Improving the welfare of farmed Atlantic salmon


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Foreword

Atlantic salmon are sentient beings and must be provided with a good quality of life in a farmed environment.

This document focuses on the seawater phase of Atlantic salmon rearing by addressing the provision of good housing, good feeding, good health and opportunities to express appropriate behaviour in line with the adapted Five Freedoms model of Welfare Quality.

GOOD ENVIRONMENT

Two key factors for the provision of a good environment are stocking density and water quality.

Stocking density

The concept of a minimum rearing space for fish is more complex than for terrestrial species as fish utilise a three dimensional medium (Conte, 2004; Ellis *et al.*, 2002a). Additionally, stocking density is not uniform at any point in time; it will increase as fish grow or decrease following grading and therefore, it is hard to measure precisely in the farm environment.

Stocking density is an important management tool for optimising farmed fish welfare but is strongly influenced by both environmental factors and fish behaviour, some of which are still poorly understood. Environmental parameters such as temperature and dissolved oxygen (DO) can fluctuate substantially within a sea cage and have a significant impact on welfare by creating areas of poor water quality (Johansson, Juell, Oppedal, Stiansen, & Ruohonen, 2007; Johansson *et al.*, 2006). Individual salmon respond to these changing conditions as well as to internal drivers, such as level of hunger and perceived threats, by making active trade-offs that often override their preferred position in the sea cage (Adams, Turnbull, Bell, Bron, & Huntingford, 2007; Ellis, 2002; Juell, Oppedal, Boxaspen, & Taranger, 2003; Oppedal, Dempster, & Stien, 2011; Turnbull, Bell, Adams, Bron, & Huntingford, 2005).

The spatial variability of water quality parameters restricts the space the fish can occupy, so that salmon may congregate at densities 1.5-20 times higher than the calculated stocking density (the total biomass divided by cage volume) which assumes salmon are spread uniformly across the sea cage (Oppedal, Vågseth, Dempster, Juell, & Johansson, 2011). In terms of fish welfare, this means that using higher calculated stocking densities may force more fish into sub-optimal environmental conditions, such as waters with high temperatures or low dissolved oxygen, and reducing stocking density will alleviate this. For example, reducing stocking density from 18-27 kg/m^3 to 7-11 kg/m^3 allowed a greater proportion of caged salmon to occupy the more favourable, but restricted volume above the pycnocline[1] (Johansson *et al.*, 2006).

Ocean temperatures have risen over the last century (Domingues *et al.*, 2008) and various scenarios predict global rises in water temperature over the next century of 1-3°C (Pachauri, R K, & Reisinger, 2007). This would give rise to longer periods of sub-optimal warm surface temperatures with increased periods of hypoxia within sea cages (from higher oxygen demand from the fish and lower solubility of oxygen in warmer water). Hypoxia will change the nature of environmental trade-offs, driving fish to limit their vertical distribution and crowd in even denser schools (Johansson *et al.*, 2006) making it even more important to limit stocking densities and for improved site selection and farm management under a changing climate scenario.

[1] A sharp density gradient generally formed by salinity or temperature differences between water layers. Often found in conjunction with large changes in dissolved oxygen.

Most stocking-density scientific studies based on commercial sea cages use calculated stocking densities rather than observed swimming densities of the fish and may underestimate how crowded conditions become. In addition, without continuous vertical environmental monitoring it is not known how severe the effects of environmental fluctuations are. What is evident from published data on Atlantic salmon based on average stocking densities is that stocking above ≈22 kg/m^3 leads to an increased susceptibility to disease, physical injuries, stress and reduced growth and water quality (Adams *et al.*, 2007; Calabrese *et al.*, 2017; Johansson *et al.*, 2006; Oppedal, Vågseth, *et al.*, 2011; Turnbull *et al.*, 2005) and are clearly associated with poor welfare (see Table 1). These detrimental effects at high stocking densities are not solely due to a deterioration in water quality as similar effects at high stocking densities were seen in salmon kept in tanks (Adams *et al.*, 2007) where water quality can be carefully controlled and was noted in the study to be "generally high". The authors postulated that the lower welfare scores obtained could be due to increased collisions between individual fish or with tank walls. (Ellis *et al.*, 2002b) suggests that competition for depths based on the trade-off preferences of salmon may be another way in which adverse welfare effects are seen at high stocking density in sea cages – or put simply, salmon need space to live and to adapt to their surroundings.

Table 1. Summary of scientific research on the effect of stocking densities in the Atlantic salmon welfare

Maximum stocking density	Details	Reference
22 kg/m^3	<22 kg/m^3 best welfare according their SWIM[2] model (Salmon Welfare Index Model)	(Stien *et al.*, 2013)
26.5 kg/m^3	Above 26.5 kg/m^3, the feed intake, growth and feed utilization declined and there was an increase in cataracts, skin and fin erosions	(Oppedal, 2011)
25 kg/m^3	Welfare score[3] lower at stocking densities of 15 and 35 kg/m^3 compared with 25 kg/m^3. Rates of aggression peaked at 15kg/m^3 in seawater tanks compared to 25 and 35 kg/m^3.	(Adams *et al.*, 2007)
7-11 kg/m^3 better than 18-27 kg/m^3	18-27 kg/m^3 stocked fish have limited abilities to position themselves at preferred temperatures compared with 7-11 kg/m^3	(Johansson *et al.*, 2006)
22 kg/m^3	Above and below 22 kg/m^3 the welfare score decreased. At high densities (>22 kg/m^3) fin damage increased.	(Turnbull *et al.*, 2005)

[2] A semantic model to make a formal and standardized assessment of fish welfare using a set of selected welfare indicators (water temperature, salinity, oxygen saturation, water current, stocking density, lighting, disturbance, daily mortality rate, appetite, sea lice infestation ratio, condition factor, emaciation state, vertebral deformation, maturation stage, smoltification state, fin condition and skin condition).
[3] The combination of several welfare parameters using a statistical model results in a welfare score.

The majority of the studies that have trialled lower stocking densities have mainly focused on feed restriction, being hard to distinguish the effect on feeding regime from the stocking densities trialled. Several of the studies showing increased aggression at lower stocking densities were carried out using set ration or restricted ration feeding in tanks rather than sea cages (where the majority of salmon are farmed) (e.g. Adams *et al.*, 1998; 2007). Appropriate stocking densities for Atlantic salmon in seawater tanks have yet to be discerned. In addition, adult Atlantic salmon fed set amount of food in meals show more “scramble competition and aggression” than do those fed to demand using a feedback control system (Andrew *et al.*, 2002 from Huntingford and Khadri, 2008) so that the above aggressive tendencies could be related to feeding methods rather than stocking densities *per se*.

Based on existing science and knowledge from industry practice, Compassion recommends that Atlantic salmon are kept at a stocking density of 10 kg/m^3 or less during the seawater phase. This is to allow salmon to disperse to more favourable areas when water conditions are sub-optimal to gain access to feed, find a preferred temperature or dissolved oxygen level (Oppedal, Vågseth, *et al.*, 2011) and prevent forcing fish into unfavourable and stressful conditions. Ideally, at each site, environmental factors should be continuously monitored over at least 4 different depths in selected sea cages and these factors taken into consideration along with the prevailing conditions and fish behaviour when deciding whether stocking density is appropriate. Poor welfare can occur at any given stocking density and stocking densities should be reviewed after every production cycle (Oppedal, Dempster, *et al.*, 2011).

