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A review of factors affecting the welfare of Atlantic salmon (Salmo salar)

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Abstract

*In the expanding salmon industry, many farmers use production methods that could result in poor welfare of the fish at various points of their lifecycle. We have reviewed methods used for producing salmon for food with the aim of identifying and drawing attention to factors likely to affect farmed Atlantic salmon (*Salmo salar*) welfare. In addition to water conditions and high stocking density at sea, other issues are important for fish welfare. Handling and transport of salmon between fresh- and seawater phases and before slaughter can have severe negative effects and research should continue to seek improved methods. Stocking densities in fresh- or seawater have substantial effects on the welfare of salmon and a reduction in densities should be considered in order to reduce fin damage in particular. Currently used feeding systems result in starvation for some fish and fin damage for others, hence new systems should be developed. Some on-demand feeding systems improve welfare. All farmed fish should be stunned prior to slaughter, not left to die of asphyxia. Carbon dioxide and electrical stunning methods do not always stun salmon humanely. The widely used methods of percussive stunning, manual or automatic, must be precise to effectively stun large numbers of fish. Welfare outcome indicators, such as fin damage, morbidity and mortality rate, should be used in standards and laws relating to salmon welfare.*

Keywords: *animal welfare, aquaculture, Atlantic salmon, fish farming, stocking density, welfare outcome indicators*

Introduction

Aquaculture is the world's fastest growing meat production industry globally, averaging approximately 6% annual growth from 2002 to 2012, after 10% growth for the 20 years prior to this (Food and Agriculture Organisation [FAO] 2014). The major producers of Atlantic salmon (*Salmo salar*) are Norway, Chile, Scotland and Canada, with the first two providing over 80% of global output (Burridge *et al* 2010). Most feed provided for salmon is derived from other fish, some of which could be used directly as human food and some could constitute a disease risk for the salmon, so efforts are being made to find alternative sources (Stones 2003). At present, up to 14% of salmon food can be of plant origin.

The production of salmon starts with the extraction of eggs and sperm from anaesthetised fish, followed by incubation in oxygenated freshwater, hatching, and then rearing in flowing water. Fingerlings (known as parr) are transferred to larger freshwater tanks, where they are in either flow-through tanks or a re-circulating system. Here, they remain until smoltification, a physiological adaptation from fresh- to seawater. The smolts are then either transported into large, floating cages in sheltered bays or sea lochs, where they grow for 1–2 years before slaughter or grown in enclosed large-tank systems throughout their life.

There is evidence to show that fish can show the physiological and behavioural responses that indicate fear and pain (Sneddon *et al* 2003; Chandroo *et al* 2004; Portavella *et al* 2004; Nordgreen *et al* 2007; Braithwaite 2010; Broom 2016). The cognitive ability of certain fish in some circumstances can be better than mammals, for example, as a result of their extensive experience in nature, cleaner fish can learn complex foraging tasks that some great ape species cannot (Salwiczek *et al* 2012). It should be noted that areas exist within the brains of fish that closely parallel those of the amygdala and hippocampus, that deal with emotion, learning and memory in mammals (Agetsuma *et al* 2010; Broom 2014). Scientific evidence indicates that salmon and other fish are sentient beings and surveys such as the Special Eurobarometer 442 (http://docplayer.net/24590693-Special-eurobarometer-442-summary-attitudes-of-europeans-towards-animal-welfare.html) indicate high levels of public concern about sentient animals. There is considerable consumer concern about salmon welfare, with them being increasingly covered by animal welfare law in many jurisdictions. Moreover, scientific information about their welfare is increasing (Broom 1999, 2007; Turnbull 2006; Grimsrud *et al* 2013; Broom & Fraser 2015).

