically stunned in water. Electrical stunning is also used to render fish immobile prior to percussive killing. Whereas electrical stunning is reversible, electrocution kills the fish outright and is achieved by varying the electrical parameters (such as voltage, current and frequency). However, electrocution does have some drawbacks, with carcasses showing muscle blood spots and broken bones. All methods are followed by exsanguination. Humane killing by anaesthetics is not permitted within the EU, where fish are intended for human consumption but can be used for emergency slaughter and culling of small-sized or sick/moribund fish. Isoeugenol (found in clove oil), followed by exsanguination, is used for food fish in several countries including New Zealand, Australia and Chile (Robb & Kestin, 2002; Keissling et al. 2008), however exposure to anaesthetics may itself induce stress.

There are a number of welfare issues at the pre-slaughter, stunning and killing stages including:

1) food withdrawal (any cleaner fish should be removed at this stage to avoid predation)
2) handling and handling related procedures (e.g. crowding, time out of water, pumping)
3) Insufficient stunning force or inaccurate blows that do not render fish immediately unconscious.

Poor stunning and slaughtering techniques can be identified and rectified by auditing the welfare at fish slaughter and assigning numerical scores to a list of welfare indicators for a set number of samples, similar to that used during terrestrial animal slaughter (Grandin 2010). Table 2 lists welfare indicators that can be recorded (adapted from terrestrial animals, Grandin 2015).

Table 2 Scoring technique to evaluate welfare at slaughter

% effectively stunned at first attempt (can be determined in fish by several behaviour indicators such as body movement, eye roll or reaction to tail pinch.
% rendered insensible
% physical body defects (e.g. damaged/eroded fins and abrasions)
% bruised carcasses
% other carcass defects

5. Finfish health and biosecurity

5.1 Escapees

Aquaculture and Fisheries (Scotland) Act 2007 allows inspectors to assess the risk of an escape of fish from a site and what control measures are in place to prevent and recover escaped fish. Fish that escape from culture systems represent lost production, as well as being a potential threat to wild fish populations (Tlusty et al. 2008).

Triploid (sterile) fish are used to alleviate the potential threat that escapee fish present to the environment. Triploid fish are produced by 'shocking' the eggs, using either pressure or temperature, resulting in three sets of chromosomes instead of two (diploids). Triploids can occur naturally and triploidy is therefore recognised as genetic manipulation rather than modification (GMO). Triploidy is already used commercially in the fruit, vegetable, oyster and trout industries. There are current problems with trying to produce triploidy in Atlantic salmon. Triploidy in salmon causes a number of deformities such as lower jaw defects, cataracts, short operculum, compressed spine, a reduced number of gill filaments (Sadler et al. 2001) as well as slower growth and higher mortality than normal diploids. It should be noted that these deformities and shortcomings can also be present in diploid fish. Possible reasons for the poorer performance and deformities in triploids are still being researched. However, it is thought that triploid fish require different rearing conditions than diploids. For example, the maximum temperature range for triploids is lower than that for diploids with no mortalities being recorded at 9°C (Atkins &Benfey 2008). Further, inappropriate diets can be problematic, for example higher dietary histidine in triploids can mitigate against cataract development (Taylor et al. 2015).

5.2 Importing live salmonids

Legislation has played a major part in preventing the introduction and spread of serious fish diseases, within the UK, by placing restrictions on the import of live fish. The Diseases of Fish Act 1937 was enacted after the importation of live rainbow trout, infected with furunculosis, devastated wild salmon stocks. The Act made the importation of live salmonids into the UK illegal at that time. Also, the importation of salmonid ova and other live fresh water fish species would require a license and the Act introduced the legal requirement to notify certain diseases (Hill, 1996). The legislation has been further amended and extended to incorporate EU directives. It is a legal requirement for all fish-farming businesses to be officially registered and to maintain records of the movement of fish and fish ova into and from their sites (Diseases of Fish Act 1983). The Diseases of Fish (Control) Regulations 1994 sets out the control measures required to be taken when certain notifiable diseases are detected within farms or wild stocks. Notifiable diseases are listed in Part II, Annex IV of Council Directive 2006/88/EC, as amended or Schedule 1 of the Aquatic Animal Health (Scotland) Regulations 2009. Directive 2006/88/EC classifies notifiable diseases into three categories; Exotic diseases, Non-exotic diseases or Other depending on the significance of the harmful effects on aquaculture and wild stock. Currently live salmonids can legally be imported from certified disease-free zones with a period of quarantine considered good practice.

6. Welfare Indicators

The development and standardisation of best management practices (*e.g.* RSPCA salmon welfare standards) and routine health checks are now considered essential to minimise disease and maintain a good welfare status in the Atlantic salmon sector. Welfare indicators have been developed to monitor health and welfare both in hatcheries and at sea (WI: see Table 3 and 4 on Welfare Indicators and related to the stressors). Such indicators need to be based on preferred environmental conditions (see Table 5 for recommended ranges), physical and physiological status or behaviour. Operational Welfare Indicators (OWI) are on-farm measurements done by farm staff, properly trained to recognise and evaluate them. Most OWI are based on routine husbandry procedures and production measurements. Consistency and correctness of data recording is key for the efficient use of OWI.

An Integrated Welfare Assessment (IWA) should be developed using both Operational and non-operational WI (those performed by specialised personnel like veterinarians, etc. health checks, blood samplings, etc.). Any IWA should include measures regarding health, physiology, behaviour and environmental parameters. The following section considers the Welfare Indicators that have been identified as most important and significant for the welfare of salmon during their production cycle (for example in FISHWELL project 2018, Norway. See Noble et al. 2018). Others like sea lice infestations and environmental parameters have already been discussed in previous sections.

Mortalities are a definitive indicator of poor health and welfare. It is important to monitor losses and distinguish between categories (death, culling and escapes). Failed smolt mortalities after transfer to sea are usually culled by anaesthetic overdose.