Water quality

Water quality has a fundamental role in the health and welfare of farmed Atlantic salmon. Indeed, one of the principal concerns about high stocking density is that it can lead to a deterioration in water quality. Oxygen, temperature, salinity and turbidity[4] are all important parameters. Water circulation also plays a vital role in disposing of waste products and allowing oxygenated water to circulate. Some of these factors can be controlled by farm management practices while others are related to the environmental characteristics of the site and should be assessed prior to starting farming.

Poor water quality can lead to both acute and chronic health and welfare problems. In particular, it can give rise to acute or chronic stress, reduced ability to control homeostasis, increased susceptibility to and incidence of disease, reduced body condition, increased fin erosion and gill damage, reduced growth and increased mortality (Ellis *et al.*, 2002; North, Ellis, *et al.*, 2006).

Ideally water quality should be assessed prior to setting up a farm at a particular site. However, once the farm is established it is important to understand how the water conditions change both spatially and temporally. This includes monitoring the environment the fish are actually experiencing and also the water quality throughout the depth of the sea cage. This information is essential to understanding how the fish congregate within the sea cage.

Both temperature and salinity can be measured outside the sea cage whilst dissolved oxygen and turbidity are affected by the fish themselves so should be measured inside the sea-cage (Noble *et al.*, 2018). Turbidity can be measured using a Secchi disc to gauge water transparency. Ideally continuous monitoring probes (e.g. CTD probes) should be used but if not available then multiple sensors at various depths can be utilised.

[4] The clarity of the water.

Table 2. Optimal water quality parameters for post-smolt Atlantic salmon in seawater cages

Parameter	Data from EFSA (2008)	Data from RSPCA welfare standards	Data from scientific literature[5]
Oxygen concentration	>70% saturation (O_2 decreases with increasing water temperature and salinity)	>70%	>80% (Lars H. Stien *et al.*, 2013)
pH	7.0-8.5°C		
Temperature	1-18°C / avoid sudden changes in temperature (preference for 16°C-18°C)	NA	10-15°C (Lars H. Stien *et al.*, 2013) 11-20°C (Johansson *et al.*, 2006)
Salinity	Salmon in the on-growing phase in sea water can tolerate a wider range of salinities		(Kim, Jo, & Lee, 1994)
CO_2	Its concentration depends on pH, temperature, salinity, respiration of fish and other organisms	<15 mg/L	(Gonçalves *et al.*, 2006)
Ammonia	< 0.02 mg/L	<0.025 mg/L	
Nitrite	< 0.1 mg/L		<0.1 mg/L (Wedemeyer, 1996)
Other metals (copper, iron, zinc and cadmium)	Hypoxic conditions, temperature increase and acidification make fish more susceptible to metal intoxication		
Total suspended solids	15 mg/L		(Thorarensen & Farrell, 2011)
Water flow	Sufficient water flow for removal of waste products and uneaten food and for oxygen provision	Sufficient to facilitate movement of the fish and not be so strong as to cause the fish injury	<1.5 body lengths/s (Noble *et al.*, 2018)

[5] A lot of the data and references used to produce this table and recommendations are compiled in the: Welfare Indicators for farmed Atlantic salmon: tools for assessing fish welfare.

Given the importance of water quality in Atlantic salmon welfare, Compassion recommends the continuous monitoring of water quality parameters (dissolved oxygen, temperature, turbidity and salinity as a minimum) at multiple depths in/around sea cages. This data is crucial to understanding how the fish behave and aggregate within a sea cage. When changes in the environment occur which lead to sub-optimal conditions within a sea cage, management steps should immediately be taken to address any welfare impacts upon the fish e.g. by oxygenating the water, reducing biomass within the cage or increasing cage volume.

GOOD FEEDING

Efficient feeding systems have not only to meet the salmons' nutrient requirements and minimise water pollution but also result in good salmon welfare. The quantity of feed offered, and the feeding method used must ensure that all the fish have access to feed and they are satiated in order to remove the need for competition and aggression. Factors such as appetite, number, size variation of fish and how the feed is distributed must be taken into account, as well as natural feeding rhythms. Daily food intake is also affected by seasonal and environmental factors such as temperature and day length.

Fasting

The predictability of the feeding time can influence feed intake and stress levels in fish. For example, an increase in frequency and severity of dorsal fin damage is seen when there is unpredictable feeding (Cañon Jones, 2012).

Withholding food from animals that have previously been fed on a regular basis is stressful (Waagbø, Jørgensen, Timmerhaus, Breck, & Olsvik, 2017) and likely to negatively impact welfare (Santurtun, Broom, & Phillips, 2018). Fish are starved prior to different husbandry procedures including sea-lice treatments, transport and slaughter. An empty gut will slow their metabolism and physical activity before handling. This serves to reduce water fouling (undigested feed, faeces and microorganisms) as fish become crowded together and also reduces the consumption of oxygen, ammonia and carbon dioxide building up in the water (EFSA, 2009; Farm Animal Welfare Committee (FAWC), 2014; Jobling, 2006; RSPCA, 2018). Atlantic salmon are also starved before slaughter to empty the gut for food hygiene reasons to minimise the risk of the flesh being contaminated with faeces during gutting (Wall, 2000). Additionally, fasting is thought to increase tolerance to stress by reducing metabolic activity (Waagbø *et al.*, 2017).

Since temperature is one of the main factors influencing gut evacuation rate and metabolic activity this should be taken into account when calculating the fasting (i.e. by utilising degree days).

Degree days = temperature °C x number of days

However, in combination with degree days, a maximum starvation period of 72 hours will be enough to allow gut evacuation at lower temperatures and is necessary to improve welfare. This will prevent excessively long starvation periods that are not essential, e.g. to allow more time for larger harvests or for perceived flesh quality benefits.

This is based on the following evidence:

- to effectively reduce salmonid metabolic rates, a fasting period of only 2-3 days is required (Einen, Waagan, & Thomassen, 1998; Krogdahl & Bakke-McKellep, 2005).
- there are few studies demonstrating additional beneficial effects on stress tolerance by starving fish for longer periods than three days (Einen *et al.*, 1998).
- although salmon slow their metabolism when fasted (including a reduced activity in swimming and digestion) there is no evidence that this reduces stress responses prior to slaughter (Waagbø *et al.*, 2017).
- despite gut emptying times being temperature dependent (with gut emptying taking longer at lower temperatures) it has been found in Atlantic salmon smolts that at 10^{o}C and 14^{o}C it takes less than 48 hours to reduce stomach contents to <5% and <72 hours at 6^{o}C (Handeland, Imsland, & Stefansson, 2008).
- Robb concludes that no evidence exists for additional benefits from fasting salmon beyond 72 hours (Robb, 2008).

Fishmeal

The content of salmon feed is also an important issue with animal welfare, and wider sustainability, consequences. As Atlantic salmon are a carnivorous species, their feed contains a percentage of animal protein and oil sourced from wild-caught fish (caught by so called 'reduction fisheries'). The use of wild-caught fish for reduction to fishmeal and fish oil (FMFO), which is then added to farmed fish feed, represents food wastage, as the majority of these fish are in fact human-edible and energy is inevitably lost during the process. For example, only 28% of protein fed to salmon results in human-edible protein (i.e. as salmon flesh) (Fry, Mailloux, Love, Milli, & Cao, 2018). The welfare of the fish caught by reduction fisheries is very poor during capture, landing and killing; there is no humane slaughter practised. Therefore, the FMFO industry has substantial negative welfare consequences, and should be addressed in addition to farmed salmon welfare.