Researchers constructing a welfare model for farmed Atlantic salmon have emphasised that consideration of multiple welfare components is essential in such a highly complex and multifaceted production process (Turnbull *et al* 2005). Following publications by the Farm Animal Welfare Council (FAWC) (1996) and European Food Safety Authority (EFSA) (2007, 2008, 2009), Stien *et al* (2013a) recently reviewed the needs of Atlantic salmon in the sea-cage phase and developed a model, using selected welfare indicators, to enable fish farmers to make an objective assessment of welfare. The same team has developed a salmon welfare model for use by fish health professionals, using the following indicators: eyes, cardiac condition, abdominal organs, gills, opercula, skeletal muscles, vaccine-related pathology, aberrant fish, necropsy of the dead fish and euthanasia (Pettersen *et al* 2014). In this paper, we primarily examine the impact of factors affecting Atlantic salmon welfare that were not covered adequately in the Stien *et al* model: handling and transport, high stocking densities during the freshwater phase, feeding systems and slaughter. We also comment on research developments since the publication of the Stien *et al* model. The initial review was undertaken in 2014, as a commissioned review for the Royal Society for the Prevention of Cruelty to Animals (RSPCA) Australia, but was extended with subsequent drafts of the report to the RSPCA and subsequently as a manuscript submitted to this journal. The main search engine utilised was Web of Science, augmented by Google Scholar and UQ internet searches, as well as accessing EFSA reviews as necessary. Our initial search term was just 'salmon' because not all relevant papers would include 'welfare' in the title or abstract. It was time-limited up to 2014. This produced 43,696 published papers in journals, including 19,804 with salmon in the title. Most were connected with ecology and pollution, some of which had relevance to the review. Of the published papers, 175 had farm in the title and were directly relevant to the review and 332 had salmon and welfare in the topic. These two sets formed the basis of the initial draft of the review. Subsequent searches conducted over the next three years of this study updated the review and introduced specific new terms, eg on fin innervation, and the final search was conducted in early 2018. References of included articles were also searched to identify studies not found in the initial database search.

Handling and transport

The transport of salmon smolts from freshwater conditions to sea cages is unavoidable and, unless stunning and killing equipment is brought to sea cages, there will also be transport at that time. This transport and any transport that occurs at other times, eg during changes of net and some sea lice treatments, is likely to have serious welfare implications.

Handling smolts

The initial procedures of gathering together, counting, capturing and loading smolts are the most stressful stages of salmon transport (King 2009; Nomura *et al* 2009). Crowding, pumping, vaccination and sorting during the freshwater phase also expose the smolts to welfare challenges. Handling for a duration of 30 s, using a net, produces an elevation of plasma cortisol in juvenile (10–14 months) salmonid species (Barton 2000) as does loading salmon smolts onto a well-boat (Gatica *et al* 2010). Cortisol elevation is known to occur in salmon kept out of water in a net for a short period and can be associated with immunosuppression (Maule & Schreck 1991). It can also injure the epithelial layer covering the surface of the body, increasing the risk of pathogen infection which, together, may impair the behaviour and survival of the fish after release (Oldenburg *et al* 2011). The use of rubber or sanctuary nets is advocated (Oldenburg *et al* 2011). The capture of the smolts leads to increases of plasma cortisol, which remain high even after 48 h, glucose and lactate (Iversen *et al* 1998). Smolts would also have increased plasma cortisol concentration in preparation for migration to the sea (Shrimpton *et al* 2000; Nomura *et al* 2009) but the effects of capture are additional to these. Recognising these concerns, some sectors of the industry have attempted to minimise air exposure by pumping smolts into water-filled tubes after grading into different size categories. Allowing the smolts to passively pass through a grid, rather than being pumped through, potentially reduces the amount of scale damage, which is greatest at fast turbine speeds (Brackley *et al* 2016).

The stress of transfer from fresh- to seawater can be ameliorated by a sedative, such as isoeugenol (Iversen & Eliassen 2009) but the full impact of this on welfare remains to be determined. The smolts may be transferred to their respective sea sites by road and then by sea transport, usually in a well-boat or by helicopter.

Road transport

Several potential stressors are involved during road transport, including handling and loading, alterations in water quality, osmoregularity disruption and novel transport containers (King 2009). Road transport of 30–60 min in a closed tank, increased plasma cortisol concentrations in Atlantic salmon smolts (Nomura *et al* 2009). Similarly, in juvenile salmonids, cortisol concentrations remained high for 1–2 days after 2 h of experimental transport (Barton 2000).

Sea transport

In 2001, there was a 13% loss rate in 135 million smolts transferred by well-boat in Norway, mostly during and shortly after sea transport. The high mortality rate was a result of disease, wounds, smoltification failure, or the transport itself (Iversen *et al* 2005). The loading of smolts before sea transport produces an initial increase in plasma cortisol (Iversen *et al* 2005), and the accumulation of smolts at the bottom of well-boat tanks may be due to their desire to aggregate there in response to the stress of the loading procedure (Nomura *et al* 2009). Unloading led to small cortisol increases (Iversen *et al* 2005), perhaps because concentrations of cortisol were already elevated. Generally, though, unloading appears less stressful than loading, with only minor cortisol increases (Iversen *et al* 2005). If conditions are good in the well-boat, in that oxygen concentration is high enough and stocking density low enough, the welfare during boat movement has much less negative effect on welfare than the loading. However, the impact of sea conditions on fish welfare is an aspect of sea transport that has not been adequately investigated. During a commercial transport between Norway and Scotland with rough sea conditions (wave height of 3–5.5 m), plasma cortisol of Atlantic salmon smolts remained high up to and including unloading and there was higher than usual mortality (Iversen *et al* 2005).