Mortalities should be recorded along with **condition and growth rates (SGR)**, which can be calculated from fish weight and length. Fulton's condition index (Fulton, 1904) can be used as a salmon condition index but requires periodical measurements of length and weight of the fish and this is easier at the husbandry stage but possibly more difficult during the on-growing phase in sea cages.

Fin damage can be a result of aggression and a sign of stress (Turnbull *et al*. 1996), and these injuries can be a portal for bacterial and fungal infections. Fin damage indices have been developed for salmon and validated and could easily be implemented as a physical OWI.

Physiological parameters can provide an early indicator of health and welfare problems, although they usually require sacrificing the fish for their evaluation. Physiological parameters that would be easy to evaluate and use as OWIs are the hepatosomatic index (HIS) that is a condition index too and gives us indication of their nutritional state. Lactate and glucose are indicators of chronic stress that is more detrimental to the animal in the long term than the acute stress indicators like cortisol. Periodic sampling for lactate and glucose in plasma blood as well as other blood metabolites and haematocrit can give a good indication of the basal stress levels and the health and welfare status of the population. Lab-on-a-chip kits for measuring glucose and lactate in blood samples are being developed and tested for their use in fish farms. Cortisol is a good indicator for short time procedures likely to produce an acute stress response to the fish like handling, pumping, vaccinating or grading. Cortisol in water has also been tested to be used as a non-invasive method to monitor the stress levels of the fish populations after stressful events or environmental stress and recovery times. Might work for RAS tanks and closed containment systems (CCS) but not applicable to flow-through, ponds or sea pens.

Behaviour can be also used as a tool for the assessment of animal welfare (Dawkins 2003; Bégout et al., 2012) to determine the real preferences of salmon at different life stages. Environmental, dietary and social preferences can be determined by choice tests or place preference tests, and routine monitoring of behaviour at salmon farms may be achieved by visually observing and recording behaviour. More quantitative techniques include sonar and acoustic tagging of sentinel fish.

Automation of data acquisition is essential for the development of the fish welfare and fish farming production in general. The introduction of the concept of Precision Farming in Aquaculture (Føre et al. 2017) has stimulated interest in new methods to innovate around data collection (big data from satellite, sensors and sonar systems) and its analysis (modelling, machine learning, etc.). Some companies have already adopted this vision and are developing integrated environmental sensors with sonar systems to monitor biomass estimations, food efficiency and fish cage distribution for example.

Table 3 List of welfare indicators (WI) based on individual fish and groups of fish. In italics the ones identified by FISHWELL as key indicators to be monitored by fish farms.

Individual fish-based WI	Physical Health	*Mortalities* *Opercula and/or gill damage* *Colour changes (e.g. eye darkening, pale gills, skin colour)* *Fin damage* *Gill health index (Parasites/Amoebic gill disease (AGD))* *Snout damage* Deformities Sea lice infestation Skin damage and Appearance: Lesions/Abrasions/Injuries/ Scale loss and Bleedings (Skin Index) Bacterial load Body condition (hepatosomatic index, Fulton condition index) Standard growth rates (SGR)
	Physiology	*Blood parameters (lactate, glucose,* cortisol*)* *Ventilation rates* *Muscle pH* Immune parameters Smoltification state Heart rates
Group based WI	Behaviour	*Crowd intensity (scale 1-5 in FISHWELL)*) Feeding and anticipatory behaviours and *recovery time after stress* Social interactions Spatial distribution (Vertical and horizontal) Abnormal (e.g. lethargy, not shoaling) / Normal behaviours Sickness behaviours Reactions to carers Activity (Swimming behaviour)
	Environment	Water quality (pH, *Oxygen*, ammonia, nitrites and nitrates) *Temperature* Turbidity *Water flow rates and current speed* Light Predators Salinity Stocking density *Scales in water* Enclosure design/substrate access

Table 4 Welfare indicators as related to the stressors over the life stage of Atlantic salmon

Life stages (FAWC 2014)	Risk factors/Stressors	Welfare Indicators
Broodstock (10-20kg, ~1500 eggs/kg)	Same as one/two winter salmon, see below	Same as one/two winter salmon, see below
Eggs	Transport Handling Water quality Disturbance (removal of unviable eggs) Light levels	Mortalities Colour changes Presence of fungus Water quality measurements-pH, DO, flow rate, temperature Lighting (should be dark) Stocking density not exceeded for trays
Young stock – Alevin Yolk still attached 0.1g – 0.3g	Light Water quality Substrate access Handling Weaning strategies (e.g. once yolk sac depleted transition to formulated feed)	Mortalities Presence of fungus Behaviours-feeding, orientation, activity, Aggressive interactions Water quality measurements -pH, DO, flow rate, temperature Lighting (should be dark) Presence of substrate on emergence Stocking density Weaning index (time of weaning)
Fry First sorted for size ('graded') at around 5g	Transfer between tanks Netting/Handling Crowding Grading Water quality Water flow Access to food Food withdrawal Agonistic behaviours Stocking density Predators (if outside tanks) Tank disturbance (cleaning) Light levels	Mortalities SGR Lesions/Injuries/Abrasions/Fin damage Deformities/Appearance/Colour changes Social/Aggressive interactions Feeding and anticipatory behaviours Activity (swimming behaviours) Normal/Abnormal behaviours Spatial distribution Water- (pH, DO, ammonia, nitrites, nitrates, flow rate, temperature) Lighting (if tanks inside) Stocking density Predator control (nets/lids on tanks etc.)
Parr Development of skin colouration for camouflage	*Same as fry with the addition of:* Vaccination Anaesthetic Transport to freshwater loch	*Same as fry with the addition of:* Body condition Indexes (liver, gill, skin) Ventilation rates/ Heart rates Health checks (blood haematology)
Smolt (Salmon) The stage of adaption to salt water, ~75g-400g depending on when smolting induced	*Same as fry (excluding tank transfer) with the addition of:* Transport to sea pens (loading, transport, unload) Salt water tolerance (osmoregulation)	*Same as fry with the addition of:* Body condition Indexes (liver, gill, skin) Ventilation rates/ Heart rates Health checks (blood haematology) Smoltification state Salinity
One/Two sea-winter salmon Matured after one year at sea, 3-4kg/18-24 months 5-10kg	*Same as fry (excluding tank transfer) with the addition of:* Harvesting (brailing, pumping) Transport to slaughter/slaughter Sea lice/ Amoebic Gill Disease Infectious diseases/ Vaccinations Treatments for disease/parasites and toxicity levels of treatments Environment (weather, temperature, water quality)	*Same as fry with the addition of:* Body condition Indexes (liver, gill, skin) Tissue sampling (e.g. pH and blood spots in muscle from poor slaughter techniques), Parasites Ventilation rates/Heart rates Health checks (blood haematology) Salinity/ Sea lice load Wind speeds, current flow