Compassion recommends that feed provided for farmed Atlantic salmon must be of optimal quality for fish and the feeding method used must minimise competition and hence aggression and ensure that all the fish have access to feed. Fasting periods should only be used when absolutely necessary and when advised by a vet. If used, for instance prior to a disease treatment, fasting periods should be no longer than is required for fish welfare benefits (i.e. to reduce oxygen requirements and waste accumulation in the water) and should not exceed 72 hours for each fish, even when calculated by degree days. Records of the dates and duration of fasting should be kept.

Compassion also recommends that the amount of FMFO in salmon feed be reduced as much as possible, while still providing for the nutrition needs of farmed salmon. This can be done by replacing some of the FMFO with other ingredients that can meet nutritional requirements, e.g. fish trimmings (or waste from other agricultural processes where suitable, e.g. poultry), algal oils, etc.

GOOD HEALTH

Health is a fundamental measure of welfare. Farmed fish are more vulnerable to disease than their wild counterparts given intensive farms often create the ideal conditions for diseases to spread e.g. keeping fish in high stocking densities and also expose salmon to higher levels of stress on a daily basis, which compromise their immune system (Fast, Hosoya, Johnson, & Afonso, 2008). Thus, an array of serious health problems (see Appendix 1 for more details) are associated with intensive fish farming. Moreover, poor health also leads to decreased adaptive responses to other stressors, reduced feeding and negative social interactions (Conte, 2004).

Common diseases

The incidence of several of the diseases that were a major problem in aquaculture has been substantially reduced through the development of effective vaccination and improved management (see Appendix 1 for more details). The vaccination procedure, however, can cause harm and stress, for example, fasting, internal or external injuries and infections, such as post-vaccine fungal infection, peritonitis and abdominal adhesions (Midtlyng (1997), Bjørge *et al.*, (2011). Sørum & Damsgård (2004) found that the growth rate of vaccinated fish was reduced by up to 20%. Choice of vaccine should depend on the level of disease threat balanced against assessment of fish welfare effect of the husbandry procedure.

In salmon farming major concerns are sea lice, infectious salmon anaemia, pancreas disease, heart and skeletal muscle inflammation, cardiomyopathy syndrome, yersiniosis (Norway) and amoebic gill disease. Several countries have reported finding Winter Ulcer Disease in salmon caused by Moritella viscosa and in addition flavobacteriosis, furunculosis and saprolegniosis (Baltic salmon)[6]. Cardiomyopathy syndrome caused by piscine myocarditis virus (PMCV) is of increasing concern in Norway as is piscine reovirus infection (PRV1)[7].

Sea lice

Efficient sea lice control remains one of the most important challenges for the salmon farming industry. Sea lice are parasitic copepods (small crustaceans) that feed on the skin and protective mucus of salmon causing mechanical tissue damage, increased mortality rates, chronic stress and may also act as a vector of other diseases (Bowers *et al.*, 2000; Johnson, 2004). While sea lice are a naturally occurring salmon parasite, and at low numbers do not cause significant damage, high parasite numbers can occur when host fish are kept in crowded, confined spaces such as salmon farms (Barber, 2007; Jansen *et al.*, 2012). This results in damage to the skin and underlying tissues, secondary infections, poor welfare and suffering for the individual fish (EFSA, 2008).

Effective methods to establish and maintain lower lice levels on salmon farms, and hence reduce their impact on health and welfare of the fish, are crucial. However, the treatments that exist to treat parasites often introduce their own welfare problems. Several key scientists have stated that for most farmed salmon where lice levels are low, frequent handling and treatment associated with delousing may be a more serious welfare issue than the lice themselves (Noble *et al.*, 2018).

The salmon farming industry has previously relied heavily on chemotherapeutants (azamethiphos, cypermethrin, deltamethrin and hydrogen peroxide) to treat sea lice either via baths or in-feed methods. However, their extensive use has caused an increase in the resistance of sea lice to many of these chemicals (Aaen, 2015), and may have detrimental environmental effects, especially where combination therapies have been employed (Fernandes *et al.*, 2001; Read & Fernandes, 2003) and (Jackson, Moberg, Stenevik Djupevåg, Kane, & Hareide, 2018).

[6] Welfare Standards for Farmed Atlantic Salmon - https://www.berspcaassured.org.uk/media/1251/rspca-welfare-standards-salmon-sept-2015-with-august-2017-updates.pdf
[7] http://www.eurl-fish.eu/Activities/survey_and_diagnosis

In the last few years treatment has shifted towards non-chemical procedures. Treatment methods using heat (Thermolicer®, Optilicer®), mechanical methods (FLS, Hydrolicer®, SkaMik – see Table 3) and the use of biological controls such as cleaner fish (A. Powell *et al.*, 2017) are all increasing in their use (see Appendix 2 for more details). For example, in Norway, more than 81% of sea lice treatments were with chemotherapeutants in 2012-2015, but by 2017 more than three quarters were thermal or mechanical (Overton *et al.*, 2018). However, all sea-lice treatments have significant negative welfare impacts to the salmon and other species, particularly non-chemical procedures which are often overlooked as being fairly benign. The Norwegian Food Safety Authority received 400 reports of lice treatment associated with mortality in excess of 0.2% during 2016 (Brit Hjeltnes *et al.*, 2012).

Table 3. Summary of mechanical sea lice treatments

Parameter	Pre-treatment	Treatment method	Efficacy
Hydrolicer®	Fish crowded and pumped	Closed pipe chamber where inverse water turbulence is used to knock lice off fish	82-100% mobile lice; effect on attached stages uncertain (Hydrolicer rep)
FLS	Fish crowded and pumped	Two low pressure (0.2-0.8 bar) washers/spray nozzles used to remove lice from fish	81-100% mobile lice, effect on attached stages uncertain (Gismervik *et al.*, 2017)
SkaMik	Fish crowded and pumped	Similar to FLS but using brushes* and pressure to mechanically remove the lice	85-95% lice removed (SkaMik rep)

* after developments to the system in 2017, SkaMik stated that the brushes are mainly used to steer salmon through the system rather than brush off the lice (Hjeltnes B, Bang-Jensen B, Bornø G, Haukaas A, 2018).

In Norway, a survey by fish health personnel (employed by farming companies and the Norwegian Food Safety Authority) scored water jets combined with brushing worst according to many health parameters (scale loss, skin bleeding, wounds, fin damage and increased delayed mortality), while thermal treatment scored badly due to acute mortality. Salmon farmers reported that scale loss and mortality was common and they also observed bleeding gill and wounds during developmental phase testing for mechanical treatments (Hjeltnes B, Bang-Jensen B, Bornø G, Haukaas A, 2018). Other injuries noted relating to mechanical treatments, included reduced appetite lasting several days, eye injury, damaged opercula, mortality related to weak fish/ gill problems, reduced mucus production and poor skin health/ ulcer development.

Cleaner fish are also extensively used as an alternative to chemical sea-lice treatments. The most commonly used are the lumpsucker and wrasse species (lumpsucker (*Cyclopterus lumpus*); goldsinny wrasse (*Ctenolabrus rupestris*); corkwing wrasse (*Symphodus melops*); ballan wrasse (*Labrus bergylta*)). These species have extremely poor welfare when used commercially; a problem that will only escalate as cleaner fish use is estimated to increase to 50 million by 2020 (10 million of which will be in the UK) (Society, 2018). Issues such as sourcing, husbandry, slaughter and high mortality all make using cleaner fish on salmon farms untenable (see Text box 1).