Water quality during transport

Sea transport may use flow-through of ambient water or water re-circulated within the ship. Flow-through systems can expose the fish to dangerous ambient water conditions, such as algal blooms or oil spills (Tang *et al* 2009). Oxygen concentrations have large effects on welfare and should be meticulously monitored (King 2009). Both CO_2 and NH_3 concentrations can also affect fish; nonetheless, it is CO_2 that most often reaches dangerous levels and results in poor welfare in the salmon (Wedemeyer 1996). Salmonids are sensitive to accumulation of expired CO_2 during transport (King 2009). The main concern regarding water re-circulation systems used on live-haul vessels, which have a closed hold, is the accumulation of CO_2, the complex and expensive measurement of which represents a challenge during commercial transport (Tang *et al* 2009). Tang *et al* (2009) recommended that movement by ship should last no more than 2.5 h at low density (70 kg m^{-3}) and movement at high density (170 kg m^{-3}), normally by helicopter, should be for no more than 19 min. This should be restricted in order to avoid reaching a partial pressure of CO_2 of 10 mm Hg, as this concentration of CO_2 could adversely affect salmon welfare but not kill them. The Norwegian industry has developed a CO_2-stripping technique to overcome this problem (Cañon Jones *et al* 2012), the use of which is predicted to improve the profitability of the industry (Noble *et al* 2012).

Recovery period after transport

A period described as 'recovery' between road and sea transport, or occurring after transport has been completed, has been reported to reduce stress of salmon (Iversen *et al* 1998; Gatica *et al* 2010). It would be scientifically surprising if recovery always occurred because, for transport of land animals, 'recovery' in sub-optimal lairage conditions usually results in worse welfare, more disease and poorer meat quality in slaughter animals than immediate slaughter or movement directly to the final, good conditions (Broom & Fraser 2015). The multiple stressors that salmon are exposed to during transport can adversely affect immunocompetence, seawater tolerance, growth and survival (Iversen *et al* 2005). Recovery from handling procedures and road transport can occur in the well-boat, which has been reported to be beneficial for fish welfare (Iversen *et al* 2005; Nomura *et al* 2009). Recovery using net pens after 2 h of transport in a tank was reported to reduce plasma cortisol and improve survival in sea cages (Finstad *et al* 2003). A recovery period of one day at the extremely high density of 108 kg m^{-3} after a well-boat transportation of 8 h in Chile was reported to reduce blood stress measures (Gatica *et al* 2010). These results emphasise that the whole procedure of moving smolts to sea-cages is stressful and methods of reducing these adverse effects are clearly necessary.

Removal from cages and transport to slaughter is also stressful. Reported beneficial effects of 'rest' after transport from sea cages to a fish processing plant (Erikson *et al* 1997) seem unlikely to be optimal practice. It has been reported that 'rest' after transport from sea cages to a fish processing plant is beneficial but experience with other animals suggests that good conditions for rest are not likely to be possible and if appropriate measures of welfare were used, benefits might not be found to occur (Erikson *et al* 1997).

Stocking density, related factors and welfare outcome indicator use

Although it is helpful to individually consider the various factors that affect salmon welfare, these factors interact. When high stocking density in salmonids was combined with insufficient water flow (Ellis *et al* 2002) or with too much disturbance (Turnbull *et al* 2005), welfare was worse than when only one adverse factor was present. In the salmon industry, perhaps because of a long-standing preoccupation with oxygen availability as a key factor affecting production, specific water flow, which takes into account flow rate per kg of biomass, is considered an important measure. However, any such measure should be combined with measures of the animals themselves that indicate the outcome of the situation (EFSA 2008). Examples of welfare outcome measures are growth rate, feed conversion efficiency, mortality rate, percentage morbidity and proportion of fish with fin damage. High stocking density can reduce growth rate and feed conversion efficiency without necessarily affecting mortality or fish body condition (Liu *et al* 2015). Serum indicators of poor welfare induced by high stocking density have also been studied, with reduced immunoglobulin M and increased cortisol being observed (Liu *et al* 2015).