6.1 Fish spatial distribution within the tanks and sea pens

Spatial distribution of fish in both natural and culture environments are indicative of welfare status. Shoaling of fish and the vertical/horizontal distribution of fish changes under stress. Both salmon and tilapia crowd together at the bottom of the tanks when stressed and swimming patterns change.

It has been suggested that the spatial distribution of fish within a rearing environment can be an indicator of the relationship between each other (Dawkins, 2004) and between the fish and the environment. Therefore, changes in the spatial distribution in a given rearing environment are likely to indicate an emergent welfare issue. Distribution will also be affected by preferred environmental conditions and management characteristics such as stocking density. High stocking densities, for example are more likely to give rise to localized sub-optimal areas into which subordinate fish may be forced (Juell &Fosseidengen 2004; Johansson *et al.* 2006). Mapping how fish move in response to different stimuli (e.g. light, infrasound) may also inform understanding of adaptive behaviour. When presented with a novel stimulus, cage-reared salmon rapidly migrated to the bottom of the cage only returning to their normal swimming depths after cessation of the stimulus, suggesting a stress response (Bui et al. 2013). Fish held at a high enough density will tend to shoal around the perimeter of tanks and sea cages and generally avoid the surface of the water until feeding time (Juell et al. 1994). Atlantic salmon in sea cages were observed to have bimodal distribution when fed a restricted diet suggesting the formation of subgroups with different motivations to feed or approach the surface (Juell et al. 1994).

Table 5 Recommended welfare indicator parameter levels for Atlantic salmon (Salmon salar) during production.

Event	Parameters		Comments
Stocking densities	*Fresh water stocking densities*		RSPCA 2018
	- Hatchery	15,000 per California basket/tray	
	- Multi level	20,000 eggs per tray	
	- First feeding tanks	10,000/m^2	
	Freshwater production		
	up to 1g	10 kg/m^3	
	> 1-5g	20 kg/m^3	
	> 5-30g	30 kg/m^3	
	> 30-50g	50 kg/m^3	
	> 50g	60 kg/m^3	
	Sea water stocking densities		[1]Turnbull et al. 2005;
	- sea water enclosure	22[1] kg /m^3	
	- site maximum	15 kg/m^3	
	Transport	Set by distance travelled but be within 60 - 100 kg/m^3	
Water quality	Temperature	10-18 ∘C (parr not above 16∘C *)	Poli 2009
	Salinity	< 40 mg/l	* RSPCA 2018
	Oxygen	6.0 - 7.0 mg/l	
	CO_2	< 10 mg/l	
	pH	6.5 - 8.5	
	$N\text{-}NH_3$	< 0.01 mg/l	
	$N\text{-}NO_2$	< 0.03 mg/l	
	$N\text{-}NO_3$	< 3.0 mg/l	
	$P\text{-}PO_4$	< 3.0 mg/l	
	Transport	Excessive changes in water temperature and pH to be avoided.	RSPCA 2018

Event	Parameters		Comments
Flow rate	Must allow fish to hold station (Adjustable in tanks/determined by site location in lochs and sea)		
Mortalities	Eggs to 1st feed (~10 weeks)	6% weekly	RSPCA 2018
	1st feed to 5 g (~10 weeks)	3 % weekly	
	5 g to smolt (~20 weeks)	1.5% weekly	
		Marine Scotland's Fish Health Inspectorate should be notified when fish mortalities exceed these levels	
Grading	Must only start when fish weigh in excess of	1.3 g	RSPCA 2018
Feeding	Alevins	Feeding must start when 90% of alevins have lost their yolk sac	RSPCA 2018
	Withdrawal periods	Not exceed 48 hours (Prior to grading, transport to sea)	
		Not exceed 72 hours (At harvesting)	
Handling	Time out of water never exceeds 15 secs unless anaesthetised. Goal is no fins above water, some fins showing acceptable.		RSPCA 2018
Crowding	Monitor crowding distress by behaviour (colour changes, escape behaviours, gasping). Use of scoring indexes to monitor and record.		RSPCA 2018
Smolting	Visual checks and observations (score colour changes) for several weeks during the period prior to smolting ATPase test preferred to test whether fish smolting. Hypertonic water testing (above 35 parts/1000) for smolt survival prohibited.		RSPCA 2018

Event	Parameters		Comments
Stress monitoring	Behaviour	Foraging behaviour, individual and group swimming behaviours, levels of aggression, fin damage (scoring indices), ventilator activity, stereotypic and abnormal behaviour.	Martins et al. 2012
	Positive welfare	Exploratory behaviours, feed anticipatory behaviour and reward related operant behaviour.	Martins et al. 2012 Galhardo et al. 2011
	Cortisol	Cortisol is a natural adaptive response and needs to be measured in conjunction with other behavioral indicators for context.	Ellis et al. 2012