Text box 1

- Wild caught cleaner fish fisheries have no legislative management – we have very little information of the state of the wild stocks.
- Extremely high mortality rates have been reported on entering sea cages – up to 75-100% in some cases (Brooker *et al.*, 2018; Johannsen, 2018; Skiftesvik *et al.*, 2014).
- If they do survive, cleaner fish suffer considerably through inadequate nutrition, handling during vaccination and poor husbandry (Powell *et al.*, 2017).
- It has been suggested that approximately one third of lumpsuckers die of starvation after only a few months – the lack of food may cause cleaner fish to target salmon fins or salmon eyes (Treasurer, 2013; Powell *et al.*, 2017).
- Inadequate housing causes significant suffering as all cleaner fish require shelter to avoid aggressive interactions and predation from salmon. It is especially important for lumpsuckers as they need a surface to attach to in order to rest overnight since they do not have a swim bladder to control their position in the water column (Imsland *et al.*, 2015; Treasurer & Feledi, 2014).
- Low efficiency of cleaner fish: only between 15 and 36% of lumpsuckers actually consumed.
- Sea lice when they were observed (Imsland *et al.*, 2018; Imsland *et al.*, 2014). Lumpfish stop consuming sea lice when they reach a certain size and wrasse go into winter dormancy at low temperatures so do not feed.
- They suffer from several diseases as bacterial infection, amoebic gill disease, furunculosis, cataracts and can also be parasitized by sea lice (Powell *et al.*, 2017).

Other methods also exist, for example underwater lasers that shoot lice off the fish (Optical Delousing™, Stingray Marine Solutions AS, Norway) have been introduced as an alternative to cleaner fish, but so far documentation of delousing efficiency in commercial farming is anecdotal (Holan *et al.*, 2017). Anti-lice lasers are now in use at several locations (Overton *et al.*, 2018).

Some of the sea lice treatments lack scientific health and welfare risk assessments for fish (see Appendix 2). Many of these treatments have led to mass mortalities events, due to the treatments process, but also because pre-existing disease has compromised fish health making them more vulnerable. Therefore, before a novel treatment method can be applied, it should be subjected to a thorough health and welfare analysis, initially in small scale trials before commercial trials are attempted. Welfare standards and recommendations on processes in sea lice treatments, as well as future ways of research, are recommended by various NGOs (Table 4).

Table 4. Recommendations on sea lice treatments from other NGOs and organisations

Source	Details
RSPCA	- Allows the use of cleaner fish but encourages prevention methods - Non-chemical sea lice treatments must be risk assessed prior their use.
OneKind	- Ask to introduce a mandatory welfare assessment before treatment methods are consented. They also suggest that future research should be on sea lice prevention, like the snorkel barrier. - Do not allow the use of cleaner fish until welfare standards are produced.
Soil Association	- Cleaner fish and freshwater baths are their first treatment option against sea lice. "You must give preference to the use of cleaner fish for biological control of ectoparasites or freshwater, marine water and sodium chloride solutions." - State that parasite treatments should only be used twice per year if the production cycle is 18 months or over.

The current situation calls for urgent research on more efficient and welfare friendly treatments, as well as improved husbandry systems to prevent sea lice infestations in farmed Atlantic salmon.

Compassion recommends that sea lice treatments that cause major welfare problems must not be used routinely and only when prescribed by a vet. The health status of the fish to be treated must be assessed and approved prior to treatment. If these treatments are used routinely the fallowing period must be extended in coordination with neighbouring sites. Cleaner fish are not allowed as a sea lice treatment and their use should be phased out.

OPPORTUNITIES TO EXPRESS APPROPRIATE BEHAVIOUR

There are several times throughout their lives when fish are crowded and/or handled in some way. These activities are carried out for breeding purposes, disease treatment, and are part of the slaughter process but are usually stressful for fish and can cause injury and mortalities. Crowding, handling and grading should therefore be avoided as much as possible but, when unavoidable, should be performed in such a way as to minimise the stress of the fish. This will involve careful management of procedures and monitoring and responding appropriately to fish welfare throughout.

Crowding

Crowding is undertaken in order to make it easier to access fish, for example, prior to grading, counting, transport and slaughter. It involves gathering the fish at a high concentration either using sweep nets or forcing the fish into a smaller volume, by lifting part or all of the cage, leading to temporarily abnormally high stocking densities. Crowding is a stressful procedure caused by restricting movement and behaviour. It may cause injuries as fish increase their swimming movements to avoid other fish, increased light intensity and the net. The increase in excitability can lead to damage to scales, skin ulceration, eye and snout damage and bruising (Wall, 2000) and negatively impact welfare. Moreover, aggression between large and small fish is probably exacerbated in the confined conditions of crowding (Wall, 2000) adding to poor welfare.

In addition to an increase in stress and injury from higher fish densities, the crowding also affects oxygen levels and water quality. The longer the crowding period the greater the potential impact on water quality, for example, as ammonia from waste products start to accumulate. Low oxygen levels can result in a further increase in excitability/movement, which depletes oxygen levels even further. Ensuring a good water flow through the crowd will remove ammonia from the water and bring in oxygen. However strong water currents can also cause net displacement changing the shape and volume of the cage and due to reduced behavioural control, may cause fish to be crushed against the net (NOFIMA).

The use of welfare scoring systems for use during crowding, such as the Humane Slaughter Association's "behavioural categories of fish during crowding"[8] provides a clear scoring and target system for improved salmon welfare during crowding. The HSA also advises using deep, narrow nets rather than shallow ones when crowding fish. However, it is important to note that fish will still be stressed in spite of a well-managed enclosure (Erikson, Gansel, Frank, Svendsen, & Digre, 2016) and therefore crowding time should be minimised as much as possible in terms of intensity and time period. RSPCA guidelines stipulate that "fish must not be crowded for more than two hours"; for slaughter "crowding and handling prior to killing must be kept to an absolute minimum" and that "no enclosure must be crowded more than twice in any one week or three times in any month" (RSPCA, 2018).

Handling / pumping

Many farm management activities, such as application of anti-parasite treatments, involve handling and movement of salmon. Handling is stressful and often entails removal from the water, therefore, it should only be carried out when absolutely necessary. Care must be taken at all stages to avoid abrasions and removal of scales and the fish's protective mucus coat, which serves as a physical and chemical barrier to infection as well as being important in osmoregulation and locomotion (Ashley, 2007). For sampling small numbers of salmon that are removed by hand, lined nets should be used to allow some water to be retained in transfer (Conte, 2004; HSA, 2005) which will provide some protection from abrasion. Once out of water the fish should be kept moist, handled using wet hands and for a maximum time of 15sec, unless anaesthetised (RSPCA guidelines).

[8] https://www.hsa.org.uk/downloads/publications/harvestingfishdownload-updated-with-2016-logo.pdf

Because moving water along with the fish should cause fewer injuries and appears to be the least stressful technique (FAWC, 1996) the use of fish pumps and transfer pipes appears to be preferable for welfare. However, effective management should ensure that the design of the system is appropriate. Pumps and pipes have the advantage of keeping the fish in water and, if well-designed, produce fewer abrasions than nets. Poorly designed pumping systems, however, can damage fish from sharp bends and uneven internal surfacing. As can allowing them to drop onto hard surfaces at the point of exit from a pipe.