When high stocking density is combined with insufficient water flow (Ellis *et al* 2002), farmed salmon kept at high stocking densities usually have damaged fins. This is often called 'fin erosion' (Ellis *et al* 2008), but this term implies that the tissue loss is a consequence of rubbing the fins against something, whereas the loss may be multi-causal, hence we use the term 'fin damage' (Broom & Fraser 2015). It does not occur in wild salmon but is generally initiated in farmed salmon by bite wounds (Turnbull *et al* 1996). Densely stocked farmed salmon (30 kg m^{-3}) show high levels of fin-biting and damage (0.35 fin bites per hour and 15% of fish with damage; Cañon Jones *et al* 2011). Damage includes total loss of the dorsal fin, necrosis and sloughing

Table 1 Freshwater production tank densities from fry, parr up to smolt stages recommended by RSPCA (2015).

Mean liveweight	Stocking density (kg m^{-3})
Up to 1 g	10
> 1–5 g	20
> 5–30 g	30
> 30 g	50

of the superficial epithelium, haemorrhagic lesions, peripheral erosion, with clefts in the surface epithelium, exposed rays with bacteria adhering to them, and epithelial hyperplasia creating visible nodules which, in most severe cases, reduces the fins' capacity for movement (Turnbull *et al* 1996). Typically, fins show evidence of secondary infection, inflammation and healing. Since the fins of salmonids appear to be highly innervated and may even function, in part, as mechanosensory organs (Buckland-Nicks *et al* 2012), any biting of fins is likely to be painful. Fin damage in trout was higher when there was food deprivation (Winfree *et al* 1998). Cañon Jones *et al* (2010), using social network analysis, showed that dorsal fin damage in salmon was positively correlated with aggression and fin-biting. It was seen only in groups subjected to feed restriction. Fish initiating aggression were less likely to have fin damage. As a result of the way in which farmed salmon are usually fed, the number of individuals that are feed-restricted increases with stocking density. Fin-biting behaviour and dorsal fin damage in salmon are higher at high than at low stocking density (Cañon Jones *et al* 2011; Hammenstig *et al* 2014). Fin damage may also occur as a result of contact with other fish or with the cage or tank. It is clear that high stocking density is a major cause of poor welfare in salmon, as measured by the number of animals with damaged fins and a range of other welfare indicators. It may be possible to mitigate adverse effects of high stocking density by providing shelter, but further research is needed to find the optimum design (Persson & Alanara 2014). Reduction in the extent of damaged fins has been observed in a re-circulation aquaculture system compared to a flow-through water circulation system, possibly because of lower water alkalinity in the latter system (Kolarevic *et al* 2014).

Stocking density during the freshwater phase

High stocking densities have the potential to adversely affect growth, feed conversion ratio and fin condition, as there is increased competition between the salmon and decreased visibility in the water (Hosfeld *et al* 2009; Riley *et al* 2009). Stocking density is usually expressed as weight of fish per unit volume of water in which they are kept, and maximum densities have been proposed to prevent poor welfare (North *et al* 2006; FW1.5 in RSPCA 2015) (Table 1), although no evidence of the sources for these recommendations is provided. Overt aggression can also be increased at low stocking densities, probably because there is more space in which to fight (Adams *et al* 2007). Great increases in aggression are observed in freshwater if water quality, including dissolved oxygen, declines, with an associated accumulation of fish metabolites, NH_3 and CO_2. The dissolved gases accumulate because of the high stocking densities and minimal water flow, especially in re-circulating water systems. Fish exposed to even low levels of ammonia experience stress and immunosuppression (Ackerman *et al* 2006), but this can be ameliorated in high pH water (Wicks *et al* 2002).

Land-based re-circulating aquaculture systems are intensive methods of rearing salmon, at various stages of development, that incorporate re-use of water after treatment. These are gaining popularity in smolt farms as they minimise water flushing and facilitate water filtration and radiation treatment when necessary. High stocking densities are an inherent feature of these systems, in part to recover the high cost of investment (Martins *et al* 2010) but, as discussed above, welfare will often be worse at higher stocking densities. Maximisation of nutrient retention by the fish and effective treatment and recovery of waste matter is critical to the success of these systems. Carbon dioxide may also accumulate in such systems to the detriment of the welfare of the fish (FAWC 2014b). Total ammonia nitrogen is particularly likely to accumulate in re-circulating water systems, but a partial water re-use system has been developed which controls accumulation of total ammonia nitrogen by make-up water and avoids the use of a biofilter (Summerfelt *et al* 2009). In Chile, potentially toxic levels of heavy metals have also been recorded, but water treatment with crushed marble or sodium silicate is possible (Pessot *et al* 2014).