6.2 Research on welfare for catfish and tilapia in comparison with salmon

The most commonly farmed finfish globally are carp, salmon, tilapia and catfish. Several species of tilapia and catfish are cultured commercially, the most important tilapia species being the Nile tilapia (*Oreochromis niloticus*). The predominance of a specific catfish species depends on location, for example, Pangasius spp. and a range of *Clarias* species are popular in South and South East Asia whereas Nigeria has developed a major industry around the African catfish (*Clarias gariepinus*). The farming of channel catfish (*Ictalurus punctatus*), long established in North America, has grown rapidly in China (HSA, 2018) which now produces considerably more than the US (227v 145k MT, 2017). Earthen ponds are by far the most common farming system for both tilapia and catfish, although tanks, raceways and cages in lakes and reservoirs are also used for more intensive farming. Tilapia and catfish are warm water fish and are tolerant of a wide range of water quality and nutritional regimes, which make them an ideal fish for aquaculture in developing countries. In Asia and Africa, feed is often still produced on-farm or by small scale semi-commercial feed manufacturers. However, these farmers and producers often lack information on the nutritional requirements for the different life cycle stages of the farmed fish. This leads to issues with poor feed formulations and reduced production (Hasan & New, 2013). Intensified production based on formulated commercial diets is increasingly common in countries with the most dynamic industries. In ponds, typically harvesting occurs after partial draining of ponds by seining, before final drainage and harvest. Earthen ponds may have deeper, harvest sumps to facilitate holding of fish live before harvest. In some areas, partial harvesting of channel catfish occurs throughout the year by using large mesh-sized nets which allow sub-market sized fish to escape. Ponds are then re-stocked with fingerlings to replace the harvested fish. In cages the nets are lifted to crowd the fish together, or moved to shallow water, and fish removed by hand net. Harvested tilapia are transported either packed ‘dry’ with or without ice in boxes or live in aerated tanks to fish markets or processing plants. If transported live they are mainly killed using ice water (FAO 2004-2018; FAO 2005-2018). The major species of Pangasius (*P. hypothalamus*), which are facultative air breathers, and raised at super-intensive levels in ponds (500mt/ha; Little and Bunting, 2016) are typically transferred from the pond side using baskets without water to well boats and then on live to processing plants.

Once at the processing plant they are slaughtered by having their gills cut and bled out. Channel catfish are transported live, in water, to processing plants where they are electro-stunned before being de-headed and eviscerated (Silva et a. 2001). Percussive stunning of tilapia and catfish is difficult due to the protection afforded by the skull in these fishes (Lines & Spence, 2014).

This section is based on a Web of Science literature search to identify and quantify the research undertaken for some of the major stressors (Table 6) and welfare indicators (Table 7), as reviewed previously in this document for salmon. The comparison is then made with similar research undertaken on tilapia and catfish. It should be noted that the generic terms for salmon, catfish and tilapia were used in the search term, so the citation numbers refer to research done for all farmed species, rather than any particular species. The search terms used are as listed in Table 6 and Table, with the emphasis on research related to welfare and events likely to cause stress. The abstracts in the search results were reviewed to determine their relevance to the topic. Where large numbers of irrelevant documents were identified the search, terms were modified to include more parameters or the criteria changed from being a topic keyword to being in the title of the document. Therefore, the number of citations for each of the terms refers to the search results minus any articles considered to be irrelevant.

It can be seen in Table 6 that research pertaining to welfare in general is less established in tilapia and catfish than salmon and for welfare indicators, in particular, is almost non-existent. Research on certification is much more established in the salmon industry than for tilapia and catfish, perhaps reflecting a bias towards high value, export species. Although tilapia and catfish exports to OECD country markets are considerable, fast-growing domestic consumption has been unappreciated by the international research community (FAO 2005-2018; Belton et al, 2017). However, no publications on the effects of certification and welfare could be identified.

Table 6 Literature search for some major stressful procedures, showing the number of citations for generic terms salmon, catfish and tilapia in article titles and the search terms as topics, unless otherwise stated (accessed November 2018)

	Terms important for welfare	Number of citations: Salmon	Catfish	Tilapia
	Welfare	276	42	50
	Welfare indicators	32	0	3
	Certification (title)	18	2	2
	Certification (title) AND welfare	0	0	0
Stressors	Transport AND stress	23	15	10
Stressors	Harvest AND welfare OR stress	23	4	4
Stressors	Harvest AND pump*	7	4	0
Stressors	Humane slaughter	7	4	3
Stressors	Slaughter AND stress	54	11	10
Stressors	Grading (title)	6	12	1
Stressors	Anaesth* (title)	21	12	11
Stressors	Sedat*	21	44	35
Stressors	Stunning	34	11	7
Stressors	Biosecurity	19	5	16
Stressors	- Biofouling	14	0	0

Little systematic research has been carried out on the harvest, transportation and slaughter of catfish and tilapia, under commercial culture condition. The difference in the more intensive salmon farming methods compared with the pond culture of tilapia and catfish is reflected in these numbers. However, research is lacking within areas of salmon culture as well, particularly in humane slaughter. A major proportion of all the research related to slaughter, sedation and anaesthetics in catfish was conducted on the silver catfish (*Rhamdia quelen*), that has assumed little status as a farmed species but clearly become favoured as an experimental animal. The effects of pre-stunning using electro-stunning (Lambooij et al. 2008) or nitric oxide (Wang et al. 2017, 2018) prior to slaughter have been researched, although it is unclear if these methods are widely used within the industry. Biosecurity is an issue for farming tilapia and catfish, particularly where a significant proportion of the industry is based on ‘open’ systems i.e. nets and cages in rivers and lakes; this makes escapes into the wider environment more likely and makes management of parasites and pathogens problematic. In areas where they are non-native, escapees are likely to have a detrimental effect on biodiversity. Both tilapia and catfish can tolerate diverse habitats, therefore competing for resources with many other species. Channel catfish, in particular, are capable of hybridising with other species (Townsend & Winterbourn, 1992) and hybridisation with local species and strains has become a major area of contention in the uptake of tilapia farming in much of Sub-Saharan Africa. Sub-contracting of harvest to specialised teams is common for both species; risks of pathogen transfer between farms and regions is therefore significant as sanitary precautions such as net disinfection is rare. (Bebak et al. 2015).