In Atlantic salmon smolts, many of the disease outbreaks take place during the first months of transfer to the sea following transport in well boats (Iversen *et al.*, 2005). This study found that the loading process was a more severe stressor than the transport itself, with plasma cortisol returning to resting levels during the time in the well boats in four out of five transports.

Grading

Fish grow at varying rates. In natural conditions, smaller fish can avoid aggression from larger ones by moving away or hiding, but in the confined conditions of intensive farming systems, larger fish may bully smaller ones and prevent them from feeding or even cannibalise them. In order to minimise this, fish are periodically graded into different sizes. In addition, as they grow larger, fish may be split into two batches to reduce the biomass in the cage. Fish may also be graded before slaughter to remove those not yet ready for slaughter. Grading is a stressful procedure (Dunlop, 2004). It can lead to physical damage to the fish and post-grading disease outbreaks; accordingly, grading should be kept to a minimum.

An alternative method is passive grading. In sea cages, before Atlantic salmon crowding, Flexi-Panel graders may be installed into the sweep net, which allows workers to enclose the big fish in the cage to the live-haul transport and encourages the smaller fish to swim through the openings in the Flexi-Panel, back into the cage.

In one such system, a sweep net is used to enclose all the fish in the cage and is then gradually lifted. The smaller fish are able to swim out through apertures in a passive grader that is inserted into the net, while the larger fish remain in the net. The benefits of passive grading are that the smaller fish are not removed from the water and a good system reduces the physical damage and stress involved in grading.

Compassion recommends that the health status of the fish must be assessed before starting any crowding operation. It is essential to closely monitor the crowding operation for signs of stress and provide oxygenation prior to starting. Gentle crowding includes fish swimming in a calm and leisurely way, only the occasional dorsal fin should be seen breaking the surface. No burrowing or fish scales in the water should be seen and only occasional white sides of the fish seen. Oxygen levels should be monitored continuously and management of the crowd adjusted based on welfare indicators such as behaviour. Any signs such as red water, free scales in the water or signs of skin/snout damage or haemorrhages on individual fish should signal immediate intervention. Crowding salmon should only be carried out for a maximum of 2 hours with time for fish to recover between successive crowds (NB the RSPCA recommends no more than 2 crowds in any one week and no more than 3 crowds in any given month). Grading should be performed only when absolutely necessary, be as gentle as possible and salmon must not be out of the water for more than 15 seconds.

Appendix 1. **Main diseases affecting farmed Atlantic salmon**

	Name	Description	Treatment/ Prevention
Infectious diseases	Infectious salmon anaemia (ISA)*notifiable	Sea lice is a vector. Poor water quality, human manipulation, mixing groups of fish. Characterised by severe anaemia and haemorrhage in internal organs.	Vaccination – no treatment and all infected fish must be slaughtered.
	Enteric redmouth (ERM) caused by Yersinia ruckeri		Vaccination
	Furunculosis caused by Aeromonas salmoncida		Vaccination
	Pancreas disease - salmonid alphavirus (SAV)	Causes necrosis of pancreatic tissues. Infected fish have been shown to be in poor condition, being thin and lethargic. Kilburn *et al.*, (2012) analysed mortalities caused by SAV in Scotland and found that there has been an increase in the prevalence in recent years.	
	Vibriosis caused by Vibrio anguillarum		Vaccination
	Winter ulcer disease caused by Moritella viscosa	Sub-optimal husbandry condition: high fish density, poor water exchange, low water temperature, previous infections with sea lice and inadequate nutrition.	Antibiotic therapy Vaccination Good husbandry methods
	Infectious pancreatic necrosis (IPN)	Sub-optimal husbandry condition: poor water quality, high stocking densities, mixing groups of fish. IPN can cause serious losses of fish in freshwater and following sea transfer of smolts. Losses can be as high as 50% with affected fish often showing few presenting symptoms. Outbreaks of clinical IPN are frequently related to levels of stress to which fish are subjected, particularly at seawater transfer (RSPCA).	

[9] Please consult https://globalsalmoninitiative.org/en/what-is-the-gsi-working-on/biosecurity/non-medicinal-approaches-to-sea-lice-management/ for illustration of the methods described in the table.

	Name	Description	Treatment/ Prevention
Infectious diseases	Cardiomyopathy syndrome-Piscine myocarditis virus (PMCV)	Affects the heart muscle and reduces their cardiovascular capacity (Garseth *et al.*, 2017). This leaves fish fragile and weak reducing the ability to cope with any further stress. CMS has been recorded as the cause for many mass mortalities (Sarah Allen, 2018).	
	Sea lice (Lepeophtheirus salmonis)	See section above	
Parasitic diseases	Amoebic gill disease (AGD) Neoparamoeba perurans	Increase in the water temperature and changes in salinity. Infestation in the gills causes an increase in mucus production which causes respiratory problems (can cause death). Water temperature, salinity, smolt size and quality are key determinants contributing to the prevalence of the disease. Can cause up to 50% mortality in salmon (Scottish Government, 2018).	Freshwater bath of 2-3h or hydrogen peroxide baths
Toxins	Algal blooms	Algae produce toxins, by reducing oxygen levels at night and when they die off, and by being directly irritant to the gills and skin.	
Nutritional diseases	Skeletal malformations: jaw and spinal deformities (freshwater phase) Example: Dietary deficiency shortened spine	Feed composition (lack of phosphorus), elevated temperatures and photoperiod manipulation, egg incubation temperature.	
	Deafness	Accelerated growth, temperature, nutritional factor, continuous light, etc.	

Appendix 2. Main sea lice treatments used in Atlantic salmon farms and their welfare implications

Sea lice treatments	Method	Main welfare issues	Further information
Thermal (Thermolicer®[10])	Fish are given a warm water bath to remove sea lice	- Crowding, pumping and fish taken out of water - The warm water may cause fish pain - Fish with compromised health such as gill disease will be subject to severe harm or death - Handling may immunosuppress the fish.	- Grøntvedt *et al.*, (2018) reported that the treatment at 34°C removes 75-100% of mobile lice. Attached lice were counted after treatment, revealing that treatment was ineffective in removing attached lice. - In 2016, 95,000 fish were killed during the use of Thermolicer® - Welfare assessment required prior to use.
Mechanical (Hydrolicer®[12], SkaMik[13])	Fish exposed to changes in pressure – may be combined with brushing (SkaMik)	- Crowding, pumping and fish taken out of water - Removes protective mucus and scales from fish which are the first defence line against pathogens - Handling may immunosuppress the fish.	- Welfare assessment required prior to use. Hydrolicer® and SkaMik systems do not have independent reports or publications examining welfare and mortality (Overton *et al.*, 2018).
Freshwater bath	Bathing infected salmon in freshwater	- Crowding and pumping - Freshwater alters the mucus layer of salmon - Freshwater treatment in well boats has shown promising results as an alternative bath treatment, and has become utilised as a delousing treatment by the industry (M. D. Powell, Reynolds, & Kristensen, 2015).	- It is not considered entirely effective, particularly against older louse stages and there is evidence of tolerance by sea lice. External injuries related to crowding are considered common after this treatment (B Hjeltnes, Walde, Bang-Jensen, & Haukaas, 2016).
Chemical: Bath treatments (e.g. Hydrogen peroxide, Dichlorvos, Azamethiphos, Cypermethrin, Teflubenzuron and Ivermectin)	Exposed using a bath treatment	- Crowding - H_2O_2 is irritant to salmon: causes damage to gills and mucosal layers compromising the immune system - Reduces growth rates.	- Sea lice can develop resistance towards hydrogen peroxide (B Hjeltnes *et al.*, 2016). 60,000 farmed salmon died after hydrogen peroxide treatment in a Scottish farm[14].