Norwegian regulations for stocking density of Atlantic salmon brood stock set an upper limit of 25 kg m^{-3} (Hosfeld *et al* 2009) but, because of the multifactorial nature of welfare responses to different stocking densities (EFSA 2008), this density might be too high if, for example, oxygen concentration was low. Adult Atlantic salmon in freshwater circular tanks have been kept at up to 125 kg m^{-3} without elevation of cortisol (Kjartansson *et al* 1988), but adaptation of cortisol response does not mean lack of problems for the fish (Broom & Fraser 2015). The main requirements are for physiological demand for oxygen and the need for space to allow for movements required for locomotion, feeding, and avoidance of contact with other fish.

The impact of stocking density on Atlantic salmon welfare has been reviewed mainly in seawater conditions (eg Stien *et al* 2013a). In terms of freshwater stocking densities, there is limited research on the different stages from egg to smolt before transfer to seawater cages. Hosfeld *et al* (2009) reviewed the impact of four different stocking densities (21, 43, 65, 86 kg m^{-3}) on pre-smolt salmon (mean weight 71 g) during fresh- and seawater stages. They found no general effects of different densities, including the maximum density (86 kg m^{-3}), on fin condition, growth, plasma glucose and chloride, and gill activity. However, they emphasised that no negative effects were found because they used high quality water conditions and sufficient food rations during experimental procedures. Cañon Jones *et al* (2011) observed smolts (mean weight 113 g) under two different densities, high (30 kg m^{-3}) and low (8 kg m^{-3}) and found that some fish in the high-density groups initiated aggression whilst others only received aggression. The more intense aggressive behaviours included fin-biting. The fish in the low-density groups were more frequently aggressive but those in the high-density groups showed more fin-biting and this resulted in more fin damage. The fish in the low-density groups had lower bodyweights and body lengths and poorer body condition, perhaps because of their greater activity. In a study that investigated effects of different densities (from 80 to 310 kg m^{-3}) on Atlantic salmon parr (mean weight 5.8 g), a density of 146 kg m^{-3} was suggested to be an appropriate maximum stocking density, provided water quality could be maintained, to avoid negative impacts on growth, food conversion or mortality, with a preferred density of less than 80 kg m^{-3} (Soderberg *et al* 1993). Soderberg *et al* (1993) and Hosfeld *et al* (2009) came to similar conclusions for the numbers of fish reared in land-based systems, but emphasised the greater importance of the quality and characteristics of water than stocking density. This conclusion was supported by Turnbull *et al* (2008). A note of caution must be sounded regarding research methodology since, in many experiments, stocking density has been varied by altering fish number, without taking into account the fact that changes in group size also affect behaviour and production.

Feeding systems

Efficient feeding systems have not only to meet the salmons' nutrient requirements and minimise water pollution (Alver *et al* 2004) but also result in good salmon welfare. Factors such as appetite, number and size distribution of fish and feed distribution influence pellet concentration in a sea cage and hence discarded pellets (Alver *et al* 2004; Alfredsen *et al* 2007). Agonistic behaviour at feeding times not only adversely affects the fish welfare, it also increases feed intake by dominant individuals and hence causes size divergence within the group, making a uniform product at a single point in time unattainable (Kadri *et al* 1996). Such an effect could lead to a positive feedback situation in which agonistic behaviour causes size disparity and this further increases agonistic behaviour. This is complicated by the fact that at least at low stocking densities Atlantic salmon show territorial behaviour and are able to defend an area within their tank or enclosure, preventing others from accessing pellets that arrive there (Kadri *et al* 1996).

Atlantic salmon are often fed with a pelleted diet through automatic feeding services which can deposit pellets at either a pre-determined rate or at a rate that increases or decreases according to fish activity ('on demand'). They are normally fed in sea cages using a pneumatic conveying system with a rotor spreader (Aarseth *et al* 2006; Oehme *et al* 2012). On-demand feeding systems have been developed to replace imposed regime systems in order that agonistic behaviour and competition are reduced and growth is more uniform within the group of salmon (Noble *et al* 2007b; Lopez-Olmeda *et al* 2012). In a study with salmon parr, the on-demand system reduced dorsal fin injuries, competition and overfed fish, leading to more efficient food conversion (Noble *et al* 2007b). Offering a single daily meal increases conspecific aggression, even though the fish are fed to satiation (Lopez-Olmeda *et al* 2012).

Pneumatic conveying systems have raised a number of concerns as pellets colliding with the pipe wall may break and not be uniformly distributed or go outside the cage and cause water pollution. Therefore, aspects such as the revolutions per minute of the air blower, particle size and spreader arrangements should be considered in the development of an efficient feeding system (Aarseth *et al* 2006; Aas *et al* 2011; Oehme *et al* 2012). Spatial distribution of pellets within an enclosure can influence food intake and water pollution with ammonia, with the type and intensity of the water current playing important roles (Jørgensen *et al* 1996). Circular water tanks with current at the edge produce a more uniform feed distribution over the entire water body compared with water tanks without such currents. Hence, the latter are not used in salmon production, as they lead to aggression, lower growth rates and more individual and group food intake variability (Jørgensen *et al* 1996).