Table 7 shows the results of the literature search on some welfare indicators (WI), as identified in this document (Table 3). The WIs have been grouped in a similar manner to that published by the FISHWELL project 2018, Norway (See Noble et al. 2018, pg. 109). The indicators have been broken down into environmental-based and animal-based WIs with the animal-based WIs further sub-divided into either group or individual based WI. An examination of the welfare indicators in table 7 again reflects the different levels of intensification characteristic of farming regimes typical for salmon and catfish/tilapia. It is likely that with any increase in intensification in catfish and tilapia farming more welfare indictors will become increasingly relevant. For example, the effects of vaccination, fasting, increasing stocking density, crowding and behaviour have, hitherto, been little researched. Catfish and tilapia can tolerate wider variations in water quality compared to salmon, but some strains don’t perform very well under these conditions. Therefore, more research is required on the effects of increasing intensification.

Table 7 Literature search for welfare indicators (WI), showing the number of citations for generic terms salmon, catfish and tilapia in article titles and the search terms as topics, unless otherwise stated (accessed November 2018)

			Number of citations		
		Terms important for welfare	Salmon	Catfish	Tilapia
Animal based WI	Individual based WI	Feed			
		- self feeding/demand feeding	10	6	11
		- feed regime	30	10	10
		Vaccin* AND stress	19	1	2
		Vaccin* AND deform*	19	0	0
		Injuries (title)	33	7	1
		Fin AND damage OR erosion	41	4	2
		Condition factor (title)	19	25	15
		Parasites AND disease AND health	664	265	140
		Parasites AND disease AND welfare	74	4	3
		Cortisol AND welfare	51	17	22
		Cortisol AND stress	355	130	169
	Group based WI	Mortality	451	81	49
		Behaviour AND welfare	90	18	16
		Spatial distribution (title)	60	7	2
		Crowding	17	2	8
		Aggression	155	24	53
		Social stress	43	9	35
	Environmental WI	Stocking density AND stress	37	19	29
		Water flow AND water quality	189	30	22
		Water flow AND water quality AND farm*	11	12	11
		Water quality AND welfare	26	4	8
		Predat* (title) AND aqua*	157	34	26
		Predat* (title) AND aqua* AND welfare	0	0	0
		Photoperiod (title/topic) AND welfare OR stress	20	10	5

7. Concluding Remarks

Salmon aquaculture production has increased and improved its standard procedures considerably as the knowledge base regarding site selection, basic husbandry, feed formulation and availability of genetically improved fish has developed. At this point in time salmon aquaculture is expanding all over the world through corporate investment in an ever more consolidated sector. A major focus for this investment has been developing novel technology to improve production and avoid the main health problems facing the industry.

Despite the pace of development many challenges for salmon aquaculture addressed in this overview still remain to be solved. Key issues like control of parasites, bacterial and viral infections continue to undermine both the welfare of the farmed animals and the profitability of the systems. Management of predators has, rightly, become increasingly subject to regulation and increased societal scrutiny as aquaculture shares space with other human activities and natural habitats. The control and mitigation of the effects of extreme events like storms or trends in temperature changes linked to climate change will require animal welfare-centred responses. Handling and vaccination and water quality, transport and stunning methods remain problematic with regards to the welfare of fish and need to be improved based on validated technology.

The main gaps to be addressed in improved welfare salmon farming also have relevance to the needs of other species. Our literature search on welfare for other species identified major areas of research still to be developed within the tilapia and catfish industry. These included, but were not limited to, water quality control (environmental monitoring), harmonisation of grading and handling protocols, biosecurity issues, staff training and professional development and harvesting and welfare. The least literature found was on welfare related to certification schemes and harvesting. Information regarding parasite control related to welfare was also very scarce. Surprisingly there was quite a lot of information related to group based operational welfare indicators like mortality, behaviour and welfare and aggression and social stress mainly for salmon and tilapia. Those two species are characterised by their high levels of aggression and hierarchical interactions both for larval and juvenile stages as well as adults. Most of the studies are related to cannibalistic behaviours and ways of mitigating it.

One of the most worrying results, and in great contrast to the salmon industry, is the relatively limited level of nutrition development in the context of rapid intensification of both tilapia and catfish. Live transport and the use of ice stunning are also welfare issues to be solved and further research on stress responses caused by this method in comparison with other recommended methods like electro-stunning should be investigated as well as the mitigation measures to decrease crowding and handling stress. Best Management Practices are urgently required in these areas.

Future challenges in salmon aquaculture that will affect fish health and welfare are expected to be mainly related to climate change, increased fish production, secure fish-feed supply, enhance disease control under new conditions and farming systems. Efforts to reduce waste and re-use of fish secondary products, prevent escapees and the likely movement of salmon aquaculture to novel environments like off-shore more exposed, high energy sites or in land Recirculation Aquaculture Systems (RAS) for on growing facilities will all raise new challenges. Many of these challenges already affect intensive and super-intensive tilapia and catfish systems, particularly in Asia, that are still managed using high levels of manual labour and relatively little labour-saving technology

With new challenges come new opportunities and so the increase in production will demand an improvement in monitoring systems and their consequent technology development. The concept of Precision Fish Farming (PFF) already developed and in current use for terrestrial systems will have to be applied in aquaculture with the use of sonar and sensor systems for feeding control and optimisation or feed and waste management. Real time fish behaviour will be monitored by sonar systems and cameras deployed in tank and sea cages. Key environmental parameters will also be monitored in real-time with sensors deployed within the tanks and cages to correlate with the fish behavioural responses to environmental stressors and husbandry procedures. The challenge that different production systems (Off-shore and in-land production systems) will face would have to be addressed.