Sea lice treatments	Method	Main welfare issues	Further information
			- Azamethiphos is highly toxic to birds and aquatic invertebrates and moderately toxic to fish[15]. - Other crustaceans affected (non-target organisms) particularly as more combination therapies are used to increase efficacy (Haya, Burridge, Davies, & Ervik, 2005).
Chemical: In-feed oral treatments e.g. SLICE® emamectin benzoate	Oral treatment of sea lice		- Negative environmental impact (accumulation in the sediment and other organisms affected) (Haya *et al.*, 2005). - The extensive use can result in drug-resistant sea lice (Aaen *et al.*, 2015; Read & Fernandes, 2003).
Prevention: Physical barrier methods	Cage depth, sea lice skirts, snorkels, deep lights and/or deep feeding systems, bubble curtains and sea lice traps	- Decrease of water exchange and therefore a decrease in oxygen levels and increase of waste products concentration - Welfare issue related to ability to refill swim bladders in submerged cages or snorkels.	- Many have potentially significant welfare implications (Oppedal *et al.*, 2017; Lars Helge Stien *et al.*, 2016; Lars Helge Stien, Lind, Oppedal, Wright, & Seternes, 2018).
Fallow periods	Leaving sites empty for a period of time to reduce sea lice load		- Needs to be part of an area management strategy[16] and the efficiency is yet to be studied. - Scotland: The Code of Good Practice for Finfish Aquaculture recommends that the minimum fallow period is 4 weeks[17]. - Norway: according to the Norwegian regulations, fallowing is applied for a minimum of 8 weeks at the end of each production cycle[18].

Sea lice treatments	Method	Main welfare issues	Further information
Biological methods: cleaner fish	Use of wrasse/ lumpfish who actively eat sea lice directly off salmon	- Lumpfish stocks can still be heavily sourced from wild caught broodstock - Half of wrasse still wild caught (currently up to 1 million wild caught wrasse per year) - Mortality rates can reach 100% - Estimated one third of lumpfish die of starvation in first few months - They suffer stress caused by inadequate nutrition, handling during vaccination and capturing, and poor husbandry quality - Welfare standards for cleaner fish in captivity are not yet developed.	Low efficiency: - Only between 15 and 36% of the lumpsuckers actually consumed sea lice (Imsland *et al.*, 2016) - Lumpfish stop eating sea lice at a certain size (A. Powell *et al.*, 2017) - Wrasse have winter dormancy so stop feeding at lower temperatures - Need supplementary feed and lumpfish require substrate to attach to (Imsland *et al.*, 2015) - Cleaner fish can pass on diseases to farmed salmon. They suffer from several diseases as bacterial infection, amoebic gill disease, furunculosis, cataracts and they can also be parasitized by sea lice (*A. Powell et al.*, 2017) - Cleaner fish fisheries are unregulated and cleaner fish are not re-used. The current practice is culling them after one salmon production cycle (Marine Conservation Society, 2018).

[10] https://www.steinsvik.no/en/products/e/seaculture/fish-health/thermolicer
[11] https://www.bbc.co.uk/news/uk-scotland-38966188
[12] https://hydrolicer.no/wp-content/uploads/2018/11/the-hydrolicer-system-1.pdf
[13] https://skamik.no/english/
[14] https://www.intrafish.com/news/751778/de-lousing-kills-32700-fish-at-marine-harvest-operation
[15] http://sitem.herts.ac.uk/aeru/ppdb/en/Reports/48.htm
[16] https://www.gov.scot/publications/scottish-fish-farm-production-survey-2017/
[17] http://thecodeofgoodpractice.co.uk/wp-content/uploads/2015/02/cogp-chapter-4-seawater-lochs2.pdf
[18] https://lovdata.no/dokument/SF/forskrift/2008-06-17-822/KAPITTEL_4#%C2%A747a

REFERENCES

Aaen, S. M., Helgesen, K. O., Bakke, M. J., Kaur, K., & Horsberg, T. E. (2015). Drug resistance in sea lice: a threat to salmonid aquaculture. *Trends in Parasitology,* 31(2), 72–81. https://doi.org/10.1016/J.PT.2014.12.006

Adams, C. E., Turnbull, J. F., Bell, A., Bron, J. E., & Huntingford, F. A. (2007). Multiple determinants of welfare in farmed fish: stocking density, disturbance, and aggression in Atlantic salmon (Salmo salar). *Canadian Journal of Fisheries and Aquatic Sciences,* 64(2), 336–344. https://doi.org/10.1139/f07-018

Barber, I. (2007). Parasites, behaviour and welfare in fish. *Applied Animal Behaviour Science,* 104(3–4), 251–264. https://doi.org/10.1016/j.applanim.2006.09.005

Bjørge, M. H., Nordgreen, J., Janczak, A. M., Poppe, T., Ranheim, B., & Horsberg, T. E. (2011). Behavioural changes following intraperitoneal vaccination in Atlantic salmon (Salmo salar). *Applied Animal Behaviour Science,* 133(1–2), 127–135. https://doi.org/10.1016/J.APPLANIM.2011.04.018

Bowers, J. M., Mustafa, A., Speare, D. J., Conboy, G. A., Brimacombe, M., Sims, D. E., & Burka, J. F. (2000). The physiological response of Atlantic salmon, Salmo salar L., to a single experimental challenge with sea lice, Lepeophtheirus salmonis. *Journal of Fish Diseases,* 23(3), 165–172. https://doi.org/10.1046/j.1365-2761.2000.00225.x

Calabrese, S., Nilsen, T. O., Kolarevic, J., Ebbesson, L. O. E., Pedrosa, C., Fivelstad, S., … Handeland, S. O. (2017). Stocking density limits for post-smolt Atlantic salmon (Salmo salar L.) emphasis on production performance and welfare. *Aquaculture,* 468, 363–370. https://doi.org/10.1016/j.aquaculture.2016.10.041

Cañon Jones, H. A., Noble, C., Damsgård, B., & Pearce, G. P. (2012). Investigating the influence of predictable and unpredictable feed delivery schedules upon the behaviour and welfare of Atlantic salmon parr (Salmo salar) using social network analysis and fin damage. *Applied Animal Behaviour Science,* 138(1–2), 132–140. https://doi.org/10.1016/J.APPLANIM.2012.01.019

Conte, F. . (2004). Stress and the welfare of cultured fish. *Applied Animal Behaviour Science,* 86(3–4), 205–223. https://doi.org/10.1016/j.applanim.2004.02.003

Domingues, C. M., Church, J. A., White, N. J., Gleckler, P. J., Wijffels, S. E., Barker, P. M., & Dunn, J. R. (2008). Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature,* 453(7198), 1090–1093. https://doi.org/10.1038/nature07080

Dunlop, R. A., Laming, P. R., & Smith, T. E. (2004). The Stress of four commercial farming practices, feeding, counting, grading and harvesting, in farmed rainbow trout, Oncorhynchus mykiss. *Marine and Freshwater Behaviour and Physiology,* 37(3), 179–192. https://doi.org/10.1080/10236240400006133

EFSA. (2008). The EFSA Journal (2008) 736, 1-31. *Animal Welfare Aspects of Husbandry Systems for Farmed Atlantic Salmon,* (June), 1–31.