Modifying fish feeding behaviour represents a useful tool for determining feeding regime efficiency (Alver *et al* 2004; Alfredsen *et al* 2007), with information on swimming patterns and spatial distribution of the fish contributing to improved feeding systems, providing that they can be accurately measured (Føre *et al* 2011). Salmon show fast swimming in a vertical orientation towards pellets during high intensity feeds, disrupting their natural schooling behaviour. Depth transmitters have revealed that fish approach the surface zone during feeding (1–2 m) and later swim to deeper areas (8–9 m) (Føre *et al* 2011).

Salmon feed in a synchronised fashion and feeding rhythms need to be considered when implementing feeding systems, as they can influence appetite, consumption, uniformity of growth, feed wastage and water pollution. Natural feeding rhythms are primarily circadian and seasonal, but tidal and lunar rhythms are also reported (Lopez-Olmeda *et al* 2012). Salmon are preferentially diurnal feeders but, at certain stages in their lifecycle, can seasonally change to nocturnal feeding under natural feeding conditions (Lopez-Olmeda *et al* 2012). Thus, season has to be considered when attempting to feed the fish at their most active time of day. Salmon parr also have natural feeding rhythms that vary with season, including a morning peak in late summer, and a midday feeding during spring (Noble *et al* 2007a). Attempts to maintain their natural behaviour, and hence welfare, should take this into account. The daily ration is also affected by seasonal and environmental factors, correlated with temperature variations and day length in on-demand feeding systems. Highest intake has been observed at 14°C and lowest at both 18 and 6°C in Atlantic salmon smolts (Handeland *et al* 2008).

The predictability of the feeding time can influence feed intake and stress levels in the fish. There is increased frequency and severity of dorsal fin damage when there is unpredictable feeding of 1+ salmon parr. However, aggression and attacks can also occur with predictable feeding, probably because of food anticipatory activity (Cañon Jones *et al* 2012). When food was distributed consistently at the same time and place, dominant fish ate first at the surface and the subordinate ones later, with the latter using different strategies, such as eating in the middle or bottom of the sea cage (Kadri *et al* 1996). Some fish may receive no food at all. In other farmed animals, feeding systems that seriously disadvantage subordinate animals are either not recommended or not permitted. Feeding systems that result in starvation (a severe deficiency in the intake of nutrients necessary for the maintenance of life; Anon 2018) and severely damaged fins for a significant number of salmon would clearly be unacceptable to most consumers. As the fish that consumed most had less variation in day-to-day intake, Kadri *et al* (1996) recommended unpredictable feeding times to make intake more even across fish. However, this might lead to more fin damage. Cañon Jones *et al* (2012) found that with an unpredictable feeding time, initiators of aggressive interactions were heavier and longer and had less fin damage in comparison with receivers. The solution would seem to be to find better feeding systems. The range of size in fish groups is normally recommended to be kept to a minimum (eg Cañon Jones *et al* 2012) but some authors suggest the use of older fish (1+ parr) within a younger group (0+ parr) to reduce agonistic behaviours (Adams *et al* 2000). The older fish should not be of a size where they might eat the younger fish so this might be difficult to manage.

Slaughter procedures

Pre-slaughter fasting

Fasting is routinely used just prior to slaughter primarily so that the fish have minimal gastrointestinal contents post-slaughter (Einen *et al* 1998). Other aims are to reduce metabolic rate and physical activity and hence oxygen consumption prior to transport to slaughter (EFSA 2009; RSPCA 2012; FAWC 2014a). The removal of food from animals that have been fed on a regular basis results in stress, as evidenced by a cortisol response (Waagbø *et al* 2017) and possibly poor welfare, and should never be carried out unless essential. Even then, food reduction should be carried out progressively, never abruptly, to a maximum of three days at normal temperatures, which is sufficient to empty the gut (Einen *et al* 1998), or up to seven days at low temperatures (Waagbø *et al* 2017). Two days of fasting will reduce tissue mass and metabolic enzyme activity (Krogdahl & Bakke-McKellep 2005). Some salmon producers use longer periods of food deprivation during periods of overproduction and oversupply but this constitutes deliberate starvation. Although salmon slow their metabolism when deprived of food in this way, including reduced activity in organs related to swimming and nutrition, there is no evidence that this reduces stress responses prior to slaughter because they are conserving energy for digestion and metabolic processes (Waagbø *et al* 2017). The argument that wild fish experience periodic food deprivation, and survive it, does not necessarily mean that it is not a welfare problem for the fish. Wild mammals also survive starvation but it is not permitted for captive mammals. However, the adaptive growth changes of fish may mean that the longer-term effects of food deprivation are less in fish than in mammals or birds. A long period of starvation (eg five weeks) may improve fillet quality (Morkore *et al* 2008) but probably harms the fish if it suppresses emergency responses.