New molecular technologies like genetic engineering and nanoparticle development for the delivery of vaccines or immune stimulant diets will have to be considered to avoid handling and excessive chemical and antibiotic treatments. Prophylaxis approaches with the use of temperature gradients within the aquaculture systems to improve disease resistant and boost the immune responses will have to be developed and assessed (behavioural prophylaxis and fever). And finally, a better understanding of the welfare of farmed fish based on the concepts of sentience and cognition is essential and future improvement on fish welfare will have to be based on the research obtained from neuroendocrine, immune and behavioural studies that evaluate the sensory world of the fish to respond to their specific needs.

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CERTIFICATION SCHEMES

8. Welfare Indicators used in some common Salmon Certification Schemes

This part of the report presents a gap analysis of welfare indicators used by the five most common certification schemes for aquaculture and makes recommendations on which ones to include and how to measure and audit them. The database, presented as part of a review study (Amundsen & Osmundsen; 2018) on sustainability indicators for salmon aquaculture, was used and searched specifically for the welfare indicators listed in Table 5 in the Fish Welfare section above. (https://sustainfish.wixsite.com/sustainfishproject/ search-indicator-database). The data was extracted and categorised from certification scheme audit documents for salmon aquaculture (Table 8).

Duplicates and irrelevant items were deleted. Duplicates arose as the same indicator was used in multiple domains within the database (i.e. Fish health and welfare, Accountability & Enforcement, Biotic effects, etc.). The total number of indicators found, relating to fish health and welfare, are presented in Table 9. These results were further categorised into *direct welfare indicators* (D WI) that are based on direct measures onto the fish (i.e. mortalities, handling) and *indirect welfare indicators* based on measures that indirectly affect the welfare of the animals (InD WI). These indirect measures were mainly based on environmental parameters or husbandry procedures (i.e. stocking density, water flow). A further category, identified as regulatory (R), indicators, was not direct measures (i.e. training of staff, documented plans for processes to ensure welfare etc.) but based on Standard Operational Procedures (SOPs) and management data from the fish farm (see Table 10). Outcomes from the different categories and welfare indicators are presented in *Annex1* with detailed specifications.

As the database only covered salmon the relevant certification schemes for tilapia and catfish were searched for welfare indicators that could be categorised as direct or indirect welfare indicators and are also shown in Table 8. As the RSPCA and SSPO certification schemes relate to salmon, only ASC and the generic GAA-BAP and GlobalGAP schemes feature for tilapia and catfish. Detailed specifications on the categories can be found in *Annex 3*.

8.1 Key points of comparison between standards

The emphasis on welfare between the five standards was highly variable based on the analysis presented, based on a simple count of the number of indicators used. RSPCA and to a lesser extent SSPO were far more welfare-orientated than the three major international standards (ASC, BAP and GlobalGAP). Among the latter, GlobalGAP appeared to have a more comprehensive assessment of welfare than BAP with double the number of direct indicators (11 vs 5). ASC has the least focus on welfare. The relative number of indicators considered to be auditable gives scope for some to be included into current standards (Table 11). The structure of the standards makes direct comparisons more difficult. Whereas ASC has separate standards for salmon, tilapia and catfish, both BAP and GlobalGAP have generic standards plus the BAP Salmon standard, which is only for the marine stage, plus seafood processing. Furthermore, the ASC catfish standard is for Pangasius rather than Ictalurus; although both pond-based, production intensity and management are highly different for the two species. Perhaps as a result, the BAP Animal Health and Welfare Standard is very non-specific stating many intentions but having very few specific auditable points, even in comparison with ASC. An example from BAP-Finfish and Crustacean Farm Standard v2.4 page 31 (section 14 on Animal Health and Welfare on Culture conditions and Practices on the implementation section) is shown below: -

"The temperature and chemical composition of culture water should be appropriately maintained, and changes in water quality should be made slowly so the species being cultivated can adjust to the changes. Adequate levels of dissolved oxygen shall be maintained"

This is not a compliance auditing clause but when you try to find the compliance points (9 in total within this section) related to this particular implementation section there is no specific standard related to this point other than the point 14.8:

14.8: Health management procedures shall be defined in a health management plan or operating manual, reviewed and approved by a fish health professional, that includes procedures to avoid the introduction of diseases, protocols for water quality management, health monitoring and disease diagnosis techniques.

A key issue is if detailed auditing guidelines are made available and adhered to for the range of species and culture systems covered by the current BAP standard. If not it's very difficult to conceive that this section of the standard is currently fit for purpose.

There are three approaches to improving the welfare component in BAP –certified facilities and more broadly in the sector.

(1) Identify **low hanging fruit** for modifications of the current standard that will improve measurability of welfare either directly or indirectly. An example of this is BAP 5.5. Records of effluent parameters are already required but these could be modified to ensure relevance for welfare as well as effluent quality. Currently only required at quarterly intervals, these would need to be modified to ensure water quality *within* the culture system was monitored and recorded rather than only at the outlet point. Minimum and maximum DO and temperature levels over a 24 hr period could be easily transformed to OWI.

(2) Address through **training &/or competency support**. An example of this might be to enhance the Standard (14.2) aiming to ensure "*Feeding shall be managed to avoid stress caused by under- or overfeeding*" through development or dissemination of species and system specific feeding tables. Similarly (14.3) the vague wording "*the facility shall define upper limits for time periods of fasting, crowding and time out of water to ensure best welfare practices and provide accurate records showing that these limits are respected'* could be supported by demonstrated competency to assess such parameters for fish species that are system and context specific. On-line materials that make use of images to score appropriate crowding levels (as developed by the RSPCA for salmon) for example could be developed to facilitate this.

(3) **Develop a high welfare auditable 'bolt-on' standard** that can supplement current generic statements such as (BAP 14.4) '*facility staff shall make regular inspections of the culture facility, water quality, and behavior and condition of crustaceans or fish'*. This might take the form of assessing welfare through behavioural responses of tilapia and Pangasius at feeding.