EFSA. (2009). Scientific Opinion of the Panel on Animal Health and Welfare on a request from the European Commission on welfare aspect of the main systems of stunning and killing of farmed eel (Anguilla anguilla). *The EFSA Journal,* 1014, 1–42. https://doi.org/10.2903/j.efsa.2009.1013

Einen, O., Waagan, B., & Thomassen, M. S. (1998). Starvation prior to slaughter in Atlantic salmon (Salmo salar). *Aquaculture,* 166(1–2), 85–104. https://doi.org/10.1016/s0044-8486(98)00279-8

Ellis, T. (2002). The relationships between stocking density and welfare in farmed rainbow trout. *Journal of Fish Biology,* 61(3), 493–531. https://doi.org/10.1006/jfbi.2002.2057

Ellis, T., North, B., Scott, A. P., Bromage, N. R., Porter, M., & Gadd, D. (2002a). The relationships between stocking density and welfare in farmed rainbow trout. *Journal of Fish Biology,* 61(3), 493–531. https://doi.org/10.1006/jfbi.2002.2057

Erikson, U., Gansel, L., Frank, K., Svendsen, E., & Digre, H. (2016). Crowding of Atlantic salmon in net-pen before slaughter. *Aquaculture,* 465, 395–400. https://doi.org/10.1016/j.aquaculture.2016.09.018

Farm Animal Welfare Committee (FAWC). (2014). Opinion on the Welfare of Farmed Fish at the Time of Killing.

Fast, M. D., Hosoya, S., Johnson, S. C., & Afonso, L. O. B. (2008). Cortisol response and immune-related effects of Atlantic salmon (Salmo salar Linnaeus) subjected to short- and long-term stress. *Fish & Shellfish Immunology,* 24(2), 194–204. https://doi.org/10.1016/j.fsi.2007.10.009

Fernandes, Eleftheriou, Ackefors, Eleftheriou, Ervik, Sanchez-Mata, … Read. (2001). The scientific principles underlying the monitoring of the environmental impacts of aquaculture. *Journal of Applied Ichthyology,* 17(4), 181–193. https://doi.org/10.1046/j.1439-0426.2001.00315.x

Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C., & Cao, L. (2018). Corrigendum: Feed conversion efficiency in aquaculture: do we measure it correctly? (2018 Environ. Res. Lett. 13 024017) . *Environmental Research Letters,* 13(7), 079502. https://doi.org/10.1088/1748-9326/aad007

Gonçalves, J., Carraça, S., Damasceno-Oliveira, A., Fernández-Durán, B., Diaz, J., Wilson, J., & Coimbra, J. (2006). Effect of Reduction in Water Salinity on Osmoregulation and Survival of Large Atlantic Salmon Held at High Water Temperature. *North American Journal of Aquaculture,* 68(4), 324–329. https://doi.org/10.1577/A05-056.1

Government., S. (2018). Amoebic gill disease (AGD).

Grøntvedt, R. N., Kristoffersen, A. B., & Jansen, P. A. (2018). Reduced exposure of farmed salmon to salmon louse (Lepeophtheirus salmonis L.) infestation by use of plankton nets: Estimating the shielding effect. *Aquaculture,* 495, 865–872. https://doi.org/10.1016/j.aquaculture.2018.06.069

Handeland, S. O., Imsland, A. K., & Stefansson, S. O. (2008). The effect of temperature and fish size on growth, feed intake, food conversion efficiency and stomach evacuation rate of Atlantic salmon post-smolts. *Aquaculture,* 283(1–4), 36–42. https://doi.org/10.1016/j.aquaculture.2008.06.042

Haya, K., Burridge, L. E., Davies, I. M., & Ervik, A. (2005). A Review and Assessment of Environmental Risk of Chemicals Used for the Treatment of Sea Lice Infestations of Cultured Salmon. Environmental Effects of Marine Finfish *Aquaculture,* 5(July), 305–340. https://doi.org/10.1002/path.1711130106

Hjeltnes B, Bang-Jensen B, Bornø G, Haukaas A, W. C. (2018). The Health Situation in Norwegian Aquaculture 2017.

Hjeltnes, B, Walde, C., Bang-Jensen, B., & Haukaas, A. (2016). The Fish Health Report 2015.

Hjeltnes, Brit, Baeverfjord, G., Erikson, U., Mortensen, S., Rosten, T., & Østergård, P. (2012). Norwegian Scientific Committee for Food Safety (VKM) Opinion of the Panel on Animal Health and Welfare of the Norwegian Scientific Committee for Food Safety Risk Assessment of Recirculation Systems in Salmonid Hatcheries Risk Assessment of Recirculation S.

Imsland, A. K., Reynolds, P., Eliassen, G., Hangstad, T. A., Nytrø, A. V., Foss, A., … Elvegård, T. A. (2015). Assessment of suitable substrates for lumpfish in sea pens. *Aquaculture International,* 23(2), 639–645. https://doi.org/10.1007/s10499-014-9840-0

Imsland, A. K., Reynolds, P., Eliassen, G., Mortensen, A., Hansen, Ø. J., Puvanendran, V., … Jonassen, T. M. (2016). Is cleaning behaviour in lumpfish (Cyclopterus lumpus) parentally controlled? *Aquaculture,* 459, 156–165. https://doi.org/10.1016/j.aquaculture.2016.03.047

Jackson, D., Moberg, O., Stenevik Djupevåg, E. M., Kane, F., & Hareide, H. (2018). The drivers of sea lice management policies and how best to integrate them into a risk management strategy: An ecosystem approach to sea lice management. *Journal of Fish Diseases,* 41(6), 927–933. https://doi.org/10.1111/jfd.12705

Jansen, P. A., Kristoffersen, A. B., Viljugrein, H., Jimenez, D., Aldrin, M., & Stien, A. (2012). Sea lice as a density-dependent constraint to salmonid farming. *Proceedings of the Royal Society B: Biological Sciences,* 279(1737), 2330–2338. https://doi.org/10.1098/rspb.2012.0084

Jobling, M. (2006). The influences of feeding on the metabolic rate of fishes: a short review*. NOTE ADDED IN PROOF. *Journal of Fish Biology,* 18(5), 615–615. https://doi.org/10.1111/j.1095-8649.1981.tb03802.x

Johansson, D., Juell, J. E., Oppedal, F., Stiansen, J. E., & Ruohonen, K. (2007). The influence of the pycnocline and cage resistance on current flow, oxygen flux and swimming behaviour of Atlantic salmon (Salmo salar L.) in production cages. *Aquaculture,* 265(1–4), 271–287. https://doi.org/10.1016/j.aquaculture.2006.12.047

Johansson, D., Ruohonen, K., Kiessling, A., Oppedal, F., Stiansen, J.-E., Kelly, M., & Juell, J.-E. (2006). Effect of environmental factors on swimming depth preferences of Atlantic salmon (Salmo salar L.) and temporal and spatial variations in oxygen levels in sea cages at a fjord site. *Aquaculture,* 254(1–4), 594–605. https://doi.org/10.1016/J.AQUACULTURE.2005.10.029

Johnson, S. C., Treasurer, J. W., Bravo, S., & Nagasawa, K. (2004). A review of the impact of Parasitic Copepods on Marine Aquaculture A Review of the Impact of Parasitic Copepods on Marine Aquaculture, (April 2004).