Pre-slaughter handling

Crowding, capture and pumping are all potentially stressful to salmon (EFSA 2009) but there is a lack of quantitative scientific data on welfare at these times. Indicators of poor welfare during the crowding procedure are: escape behaviour, air gasping, colour change, lateral rotation, increased number of tail beats and turns and presence of fish scales in the water (EFSA 2009; FAWC 2014a). It is recommended that the maximum total duration of periods of such treatment should be 2 h (RSPCA 2012; FAWC 2014a) and that high stocking densities should be avoided at these times (FAWC 2014a). Inadequate pumping systems may produce physical damage and stress, and therefore observations must take place after this to guarantee that the fish can swim and maintain equilibrium, without inversion, signs of asphyxiation or leaping out of the water (HSA 2005; EFSA 2009; Lines & Spence 2012).

Pre-slaughter chilling

Chilling of salmon is commonly used to cool their muscles, reduce activity before slaughter, avoid panic responses to crowding and delay the onset of rigor (Foss *et al* 2012). Scientific studies since the Stien *et al* model have shown that salmon cope with a reduction of water temperature from 16 to 4°C in 1 h and or 16 to 0°C in 5 h without an increase of cortisol (Foss *et al* 2012). More extreme chilling, from 16 to 0°C in 1 h, resulted in severe stress and death. Live-chilling procedures can attenuate pre-slaughter stressors, such as crowding (Skjervold *et al* 2001; Foss *et al* 2012), but a review of studies of the effects of chilling on various species of fish has concluded that cold shock may paralyse the fish so that they lose sensibility slowly and are unable to display signs of suffering (Lines & Spence 2014).

Methods of stunning pre-slaughter

The aim of any method used to slaughter fish is to produce instantaneous unconsciousness without stress and pain (EFSA 2009). Although early research indicated that electrical stunning had reduced effectiveness compared with percussive stunning, with injuries to the spinal cord, aorta and veins (Roth *et al* 2003) and death as a frequent outcome (Roth *et al* 2007), more recent research has indicated that electrical stunning of small fish is humane (Roth *et al* 2012; Kleingeld 2013). If used for salmon, either in water (wet stunning) or out of water (dry stunning), they are likely to die from hypoxia before they are able to recover consciousness (Lines & Spence 2014). The placement of fish to avoid pre-stun shocks is important. Percussive stunning using a club, or 'priest', is the traditional method, but automated percussive stunning is the method recommended in Europe (EFSA 2009; FAWC 2014a). The method must be prepared according to fish size (Lines & Spence 2012), and the type of hammer and force used are two key aspects that must be considered to minimise the number of fish that fail to be effectively stunned and avoid injuries (Roth *et al* 2007). According to Roth *et al* (2007), the cylindrical hammer is the best shape that produces a general shaking of the entire brain, rather than other shapes that damage the skull but may not stun the fish. Other shapes are problematic because of the small size of the brain. The scientific evidence about the force applied to the head of the salmon is that forces below 72 N do not reliably produce unconsciousness in some fish. Forces incorrectly applied, which may be higher forces than this, affect welfare if the fish is not stunned but has painful damage, such as eye haemorrhage or eye burst. Manual percussive stunning should be avoided as this is a less-efficient method, except in those cases where the automated method fails (FAWC 2014a). In both cases, consciousness could be checked by seeing if a fish shows eye roll and breathing reflexes (EFSA 2009).

EFSA (2009), Kleingeld (2013) and FAWC (2014a) do not recommend the use of carbon dioxide (CO_2) (with or without chilling water) and asphyxia as these methods have resulted in evidence of very poor welfare and slow onset of insensibility in different farmed fish species, including Atlantic salmon. Norway recently banned the use of CO_2 as a stunning method (Bjørlykke *et al* 2013). Erikson *et al* (2006) suggest that mild carbon dioxide CO_2 combined with live chilling is a less stressful procedure than traditional CO_2, but physiological and behavioural indicators of poor welfare were not included in their study, so their conclusion is not justified. If fish are not stunned but left to die of asphyxia in air, the welfare will be very poor for the period prior to unconsciousness. This period is much longer if the fish are on ice. In trout, the period before unconsciousness during asphyxia in air is 10 min at 2°C as compared with 3 min at 14°C (Robb & Kestin 2002).