9. Criteria for incorporating welfare indicators in certification schemes

Welfare indicators that are considered directly auditable are based on a number of criteria:

1. Quantifiable (or at least qualitatively assessed by scoring or checklist).
2. Relevant to the welfare status of the animal

3. Able to be assessed by the farm staff and not disruptive of normal site operations.

From Table 10 we extracted all auditable welfare indicators and commented on in Table 11. In *Annex 2* these indicators are explained and how the audit should be implemented with recommended values for scoring or collecting raw data. This refers to salmon but can be adapted to other species. Values should be found in literature, reports or SOPs (Standard Operation Procedures) from each company and different species.

10. List of recommended welfare measures that can be incorporated and audited

Recommendations to improve fish welfare are proposed based on the salmon overview and the comparison between certification schemes and associated auditing methods.

1. Training staff: if they had training or not (formal or by other members of staff and number of external CPD courses)
2. Each farm should have a list of direct OWI and health monitoring sampling protocols in place.
3. Number of monitoring systems available for:
    a. Monitoring behavior of the animals (stress indicators)
    b. Monitoring the environment (sensors for DO, ammonia, nitrates, salinity, turbidity, algal blooms)
4. Humane killing method identified by each species.
5. Reduce and mitigate handling stress by pumping, conditioning, etc.
6. SOPs available for each procedure and handed: grading, vaccination, chemical treatments, transport (primary and secondary),
7. Mitigation measures: enrichment, temperature, light, flow rates and currents (each require recommended levels and auditing methods)

Table 8 Certification schemes and standards used in the search for direct and indirect welfare indicators

				# of indicators	
Certification scheme	Standard	Version	Species	Direct	Indirec
Aquaculture Stewardship Council (ASC)	ASC Salmon Standard	v1.1 Apr 2017	Salmon	3	3
	ASC Pangasius Standard	v1.0 Jan 2012	Pangasius	2	6
	ASC Tilapia Standard	v1.1 Apr 2017	Tilapia	1	4
Global Aquaculture Alliance (GAA)/Best Aquaculture Practices (BAP)	Finfish & Crustacean/Sea food BAP salmon	v2.4/v4.2 v2.3	Salmon	5	10
Global Aquaculture Alliance (GAA)/Best Aquaculture Practices (BAP)	Finfish & Crustacean/Sea food	v2.3/v4.2	All finfish	5	9
Global GAP	Aquaculture/GRASP	v5.0/v1.3	All finfish	11	6
Royal Society for the Prevention of Cruelty to Animals (RSPCA)	Farmed Atlantic Salmon	Sep-15	Salmon	52.5	39.5
Scottish Salmon Producers Organisation	Code of Good Practice Seawater lochs	Feb-15	Salmon	19	17

Table 9 Total number of welfare indicators listed in each certification scheme (for salmon)

	ASC	GAA	GlobalGAP	RSPCA	SSPO
Stocking density	2	3	2	15	2
Water quality	7	12	3	13	5
Flow rate	0	0	1	2	0
Mortalities	4	1	6	7	3
Grading	0	0	2	23	4
Feeding	0	2	11	17	11
Handling	0	2	1	10	2
Crowding	0	1	1	9	10
Smolting	2	1	0	7	4
Behaviour	0	0	0	5	4
Positive welfare	0	0	0	0	0
Cortisol	0	0	0	0	0
Stress	0	1	3	13	7
Slaughter	0	2	3	2	0
Harvest	0	2	7	7	10
Physical Health	4	1	3	15	5
Total	19	28	43	145	67

Table 10 Number of welfare indicators, in each salmon certification scheme, broken down into direct welfare indicators (D WI) based on animal measures, indirect welfare indicators (InD WI) based on environmental variables and Regulatory (R) based on regulations and documentation, for example ensuring staff have appropriate training to recognise conditions that compromise welfare. A 0.5 mark indicates a particular indicator that covers both direct and indirect indicators.

	ASC			GAA-BAP			GlobalGAP			RSPCA			SSPO		
	R	D WI	InD WI	R	D WI	InD WI	R	D WI	InD WI	R	D WI	InD WI	R	D WI	InD WI
Stocking density	2	0	0	2	0	1	0	0	2	4	0	11	1	1	0
Water quality	5	0	2	4	1	7	2	0	1	4	0.5	8.5	3	0.5	1.5
Flow rate	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0
Mortalities	2	2	0	1	0	0	4	2	0	3	4	0	3	0	0
Grading	0	0	0	0	0	0	1	0	1	10	12	1	1	3	0
Feeding	0	0	0	2	0	0	9	1	1	5	8	4	0	3	8
Handling	0	0	0	1	1	0	1	0	0	4	6	0	1	1	0
Crowding	0	0	0	0	1	0	0	1	0	3	2	4	4	2	4
Smolting	1	1	0	1	0	0	0	0	0	3	3	1	3	1	0
Behaviour	0	0	0	0	0	0	0	0	0	0	5	0	1	2.5	0.5
Positive welfare	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cortisol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stress	0	0	0	1	0	0	1	2	0	2	6	4	0	4	3
Slaughter	0	0	0	0	2	0	2	1	0	2	1	0	0	0	0
Harvest	0	0	0	1	0	1	6	1	0	5	2	0	9	1	0
Physical Health*	* No indicators found in certification scheme database for colour changes (eye darkening), body condition, opercula or gill damage, SGR/growth rates.														
- Injury/damage	0	0	0	0	0	0	0	1	0	0	1	5	1	0	0
- bleed	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0
-sea lice	3	0	1	0	0	1	0	0	0	6	2	0	4	0	0
Total	13	3	3	13	5	10	26	11	6	53	52.5	39.5	31	19	17