Juell, J.-E., Oppedal, F., Boxaspen, K., & Taranger, G. L. (2003). Submerged light increases swimming depth and reduces fish density of Atlantic salmon Salmo salar L. in production cages. *Aquaculture Research,* 34(6), 469–478. https://doi.org/10.1046/j.1365-2109.2003.00833.x

Kim, D. S., Jo, J.-Y., & Lee, T.-Y. (1994). Induction of triploidy in mud loach (Misgurnus mizolepis) and its effect on gonad development and growth. *Aquaculture,* 120(3–4), 263–270. https://doi.org/10.1016/0044-8486(94)90083-3

Krogdahl, Å., & Bakke-McKellep, A. M. (2005). Fasting and refeeding cause rapid changes in intestinal tissue mass and digestive enzyme capacities of Atlantic salmon (Salmo salar L.). Comparative Biochemistry and Physiology - A Molecular and Integrative Physiology, 141(4 SPEC. ISS.), 450–460. https://doi.org/10.1016/j.cbpb.2005.06.002

Midtlyng, P. J. (1997). Vaccinated fish welfare: protection versus side-effects. *Developments in Biological Standardization,* 90, 371–379.

Noble, C., Gismervik, K., Iversen, M. H., Kolarevic, J., Nilsson, J., Stien, L. H., & Turnbull, J. F. (2018). Welfare Indicators for farmed Atlantic salmon : tools for assessing fish welfare.

North, B. P., Ellis, T., Turnbull, J. F., Davis, J., & Bromage, N. R. (2006). Stocking density practices of commercial UK rainbow trout farms. *Aquaculture,* 259(1–4), 260–267. https://doi.org/10.1016/j.aquaculture.2006.05.043

Oppedal, F., Dempster, T., & Stien, L. H. (2011). Environmental drivers of Atlantic salmon behaviour in sea-cages: A review. Aquaculture, 311(1–4), 1–18. https://doi.org/10.1016/J.AQUACULTURE.2010.11.020

Oppedal, F., Samsing, F., Dempster, T., Wright, D. W., Bui, S., & Stien, L. H. (2017). Sea lice infestation levels decrease with deeper 'snorkel' barriers in Atlantic salmon sea-cages. *Pest Management Science,* 73(9), 1935–1943. https://doi.org/10.1002/ps.4560

Oppedal, F., Vågseth, T., Dempster, T., Juell, J.-E., & Johansson, D. (2011). Fluctuating sea-cage environments modify the effects of stocking densities on production and welfare parameters of Atlantic salmon (Salmo salar L.). *Aquaculture,* 315(3–4), 361–368. https://doi.org/10.1016/J.AQUACULTURE.2011.02.037

Overton, K., Dempster, T., Oppedal, F., Kristiansen, T. S., Gismervik, K., & Stien, L. H. (2018). Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review. *Reviews in Aquaculture,* 1–20. https://doi.org/10.1111/raq.12299

Pachauri, R K, & Reisinger, A. (2007). Climate change 2007. Synthesis report. Contribution of Working Groups I, II and III to the fourth assessment report (p. 104). Switzerland.

Powell, A., Treasurer, J. W., Pooley, C. L., Keay, A. J., Lloyd, R., Imsland, A. K., & Garcia de Leaniz, C. (2017). Use of lumpfish for sea-lice control in salmon farming: Challenges and opportunities. Reviews in Aquaculture. https://doi.org/10.1111/raq.12194

Powell, M. D., Reynolds, P., & Kristensen, T. (2015). Freshwater treatment of amoebic gill disease and sea-lice in seawater salmon production: Considerations of water chemistry and fish welfare in Norway. *Aquaculture,* 448, 18–28. https://doi.org/10.1016/j.aquaculture.2015.05.027

Read, P., & Fernandes, T. (2003). Management of environmental impacts of marine aquaculture in Europe. *Aquaculture,* 226(1–4), 139–163. https://doi.org/10.1016/S0044-8486(03)00474-5

Robb, D. H. F. (2008). Welfare of fish at harvest. In E.J. Branson (Ed.), Fish welfare (pp. 217–242). Blackwell Publishing Ltd.

RSPCA. (2018). RSPCA welfare standards for farmed Atlantic salmon.

Santurtun, E., Broom, D. M., & Phillips, C. J. C. (2018). A review of factors affecting the welfare of Atlantic salmon (Salmo salar), 442, 193–204. https://doi.org/10.7120/09627286.27.3.193

Sarah Allen. (2018). FISH WELFARE ON SCOTLAND'S SALMON FARMS. Retrieved from https://www.onekind.scot/wp-content/uploads/Salmon-farm-report-2018.pdf

Society, M. conservation. (2018). Use of cleaner fish in salmon farming: Current use, concerns and recommendations.

Sørum, U., & Damsgård, B. (2004). Effects of anaesthetisation and vaccination on feed intake and growth in Atlantic salmon (Salmo salar L.). Aquaculture, 232(1–4), 333–341. https://doi.org/10.1016/S0044-8486(03)00529-5

Stien, Lars H., Bracke, M. B. M., Folkedal, O., Nilsson, J., Oppedal, F., Torgersen, T., … Kristiansen, T. S. (2013). Salmon Welfare Index Model (SWIM 1.0): A semantic model for overall welfare assessment of caged Atlantic salmon: Review of the selected welfare indicators and model presentation. *Reviews in Aquaculture,* 5(1), 33–57. https://doi.org/10.1111/j.1753-5131.2012.01083.x

Stien, Lars Helge, Dempster, T., Bui, S., Glaropoulos, A., Fosseidengen, J. E., Wright, D. W., & Oppedal, F. (2016). 'Snorkel' sea lice barrier technology reduces sea lice loads on harvest-sized Atlantic salmon with minimal welfare impacts. *Aquaculture,* 458, 29–37. https://doi.org/10.1016/J.AQUACULTURE.2016.02.014

Stien, Lars Helge, Lind, M. B., Oppedal, F., Wright, D. W., & Seternes, T. (2018). Skirts on salmon production cages reduced salmon lice infestations without affecting fish welfare. *Aquaculture,* 490, 281–287. https://doi.org/10.1016/J.AQUACULTURE.2018.02.045

Thorarensen, H., & Farrell, A. P. (2011). The biological requirements for post-smolt Atlantic salmon in closed-containment systems. *Aquaculture,* 312(1–4), 1–14. https://doi.org/10.1016/J.AQUACULTURE.2010.11.043

Treasurer, J., & Feledi, T. (2014). The Physical Condition and Welfare of Five Species of Wild-caught Wrasse Stocked under Aquaculture Conditions and when Stocked in Atlantic Salmon, Salmo salar, Production Cages. *Journal of the World Aquaculture Society,* 45(2), 213–219. https://doi.org/10.1111/jwas.12099

Turnbull, J., Bell, A., Adams, C., Bron, J., & Huntingford, F. (2005). Stocking density and welfare of cage farmed Atlantic salmon: application of a multivariate analysis. *Aquaculture,* 243(1–4), 121–132. https://doi.org/10.1016/J.AQUACULTURE.2004.09.022

Waagbø, R., Jørgensen, S. M., Timmerhaus, G., Breck, O., & Olsvik, P. A. (2017). Short-term starvation at low temperature prior to harvest does not impact the health and acute stress response of adult Atlantic salmon. *PeerJ,* 5, e3273. https://doi.org/10.7717/peerj.3273

Wall, A. J. (2000). *Ethical considerations in the handling and slaughter of farmed fish. Farmed fish quality.* Eds. Kestin S.C. & Warris P.D., Oxford, Fishing News Books.

Wedemeyer, G. A. (1996). *Physiology of Fish in Intensive Culture Systems.* Springer US.