Despite the fact that carbon monoxide (CO) is largely insoluble in water, it has been investigated as an alternative stunning method (Bjørlykke *et al* 2011, 2013). Bjørlykke *et al* (2013) investigated CO at two concentrations for 60 and 120 min. Cortisol elevation and behavioural observations indicated an aversive response to CO, but this could have been due to other elements of the experiment, such as turbulence and handling. However, it took 30 min for respiration to cease after a transition period with significant gasping. The very low solubility makes it unlikely to be usable for killing fish.

Research developments since the publication of the Stien *et al* model

Publications on fish welfare continue to increase in number and impact (Huntingford & Kadri 2014). As well as providing a means of reducing sea lice infestation, Stien *et al* (2013b) recognised the importance of using submersible lighting in sea cages to avoid salmon schooling at high densities near the surface at night to obtain light and potentially leading to frustration. A study by Handeland *et al* (2013) has identified that provision of adequate light is also important during the smolt stage in Atlantic salmon. Light intensities between 10 and 650 lux were tested. Although a minimum of 43 lux was required to avoid suppressing growth and quality of the smolts, the major welfare concern of inadequate light, that of spinal abnormalities, was kept within 1–3% of the fish at all intensities except 10 lux, when it increased significantly to 6.9% of the fish.

Several advances in identifying nutritional requirements of Atlantic salmon have been made, which could be used to elaborate on the definition of adequate nutrition in the Stien *et al* (2013a) model. The model used two output (animal-related) rather than input (feed-related) measures: emaciation and fish condition. Adequate histidine supply is vital in avoidance of cataracts, with a critical level of 14.4 g histidine per kg feed determined (Remo *et al* 2014). Stien *et al* (2013a) had identified that high stocking density at sea was a factor influencing the development of cataracts, particularly when density exceeded 26.5 kg m^{-3}. Similarly, a high energy diet has been linked to fatty deposits in the cardiac ventricles of farmed, but not wild, Atlantic salmon, potentially predisposing them to cardiac disease (Kristensen *et al* 2012). Whilst it is recognised that it is not possible to incorporate these dietary requirements into the Stien *et al* (2013a) model, further developments along these lines would enable more accurate dietary standards for fish welfare (rather than growth and development) to be developed.

Animal welfare implications and conclusion

As with other farm animal species, the transport of salmon can cause poor welfare and increased mortality. To minimise poor welfare, it is important to reduce the time spent handling and capturing juvenile fish, build land facilities close to seawater facilities, and improve loading procedures and water quality. Adaptation to the sea-cage condition requires further research.

Stocking density should be considered as one of the most important of the interacting factors that affect Atlantic salmon welfare (Turnbull *et al* 2008). In order to propose an appropriate maximum density for Atlantic salmon during the freshwater stage, the specific conditions used to maintain juvenile salmon should be investigated, taking into account water characteristics, the design of tank and feeding systems in particular. When deciding on new laws and standards, or revising old ones, both maximum stocking density and other welfare indicators should be specified to ensure fish welfare. Stocking densities of salmon in fresh- or seawater should be lower than those that result in fin damage.

In order to guarantee an adequate feed intake by all salmon, several factors should be considered and reviewed, such as feeding rhythms, optimal temperature for feeding and water current, among others. Many currently used feeding systems result in starvation for some fish and fin damage for others, so hence they are unacceptable. On-demand systems seem to be a better solution as they have improved welfare, nonetheless further research should take place integrating additional welfare measurements.

All farmed fish should be stunned, not left to die of asphyxia. Electrical stunning is widely used for smaller fish species but some currently available equipment may not be suitably set for salmon (EFSA 2009; Line & Spence 2014). Carbon dioxide does not stun salmon humanely. The widely used methods of percussive stunning, manual or automatic, have to be precise to effectively stun large numbers of fish. Alternative methods have been investigated but, so far, they do not produce better welfare or carcase quality.

Our ability to assess pain and other welfare problems in salmon is improving rapidly. Welfare outcome indicators, such as fin damage, morbidity and mortality rate, should be used in standards and laws relating to salmon welfare. Standards are already used in accreditation schemes as many consumers prefer ethically produced Atlantic salmon (Martinez-Espirana *et al* 2015). All of the concerns listed above, some of which are not included in the Stien *et al* (2013a) model of animal welfare, should be taken into account when monitoring the welfare of fish in the Atlantic salmon industry. Those in the industry who change methodologies to improve salmon welfare before more consumers start avoiding purchasing the product will benefit from doing so.

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