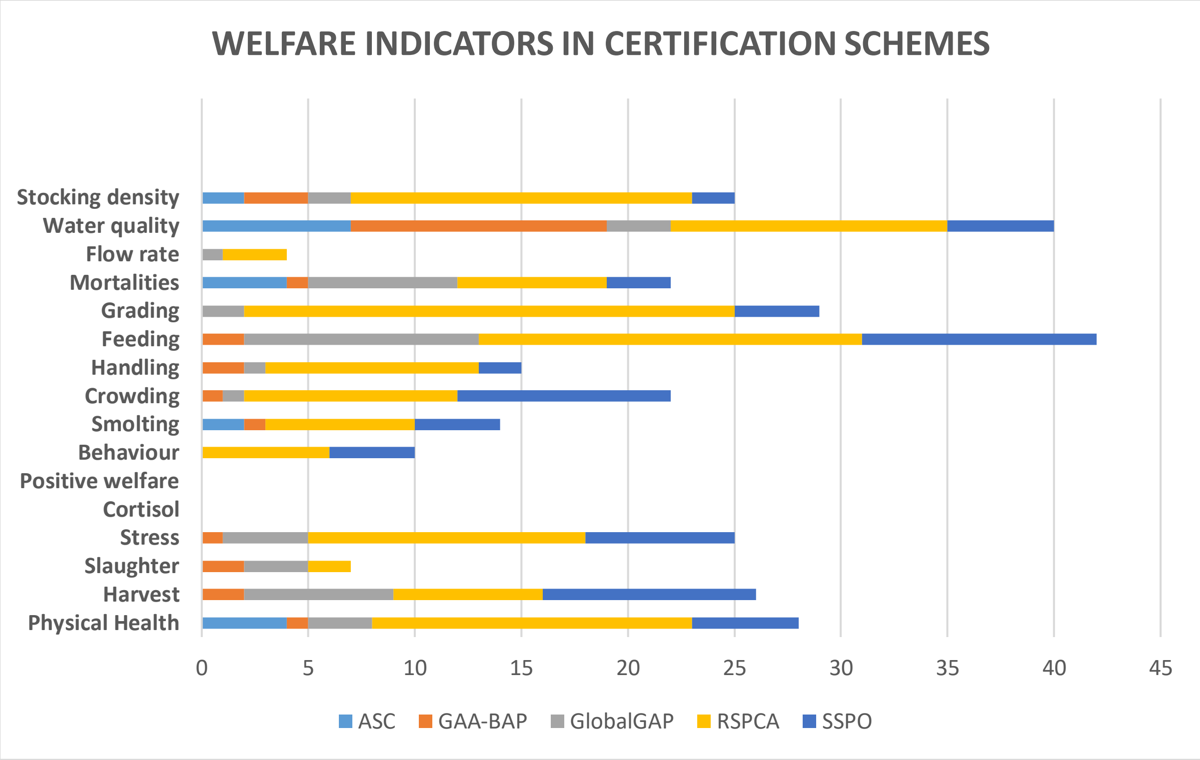

Figure 1 Number of regulatory, direct and indirect welfare indicators that are audited in each of the Certification schemes analysed (detailed in Table 9).

Table 11 Number of direct and indirect welfare indicators that are considered directly auditable, extracted from Table 10. See Annex 2 for details.

	ASC			**GAA-BAP**			**GlobalGAP**			**RSPCA**			**SSPO**			**COMMENTS**
	R	D	InD	R	D	InD	R	D	InD	R	D	InD	R	D	InD	
Stocking density						1						11	1			Record stocking density, retrievable mortalities and final survival. *Raw data or %*
Water quality			2			2						7			2	Already incorporated in most certification schemes. *Checklist and raw data*
Flow rate												1				Important parameter in itself and to calculate water exchange; system specific. *Raw data*
Mortalities		2									2					Monitored if possible –to detect timing of any acute episodes as well as calculated at harvest-see SD above. *Raw data*
Grading										1	6					Easy to include in farm records either as grade or no grade at different sizes or % in different size cohorts. *Checklist or raw data*
Feeding											4			2		Feeding levels should be in farm records to allow independent auditing of feeding consistency and as a proxy for feed response and vitality. Temperature dependent. *Raw data*
Handling					1						4			1		Class handling into 'likely to physically damage for example/scale loss scoring index. Likely related to species and size. Training by use of optimal technique by video. *Checklist and evaluation of training and*
Crowding					1							3			2	Working volumes recommended, use of aeration/DO levels/duration of crowding event. *Scoring system from best to worst conditions*
Smolting											2	1				Only applicable for salmon. Similar indicators for other species would be sexual maturation. *Scoring system*
Behaviour																Feeding response after stressor: transport, vaccination, grading, etc. *Raw data by latencies to eat or scoring system (% of fish eating/time from stressor applied)*
Positive welfare																e.g. in tilapia breeding systems provision of nest environments *Checklist (yes/no)*
Cortisol																Not operational unless reactive strips are developed for cortisol in mucus. Invasive by blood sampling. *Raw data*
Stress														1		Behavioural indicators of stress e.g. feeding response (see in feeding), shoaling.
Slaughter					1		1				1					Strong national rules. *Check list or scoring system from more to less humanely*
Harvest											3			1		
Physical Health*	* No indicators found in certification scheme database for colour changes (eye darkening), body condition,															Direct Operational Welfare Indicators (OWI) by *scoring systems*
- Injury/damage											1	2				Often linked to handling.
- bleed								2			1					When dead. *Checklist*
-sea lice											2					Only in salmon. Other parasites for other species
Total	**0**	**2**	**2**	**0**	**3**	**3**	**1**	**2**	**0**	**1**	**26**	**25**	**1**	**5**	**4**	

References

Amundsen, V. S., & Osmundsen, T. C. (2018). Sustainability Indicators for Salmon Aquaculture. Data in Brief. https://doi.org/10.1016/j.dib.2018.07.043

Annex 1 List of fish welfare indicators from 5 certification schemes

(separate document)

Annex 2 List of directly auditable indicators (subset of Annex 1)

(separate document)

Annex 3 List of indicators relevant to fish welfare for tilapia and Pangasius

(separate document)